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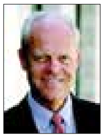

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Conference 10082: Solid State Lasers XXVI: Technology and Devices

Monday - Thursday 30–2 February 2017

Part of Proceedings of SPIE Vol. 10082 Solid State Lasers XXVI: Technology and Devices

10082-1, Session 1

Engineering beams in space and time with higher order Bessel beams *(Invited Paper)*

Eric G. Johnson, Keith Miller, Yuan Li, Indumathi Raghu Srimathi, Wenzhe Li, Kaitlyn Morgan, R. Watkins, Clemson Univ. (United States)

Laser beam shaping in space and time has numerous applications in high power lasers for machining, sensing, and communication systems. In recent years, technological advances in lasers and optics have enabled a variety of new functions that can be integrated into a laser platform with spatial and temporal control. This talk will provide an overview of recent advancements in this subject with specific examples using spatial and temporal multiplexing for underwater communications to high power laser beam propagation.

10082-2, Session 1

Optical vortex pumped solid-state Raman laser

Yoshihiro Nishigata, Chiba Univ. (Japan); Cheng-Yeh Lee, National Chiao Tung Univ. (Taiwan); Yuji Miyamoto, Katsuhiko Miyamoto, Chiba Univ. (Japan); Yung-Fu Chen, National Chiao Tung Univ. (Taiwan); Takashige Omatsu, Chiba Univ. (Japan)

Optical vortex carries orbital angular momentum characterized by an integer l called the topological charge arising from the azimuthal phase in a cylindrical coordinate. To date, the nonlinear frequency conversion of the optical vortex, e.g. second harmonics generation, sum frequency generation and optical parametric generation based on the second-order nonlinearity has been widely investigated, in which the conservation of topological charge between the pump and the resulting photons has been observed experimentally.

The Raman laser based on the stimulated Raman scattering is also a practical and efficient solution to offer laser radiation with the spectrum that are difficult to achieve using conventional technology. However, there are few reports, to our best knowledge, of the optical vortex pumped Raman lasers, in which the topological charge of pump beam is shared by the Stokes output and the phonon.

In this paper, we demonstrated a 532nm nanosecond optical vortex pumped solid-state Raman laser formed of a Raman active crystal, $Ba(NO_3)_2$, to efficiently generate cascaded vortex first- and second-Stokes outputs. The topological charges of the first- and second-Stokes outputs were also investigated by utilizing a self-referenced interferometric technique.

When the system was pumped by the second-order optical vortex, the first- and the second-Stokes vortex outputs exhibit the topological charge of 1, indicating the topological charge sharing between the Stokes output and the phonon. The optical-optical conversion efficiencies from the pump output to the first- and second order Stokes output were obtained to be 16.4% and 6.6%, respectively.

10082-3, Session 1

Radially-polarised beam amplification in an Yb:YAG thin-slab architecture

Callum R. Smith, Stephen J. Beecher, Jacob I. Mackenzie, W. Andrew Clarkson, Optoelectronics Research Ctr., Univ. of Southampton (United Kingdom)

Radially-polarised beams are attracting growing interest owing to their unique properties and numerous applications. Power-scaling whilst preserving the polarisation-purity of radially-polarised beams is challenging, with efforts predominantly focused on cylindrically-symmetric systems.

We explore an alternative strategy for power-scaling radially-polarised beams using a thin-slab amplifier geometry, which, to the best of our knowledge, has not been previously investigated. We show that very high radial polarisation-purity can be maintained in an architecture that can be operated at high powers.

A radially-polarised seed-source was constructed using an Yb:YAG rod in a plane-parallel configuration, pumped by a capillary delivery-fiber which provided effective overlap with the LG01 mode. By tuning the cavity length and utilising thermally-induced birefringence, a robust multi-Watt LG01 mode was generated with an excellent radial polarisation-purity of 15dB and good beam quality M2=2.2.

The Yb:YAG slab was pumped by a diode-bar producing a highly-elongated inversion region. The seed was amplified in a double-pass configuration, using a cylindrical lens to spatially-match the inversion. The output beam was re-collimated by the cylindrical lens, and compensation for the Gouy phase-shift was made using a half-waveplate.

At 50W of incident pump power we obtained a small-signal gain of 7.5dB and a power gain of 4.5dB for 1.45W seed power. At maximum pump power the radial polarisation-purity was maintained at 15dB, and the beam quality only degraded slightly to M2=2.3. Further optimisation of slab design and pump geometry will be discussed in addition to power-scaling the system to higher output powers necessary for a range of applications.

10082-4, Session 1

Pulsed amplification of 2 μm composite vortex beams

Keith Miller, Yuan Li, Wenzhe Li, Clemson Univ. (United States); Ramesh K. Shori, SPAWAR Systems Ctr. (United States); Eric G. Johnson, Clemson Univ. (United States)

In this effort, we report on the preservation of the spatial mode quality as composite vortex beams propagate through a flashlamp pumped amplifier system. Because of the spatially asymmetric nature of the transient thermal lensing, a laser beam propagating through this type of amplifier will be distorted. This makes an ideal environment to assess the mode integrity of propagating composite vortex beams. We demonstrate that a 3-lobe composite vortex beam can propagate under extreme transient thermal lensing and maintain the mode structure through the amplification process. Even though the actual amplification wasn't the main thrust of this effort, we demonstrate gain greater than a factor of 4 for two different seed energy levels. Since the flashlamp pumped system is an extreme case, this result shows the potential for using concentric vortex beams in high power amplifiers and could open up new applications in propagation and sensing.

10082-5, Session 1

Utilizing non-Gaussian beams to tailor laser propagation *(Invited Paper)*

Lawrence Shah, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

This presentation will report results from several research efforts

demonstrating the utility of phase plates to generate tailored beam distributions. The applications utilizing such beams are wide ranging. These span from mitigation of turbulence and thermal lensing/blooming associated with the propagation of lasers in the 2 um wavelength regime to structuring the spatial phase of femtosecond laser beams for the generation of arrays of filaments.

10082-6, Session 1

Recent advances in high-power radially and azimuthally polarized thin-disk lasers

(Invited Paper)

Michael Eckerle, Marwan Abdou Ahmed, Univ. Stuttgart (Germany)

No Abstract Available

10082-7, Session 2

Lasing efficiency of Er-Yb-Cr-glass: A temperature study

Simi A. George, Joseph S. Hayden, Mark J. Davis, SCHOTT North America, Inc. (United States)

Retina-safe operation in open-air is of high interest to the next generation of lasers that are being utilized for many industrial, defense and medical applications. Those wavelengths that are considered to be the best for retina safe operations (also called eye-safe) fall in the range between 1400nm and1800nm. This wavelength region also coincides with the low loss window of fused silica fibers used for optical fiber communications [1], where the S and C bands near 1500nm are heavily utilized for long range communications due to the lowest attenuation losses possible in the fiber. The trivalent Er ion can produce direct emission into the 1540 nm wavelength, thus, it is the rare-earth emitter of choice for many eye-safe applications. In recent years, the need for high beam quality under passive operation in open air applications have renewed interest in Er-doped bulk glasses as the gain material of choice for solid-state eye-safe lasers.

The need for performance stability under a broad operating range from -400C to 1000C without active cooling is a challenge for amorphous gain materials. Moreover, there is very little known about how temperature may affect performance. In this study, we describe our first attempts to understand material behavior by systematically analyzing temperature driven variations exhibited in absorption and emission from the commercially available gain materials. As part of these investigations, we will also present our method for assessing quantum efficiency through measurements for critical evaluation from laser community at large.

10082-8, Session 2

Compact sources for eye-safe illumination

Nadia Baranova, Q-Peak, Inc. (United States); Rui Pu, Celera Motion (United States); Kenneth E. Stebbins, Ilya Bystryak, Michael Rayno, Kevin M. Ezzo, Chris DePriest, Q-Peak, Inc. (United States)

Q-Peak has demonstrated a novel, compact, pulsed eyesafe laser architecture operating with >10 mJ pulse energies at repetition rates as high as 160 Hz. The design leverages an end-pumped solid-state laser geometry to produce adequate eyesafe beam quality (M2 ~4), while also providing a path towards higher-density laser architectures for pulsed eyesafe applications. The baseline discussed in this paper has shown a unique capability for high pulse repetition rates in a compact package, and offers additional potential for power scaling based on birefringence compensation.

The laser consists of an actively Q-switched oscillator cavity producing pulse-widths <30 ns, and utilizing an end-pumped Nd:YAG gain medium with a Rubidium Titanyl Phosphate (RTP) electro-optical crystal. The oscillator provides an effective front-end-seed for an optical parametric oscillator (OPO), which utilizes Potassium Titanyl Arsenate (KTA) in a linear OPO geometry. This laser efficiently operates in the eyesafe band, and has been designed to fit within a volume of 3760 cm3.

We will discuss details of the optical system design, modeled thermal effects and stress-induced birefringence, as well as experimental advantages of the end-pumped laser geometry, along with proposed paths to higher eyesafe pulse energies.

10082-9, Session 2

Er:YGG planar waveguides grown by pulsed laser deposition for LIDAR applications

Jacob I. Mackenzie, James A. Grant-Jacob, Stephen J. Beecher, Optoelectronics Research Ctr., Univ. of Southampton (United Kingdom); Haris Riris, Anthony W. Yu, NASA Goddard Space Flight Ctr. (United States); David P. Shepherd, Robert W. Eason, Optoelectronics Research Ctr., Univ. of Southampton (United Kingdom)

Differential absorption LIDAR (LIght Detection And Ranging) from earth orbiting satellites provides a route to mapping, with unprecedented detail, the creation, movement and storage of various gas species in our atmosphere. For two key green-house gases, CO2 and methane, it is possible to exploit LIDAR in the 1.6-micron regime where there are suitable absorption features and good photodetectors. Planar waveguide amplifiers (PWAs) provide a route for achieving high gains in compact devices, through their ability to maintain strong population inversions over longer distances than possible in bulk systems, and in a MOPA configuration, could enable direct amplification of low-powered single-frequency diode lasers to the required power levels. Er:YGG planar waveguides are promising amplifier candidates, offering emission peaks aligned with absorption bands of both gas species of interest. We have grown, for what we believe is for the first time, erbium-doped YGG crystal planar waveguides, demonstrating fast 20micron/hour growth of low-loss (<<1dB/cm) single-crystal films and a capability to engineer the crystal and waveguide properties. Preliminary analysis of the active core demonstrates we have a high-quality ~1at.% Er-doped YGG crystal, with single-pass internal gain measurements made at 1533 nm and 1572 nm, which, with new PWA configurations and increased pump power will enable these devices for LIDAR applications.

10082-10, Session 2

2μm solid-state laser with compact mechanical and passive Q-switches

Brian J. Cole, Lew Goldberg, U.S. Army RDECOM CERDEC NVESD (United States)

Q-switched lasers at 2μm are required for medical applications, spectroscopy, LADAR, and as a pump for mid-IR Optical Parametric Oscillators. In this paper, we describe a diode-pumped, Tm:YALO solid-state laser with a compact mechanical Q-switch. This approach for Q-switching the 2μm laser has significant size, power and cost advantages compared to acousto-optic or electro-optic Q-switching methods. The Q-switch used a mirror mounted on a resonant metal cantilever that was driven by a small electromagnetic coil at multi-kHz frequencies. The laser used a 7 mm long 4 at.% Tm:YALO crystal that was end-pumped using a 794nm fiber coupled pump. When the mechanical Q-switch was operated at 2kHz resonant frequency, a 4kHz Q-switched pulse train was generated under CW pumping conditions. An optical slope efficiency of 43% and an optical-to-optical

conversion efficiency of 30% was measured. At a 16W pump power, the laser emitted 1.3 mJ, 30 ns FWHM Q-switched pulses, generating 5W of average power. This paper will address the merits of mechanical Q-switching for compact 2μm lasers, and compare its performance to that achieved in the same laser cavity when passive Q-switching using Cr:ZnS was employed.

10082-11, Session 2

Initial characterization of a Tm:Lu2O3 ceramic disk laser

Drew A. Copeland, John Vetrovec, Amardeep S. Litt, Aqwest, LLC (United States); Eldridge Briscoe, Steven Jensen, General Atomics Aeronautical Systems, Inc. (United States)

We report on initial testing of Tm:Lu2O3 disk laser with tunable output in the vicinity of 2-μm. The laser uses a novel Tm:Lu2O3 ceramic gain material offering much smaller saturation fluence and improved slope efficiency than the traditionally used Tm:YLF and Tm:YAG materials. The Tm:Lu2O3 disk is edge-pumped by 796-nm diodes, which results in a very simple and compact laser gain module. The "2-for-1" energy transfer mechanism of Tm ion enables high efficiency. High thermal conductivity of the Lu2O3 host in combination with low heat fraction supports operation at high-average power. Ceramic nature of the Lu2O3 host overcomes the scalability limits of single crystal sesquioxides. Tm:Lu2O3 offers wide-bandwidth amplification of ultrashort pulses in a chirp-pulse amplification (CPA) system. Measurements of spectral properties, output wavelength tuning, laser power, and thermal response of the gain material under kW-class pumping are presented. This work was supported in-part by the US Department of Energy grant number DE-SC0013762.

1. J. Vetrovec, D. Copeland, A. Litt, E. Briscoe, "Wide-Bandwidth Ceramic Tm:Lu2O3 Amplifier," SPIE 9834-4

10082-12, Session 3

Cr:ZnSe guided wave lasers and materials *(Invited Paper)*

Sean McDaniel, Air Force Research Lab. (United States) and Leidos, Inc. (United States); Adam Lancaster, Heriot-Watt Univ. (United Kingdom); Ronald W. Stites, Air Force Research Lab. (United States); Fiona Thorburn, Ajoy K. Kar, Heriot-Watt Univ. (United Kingdom); Gary Cook, Air Force Research Lab. (United States)

We describe a variety of technological advances in the development of efficient, powerful, and continuously tunable Cr:ZnSe lasers operating in the 2.3-2.7 μm spectral region. This includes the development of compact "single chip" waveguide Cr:ZnSe lasers, waveguide mode-locked Cr:ZnSe lasers, and the creation of homogeneously broadened laser material.

10082-13, Session 3

Near-IR, visible and UV laser sources via harmonic conversion of 2-um holmium lasers

Michael Bethel, Alex Dergachev, Dan Perlov, IPG Photonics Corp. (United States)

Resonantly-pumped Holmium-doped lasers are extremely versatile, high-beam quality laser sources near 2-um-wavelength capable to produce high pulse energy and/or high average power with laser pulse width at ns- or ps-time scale.

Frequency conversion of high-energy, high-pulse-rate 2-um, Ho-lasers is an efficient way to achieve multi-mJ pulse energies in near-IR, visible and UV spectral ranges via variety of harmonic generation schemes. Multitude of mixing interactions (starting with fundamental wavelength of 2-um) allows generation of any harmonic from 2nd thru 12th.

Here we report efficient generation of the 2nd (1025 nm), 3rd (683 nm), 4th (512.5 nm) and 8th (256 nm) harmonics with record efficiency reaching 60-70% and tens of mJ pulse energy utilizing RTP, LBO and BBO crystals.

As a pump source we utilized a Tm-fiber-laser pumped Ho:YLF laser with diffraction-limited beam quality operating at 2050 nm. The maximum pulse energy was limited to ~45 mJ when operating at up to 1 kHz pulse rates. Typical laser pulse width was ~10-14 ns range resulting in maximum peak power of ~ 4.5 MW.

10082-14, Session 3

Fe:CdMnTe active material spectroscopic properties and laser generation around 5 um

Helena Jelínková, Czech Technical Univ. in Prague (Czech Republic); Maxim E. Doroshenko, A. M. Prokhorov General Physics Institute of the Russian Academy of Sciences (Russian Federation); Michal Jelínek Jr., Jan ?ulc, Czech Technical Univ. in Prague (Czech Republic); Vjatcheslav V. Osiko, A. M. Prokhorov General Physics Institute of the Russian Academy of Sciences (Russian Federation); Nazar O. Kovalenko, Andrey S. Gerasimenko, Institute for Single Crystals (Ukraine)

Fe:Cd(1-x)Mn(x)Te solid solution spectroscopic and lasing properties depending on temperature and Mn concentration were investigated. A set of Fe2+:Cd(1-x)Mn(x)Te crystals with different concentration of Mn (x = 0.1, 0.52, 0.68 and 0.85) was synthesized using Bridgeman technique with Fe2+ ions doping (c ~ 1017 cm-3) during the synthesis process. The absorption spectra are broad covering the range from 2700 to 6000 nm with the maximum around 3500 nm. The fluorescence spectra are also broad lasting from 3500 nm to 7000 nm. For x=0.1 the maximum is located around 5150 nm and it is shifted further to ~5300 nm for x=0.85.

The low temperature (77 K) lifetime of Fe2+ ions was measured to be 155 us for x=0.1 slightly decreasing to 135 us for x=0.85. In the laser experiments the Fe:CdMnTe samples were placed in a cryostat between the flat dichroic pumping mirror (HR at 5000-5800 nm, T~70 % at 4 um) and concave output coupler (r = 150 mm, R = 99 % at 5100-5500 nm). Laser oscillations from this active material were achieved for the first time with the output energy of several microjoules. The central output wavelength at 77 K was 4950 nm for x=0.1 and 5250 nm for x=0.85. Long wavelength shift of oscillation wavelength with temperature (4950-5290 nm for x=0.1) was observed.

10082-15, Session 3

Mid-IR CW Cr:ZnS laser tunable with acousto-optical filter

Dmitry V. Martyshkin, Taylor Kesterson, Vladimir V. Fedorov, Sergey B. Mirov, The Univ. of Alabama at Birmingham (United States)

Transition metal (Fe, Cr) doped II-VI chalcogenide lasers are known to have very attractive features such as broad emission spectra, allowing access to an appealing middle-infrared (mid-IR) spectral range, and broad absorption spectra, allowing for a variety of pump sources. A major interest in lasing in this mid-IR regime comes in remote sensing of organic compounds for environmental, industrial, and medical applications. Such sensing requires narrow-linewidth mid-IR lasers with broad tuning range as well as fast switching between oscillation wavelengths and/or random access to the oscillation wavelength. Mid-IR lasers based on chromium and iron doped ZnSe/ZnS/CdSe gain elements have demonstrated 1.9-6.0 μm tuning range and narrow oscillation linewidth (<70 kHz), making them perfect candidates for a variety of sensing applications. Acousto-Optic Tunable Filters (AOTF) based on Bragg diffraction are able to adjust the oscillation wavelength without the use of mechanically moving parts: programmable and fast switching between pre-selected wavelength. Here, we report on the CW acousto-optically tuned Cr:ZnS laser pumped by CW Er-fiber laser. The laser oscillation tuning from 1890 nm to 2785 nm spectral range was demonstrated by varying the radio-frequency at the TeO2 AOTF from 30.3 MHz to 20.12 MHz. The slope efficiency in the maximum of tuning curve was measured to be 40% with respect to pump power with pump threshold at 2W of incident power. The linewidth of the Cr:ZnS laser measured at central wavelength was <0.8 nm. A maximum output power of 2.8 W was achieved at 2.23 μm under 10.7 W of pump power.

10082-16, Session 4

Yb:YAG disc for high energy laser systems

Karel Nejezchleb, Jan Kubát, CRYTUR spol s.r.o. (Czech Republic); Jan ?ulc, Helena Jelínková, Czech Technical Univ. in Prague (Czech Republic)

Large Yb:YAG crystals were grown using of new improved technology of crystal growth, which enables to grow YAG crystals without central growth defect. The diameter of crystals reached 115 - 120 mm. Central homogenous part of crystals was useful for manufacturing of both sides polished and coated discs of the diameter larger than 55 mm. Doping concentration of Yb3+ ions in Yb:YAG crystals was measured using of X-ray fluorescence spectrometry. Absorption coefficient was measured for different doping concentrations of Yb:YAG at main pumping wavelengths of 940 and 968 nm. Fluorescence decay time of Yb:YAG was measured at the temperatures of 300 K and of 80 K. We found the fluorescence decay time of the values of 0.95 - 1 ms at both temperatures stable and independent on the Yb3+ doping concentration in the range of 1 – 10 at. % Yb/Y, which demonstrates high chemical purity of grown crystals. Optical homogeneity as measured using of Fizeau double pass interferometer at 633 nm resulted with PV values lower than 0.15 lambda on clear aperture of 35 mm. Polished surfaces were ideally parallel with the wedge lower than 2 arcsec. Uniformity of laser properties of Yb:YAG was verified by scanning of the disc as active media in plan-convex pulsed laser resonator pumped by semiconductor diode beam of the diameter of 100 microns and the wavelength of 969 nm. It was confirmed, that newly developed technology allows to manufacture very large high-quality Yb:YAG discs suitable for high power lasers and amplifiers.

10082-17, Session 4

Analytical calculation of temperature profiles in solid state laser disks mounted on multi-layered heat spreaders using Hankel transforms

Norman Hodgson, Andrea Caprara, Coherent, Inc. (United States)

The main challenge in disk laser design is the realization of efficient heat removal from the pumped area by optimizing the heat spreader design and the water impingement cooling. This generally requires the calculation of the temperature distribution in the disk by numerically solving the heat conduction equation using finite element algorithms.

We have developed a simple method to calculate disk temperature profiles that is based on analytically solving the heat conduction equation in Hankel Transform Space. This method can be applied to disks that are mounted on multi-layered, water-cooled heat spreaders, which may include glue or solder layers and dielectric coating layers. The temperature and heat fluxes at the interfaces of the layers are connected by a heat transfer matrix, which allows for straight-forward incorporation of additional heat sink layers or adding un-doped caps into the model. This leads to a generalized model to calculate the heat distribution in pumped solid state laser and semiconductor laser disks which enables the parametric optimization of the heat removal without having to use finite-element programs.

We will present the theoretical model and apply it to different disk geometries. The effects of the heat spreader material, the heat spreader thickness, the glue layer thickness, and of capping the disk with additional heat spreaders will be discussed.

10082-18, Session 4

Multi-pass resonator design for energy scaling of mode-locked thin-disk lasers

Karsten R. F. Schuhmann, Klaus S. Kirch, Aldo S. Antognini, ETH Zürich (Switzerland)

We present a resonator design which solves present energy scaling limitations of mode-locked multi-pass lasers. Contrarily to the state-of-the-art layouts based on 4f imaging the stability region of our multi-pass oscillator does not shrink with the number of passes at the active medium. Hence our design sustains an order of magnitude larger thermal lens variations compared to present multi-pass designs implying that an order of magnitude larger output power can be reached.

Our resonator consists of a succession of the same optical segment. Each segment represents a stable optical cavity containing at least one pass at the active medium. Disruption of the stability region seems to occur when we allow for segment-to-segment deviations related with the practical realization of the multi-pass system. However, we demonstrate that the inclusion into the simulations of aperture effects which naturally occur in an active medium suppresses these instabilities. The resulting stability region of the multi-pass resonator becomes as large as the stability region of the single segment. Therefore the stability region of our multi-pass resonator does not scale with the number of passes. Simulation of the eigen-mode of this multi-segment resonator thus requires considering aperture effects. This can been achieved by implementing effective Gaussian apertures into the ABCD-matrix formalism as lenses with imaginary focal length.

10082-19, Session 4

High-average power picosecond thin-disk regenerative amplifiers

Knut Michel, Christoph Wandt, Sandro Klingebiel, Marcel Schultze, Stephan Prinz, Catherine Y. Teisset, Sebastian P. Stark, TRUMPF Scientific Laser GmbH + Co., KG (Germany); Christian Grebing, TRUMPF Scientific Lasers GmbH + Co KG (Germany); Robert Bessing, Tobias Herzig, Matthias Häfner, Thomas Metzger, TRUMPF Scientific Laser GmbH + Co., KG (Germany)

Today thin-disk lasers routinely provide high pulse energies at picosecond pulse durations and kHz repetition rates. Systems with more than 200mJ per pulse are commercially available. After the introduction of the Dira 200-1, providing 200mJ at 1kHz, TRUMPF Scientific Lasers complements its thin-disk regenerative amplifier product portfolio by systems with a few hundred Watts of average output power. Still based on a single disk a flexible laser system with more than 500W was realized. Originally, it was designed for a 50kHz operation, delivering 10mJ pulses, but it also can be set-up for different repetition rates like 10kHz or 100kHz. TRUMPF Scientific Lasers regenerative amplifiers show an excellent long-term performance.

The 500W system has a power stability of 0.5%.

Scientific applications often require higher average output powers, even with high pulse energies. Based on the extensive experience with highest average power continuous wave laser systems by TRUMPF a more powerful regenerative amplifier system is currently under development by TRUMPF Scientific Lasers. This laser uses two disk laser heads inside the same cavity to provide more than 1kW average output power. First tests show an average power of more than 900W inside the cavity only limited by the current available pump power of 2.7kW. The performance is independent on the repetition rate of the laser system. All measurements were carried out at 5kHz and 20kHz, respectively. This system has the potential for kW average output power combined with output energies up to 200mJ per pulse with pulse durations below 2ps.

10082-20, Session 5

Passively Q-switched VCSEL-pumped Nd:YAG laser with 47 mJ pulse energy

Robert Van Leeuwen, Bing Xu, Qing Wang, Guoyang Xu, Delai Zhou, Princeton Optronics, Inc. (United States); Alexey Kovsh, Princeton Optronics Inc (United States); Jean-Francois Seurin, Chuni L. Ghosh, Princeton Optronics, Inc. (United States)

Compact, low-cost, Q-switched diode-pumped solid-state lasers (DPPS) with high pulse energy are needed for many applications, such as laser range finders, laser designators, laser breakdown spectroscopy, and laser ignition. In many of those applications the lasers need to operate at high temperatures where typical edge-emitting laser diode pump lasers show poor reliability. High power vertical-cavity surface-emitting laser (VCSEL) arrays make excellent pump sources for diode-pumped solid-state lasers. Key advantages over the existing edge-emitter technology include simpler coupling optics, reduced wavelength sensitivity to temperature, and increased reliability, especially at high temperatures, low-cost manufacturing, and two-dimensional planar scalability. These features make VCSEL technology very well suited for constructing low-cost DPSS lasers with high pulse energy. Last year we reported on a passively Q-switched Nd:YAG laser with 19 mJ laser pulse energy and 13% optical conversion efficiency [1]. Recently, 808 nm pump modules were developed with strongly improved performance in terms of pump power and electrical power conversion efficiency, which translated into a significant improved performance of the Nd:YAG laser. Here we report on a compact passively Q-switched Nd:YAG laser end-pumped by a 2.3 kW 808 nm VCSEL pump module operating in a pulsed mode at 15 Hz pulse repetition frequency producing 47 mJ laser pulse energy at 1064 nm with 16.1% optical conversion efficiency.

1. R. Van Leeuwen, B. Xu, T. Chen, Q. Wang, J. F. Seurin, G. Xu, D. Zhou, and C. Ghosh, “VCSEL-pumped passively Q-switched monolithic solid-state lasers,” Solid State Lasers XXV Proc. SPIE Vol. 9726 97260U-1 (2016)

10082-21, Session 5

A 100J-level nanosecond pulsed DPSSL for pumping high-efficiency, high-repetition rate PW-class lasers

Mariastefania De Vido, Klaus G. Ertel, Paul D. Mason, Saumyabrata Banerjee, Jonathan Phillips, Jodie M. Smith, Thomas J. Butcher, Oleg V. Chekhlov, STFC Rutherford Appleton Lab. (United Kingdom); Martin Divoky, HiLASE Ctr. (Czech Republic); Jan Pilar, HiLASE Ctr., Institute of Physics of the ASCR, v.v.i. (Czech Republic); Chris J. Hooker, Waseem Shaikh, STFC Rutherford Appleton Lab. (United Kingdom); Antonio Lucianetti, HiLASE Ctr. (Czech Republic); Cristina Hernandez-Gomez, STFC Rutherford Appleton Lab. (United Kingdom); Tomas Mocek, HiLASE Ctr. (Czech Republic); Chris Edwards, John L. Collier, STFC Rutherford Appleton Lab. (United Kingdom)

Laser amplifiers capable of producing energetic nanosecond pulses are required for a wide range of commercial and scientific applications. Recent developments in diode-pumped solid state laser (DPSSL) technology have allowed the realisation of efficient high-energy sources operating at multi-Hz repetition rates. Direct applications of such systems include materials processing, such as laser shock peening, and compression of matter to extreme densities. Alternatively, these lasers can be used as pump sources for Ti:sapphire or OPCPA amplifier chains, for the realisation of the next generation of PW-class lasers. The DiPOLE amplifier concept, developed at the STFC Central Laser Facility, consists in scalable, high-energy DPSSL amplifiers based on cryogenically-cooled, multi-slab ceramic Yb:YAG. In this paper, we report on the successful demonstration of a 100 J level DPSSL system operating at 1 Hz repetition rate and 10 ns pulse duration with an optical-to-optical efficiency of 21% developed for and in collaboration with the HiLASE facility (Czech Republic). To the best of our knowledge, this is the highest energy level and efficiency reached by a nanosecond DPSSL. Frequency doubling of the output beam allows pumping femtosecond amplifier chains for the realisation of high-efficiency, high repetition rate PW-class laser systems. As high output polarisation purity is required in order to achieve a good quality frequency doubled beam, particular attention needs to be devoted to the control of undesired thermal-stress-induced birefringence effects affecting the laser gain medium. In this paper, we present results from thermo-optical simulations performed in order to identify optimal cooling parameters.

10082-22, Session 5

High energy high repetition rate compact picosecond Holmium YLF laser for mid-IR OPCPA pumping

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Here we report a compact Ho:YLF picosecond CPA operating at 2.05 ?m developed for purpose of mid-IR OPCPA pumping. The Ho:YLF CPA consists of bulk stretcher and compressor based on Volume Bragg Gratings (VBG) and of 2 amplification stages, a regenerative amplifier and a cryogenically-cooled multipass amplifier both pumped by a cw Thulium-doped fiber laser operating at 1.9 ?m. The CPA is seeded by a fiber oscillator delivering from the same initial beam the narrowband seed for the 2.05 ?m laser and the broadband seed through a DFG step for the 7 ?m signal of the OPCPA The regenerative amplifier which uses a RTP Pockels cell is operated at room temperature and delivers typically an output energy of 4 mJ for less than 10 W cw pump power whereas the cryogenically-cooled multipass amplifier delivers an energy per pulse up to 100 mJ after 2 passes at a repetition rate of 100 Hz for a pump level about 50 W. We have obtained an energy per pulse of 100 mJ at 100 Hz before compression and the maximum energy achievable after compression by the VBG is 73 mJ with a pulse duration of 17 ps. As current level is limited by laser damage threshold and size of VBG, further energy scaling up to 200 mJ after compression is expected through compression with large area conventional gratings which will allow to use all available pump power.

10082-23, Session 5

High-power optical parametric frequency converters with addressable wavelengths in the infrared

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Based on established short pulse lasers with an output wavelength around 1 µm optical parametric frequency converters open up the spectral range between 1.4 and 4.0 µm for the first time in a power range of interest to laser material processing. The systems can be flexibly adapted as regards wavelength, pulse parameters and spectral properties to the requirements of various applications.

We will discuss technical implementation and characterization of different optical parametric generators (OPG) based on periodically poled Lithium Niobate (PPLN) to show the parameter flexibility of this approach as well as current technical limits. Actual design examples will address output wavelengths around 1.6 µm, 2 µm and 3 µm with output powers ranging from several watts to tens of watts. The pulse parameters of these lasers range from a pulse duration of 9 ps with a repetition rate of 86 MHz to 1.5 ns and 100 kHz.

The spectral bandwidth of the OPG examined can be very large. In particular, spectral bandwidths of about 100 nm are measured at the degenerated point, where the output wavelength is equal to twice the pump wavelength. Even beyond this point, a spectrum of typically a few tens of nanometers width generally accompanies a large conversion efficiency (> 50%). For applications that require a narrower spectrum, the OPG can be operated in a seeded mode, where only a few milliwatts of power from a continuously emitting laser diode are sufficient to seed a pulsed high power OPG efficiently.

10082-24, Session 5

First pulse effect self-suppression picosecond regenerative amplifier

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First pulse effect, commonly seen in nanosecond cavity-dumped lasers and picosecond regenerative amplifiers, not only leads to degradation of processing quality, but also acts as potential threat to optical switching elements. Several methods have been developed to suppress that effect, including electronic controls, polarization controls, and diffraction controls.

We present a new way for first pulse self-suppression without any additional components. By carefully arranging the cavity mirror of a regenerative amplifier, we realized 'parasitic lasing like' radiation. When the regenerative amplifier works in 'operation ready' status, the parasitic lasing occurs and prevents the gain crystal from saturation. When the regenerative amplifier starts working and amplifying pulses, the first pulse in a pulse train will not get much more gain and energy than pulses following it. As parasitic lasing disappears at the same time, the average output power of the amplifier does not significantly reduce.

This cost effective method does not require any additional component. In addition, as it is not polarization dependent, this method is widely suitable for different kinds of regenerative amplifiers. It's the easiest and cheapest way to suppress first pulse effect, to the best of our knowledge.

10082-25, Session 5

Subnanosecond Nd: YAG laser with multipass cell for SBS pulse compression

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Last decade showed growing demand in medical lasers with subnanosecond pulse duration, in particular, for tattoo removal. Several new devices, such as "PicoSure", "Discovery Pico", "PiQo4", etc, were presented at medical laser market. Following the specification of these devices, we develop compact and simple Nd: YAG laser , using multipass liquid cell for stimulated Brillouin scattering (SBS) pulse compression. Laser is presented by 2 models.

The first model includes Q-switched master oscillator, SBS-compressor, Faraday isolator, double-pass preamplifier and one single-pass amplifier. The second, more powerful model includes one additional single-pass amplifier. The first model has output pulse energy 0.5 J, the second – up to 1.1 J. Pulse duration and repetition rate of the both lasers is 0.65 ns and 10 Hz. Pulse energy deviation at preamplifier output is less than 2%.

SBS pulse compression is well known and convenient method to transform Q-switched pulses with nanosecond duration to subnanosecond pulses. Serious limitation for application of this method in compact devices is the requirement of relatively big interaction length L: L > 0.5 LPULSE , where LPULSE is geometrical length of input pulse. We developed multipass SBS generator – amplifier cell, reducing cell length to 25 cm for compression of 5.5 ns pulses from master ocscillator.

Overlapping of pump beams during multiple passes along cell leads to several processes, which can produce negative influence on output pulse performance. We observed pulse stability reduction, beam distortions, generation of second Stokes component and other effects, which, to our best knowledge, were not described in previous publications, related to SBS pulse compression. These effects were investigated and eliminated.

10082-26, Session 6

Rectangular pulsed LD pumped saturable output coupler (SOC) Q-switched microchip laser

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SESAM Q-switched microchip laser is a very promising device to replace mode locked laser to obtain less than 100 ps laser pulses. However the relatively larger timing jitter degrades the performance of such a compact microchip laser. Rectangular pulsed LD is proposed to be used in order to reduce the timing jitter of passively Q-switched microchip laser. Both theoretical and experimental analysis are done in this paper. From theoretical model we find that by pumping with pulsed LDs, the gain inversion population keeps accumulation with pumping pulses until one last pump pulse comes and makes the total gain inversion population reaches the threshold and the microchip starts to lase, which will help to reduce the timing jitter. Experimentally a pulsed LD with 650 mW peak power and 200 ns pulse duration is used as pump source. By tuning the pump spot size, the output laser frequency could be changed. At 1000 kHz output laser frequency, i.e. one pump pulse brings out one output laser pulse, the relative timing jitter is measured as 0.146%, which is about 10 times smaller than pumping by a cw LD with same average pump power as pulse LD. With increasing pump spot size, the output laser frequency decreases while the relative timing jitter increases. The smallest relative timing jitter is measured as 0.0315% when 9 pump pulses are used to obtain one output pulse, which is about 100 times smaller than cw pumping scheme.

10082-27, Session 6

Development of a diode-pumped stable pump laser for low-jitter OPCPA

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An optically synchronized 100 mJ, 532nm, 1 ns pump source is under development for low-jitter optical parametric chirped-pulse amplification (OPCPA) preamplifier in petawatt-class laser system. A part of pulses supplied from a Ti:Sapphire oscillator is used for seed pulses of the pump laser. The seed pulses are focused into photonic crystal fiber to extend spectra. Output pulses including a wavelength of 1064 nm are generated by adjusting input power and polarization. The stability of center wavelength with an original feedback system is less than 0.1 % at root mean square (RMS). The stabilized pulses are amplified with a fiber system fabricated by Yb:fiber amplifiers and fiber bandpass filters for 1064 nm. The output power is 150 mW at 80 MHz. The pulse duration is stretched to 1 ns with a fiber Bragg-grating in the fiber system. The beam size of pulses from the fiber system is expanded to 5.5 mm at 1/e2. The repetition rate of the pulses are reduced to 1 HZ by a pockels cell. The pulses are amplified with a diode-pumped Nd:YAG regenerative amplifier and an energy of 135 mJ is achieved by increasing number of round trips. The regenerative amplifier is currently being increased the repetition rate up to 10 Hz. The amplified pulses will be then doubled to 532 nm by LBO crystal to obtain over 100 mJ pulse energy.

10082-28, Session 6

Multi-watt passively Q-switched Yb:YAB/Cr:YAG microchip lasers

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A trigonal 5 at.% Yb:YAl3(BO3)4 (Yb:YAB) crystal is employed in continuous-wave (CW) and passively Q-switched microchip lasers diode-pumped at 978 nm. The possibility of microchip laser operation with this crystal cut along both principal directions (a-cut and c-cut) is due to the positive thermal lensing determined by the positive dn/dT coefficients, 3.5 and 6.0?10-6 K-1 at ~1 ?m for ?- and ϖ-polarizations, respectively. Using a 3 mm-thick, c-cut Yb:YAB crystal, which has a higher pump absorption efficiency, efficient CW microchip laser operation is demonstrated. This laser generated a maximum output power of 7.18 W at 1041–1044 nm with a slope efficiency ? of 67% (with respect to the absorbed pump power) and an almost diffraction-limited beam, M2x,y < 1.1. Inserting a Cr:YAG saturable absorber, stable passive Q-switching of the Yb:YAB microchip laser was obtained. The maximum average output power from the Yb:YAB/Cr:YAG laser reached 2.82 W at 1042 nm with ? = 53% and a conversion efficiency with respect to the CW mode of 65% (when using a 0.7 mm-thick Cr:YAG). The latter corresponded to a pulse duration and energy of 7.1 ns / 47 ?J at a pulse repetition rate (PRR) of 60 kHz. Using a 1.3 mm-thick Cr:YAG, 2.02 W were achieved at 1041 nm corresponding to ? = 38%. The pulse characteristics were 4.9 ns / 83 ?J at PRR = 24.3 kHz and the maximum peak power reached 17 kW. Yb:YAB crystals are very promising for compact sub-ns power-scalable microchip lasers.

10082-29, Session 6

Development of cryogenic Yb:YAG ceramics amplifier for over 100 J DPSSL

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A high gain cryogenic Yb:YAG ceramics laser amplifier for a high energy laser amplification system has been demonstrated. The laser system consists of a fiber oscillator and two stage LD pumped cryogenic Yb:YAG ceramic amplifiers. The preamplifier has one 5-pass amplifier and the main amplifier has a 2-pass amplifier, respectively. The preamplifier obtained an average stored energy density of 0.8 J/cc and small-signal gain (SSG) of 60 with 93 J of absorbed energy. A total gain at 5 pass reached to 6.41 x 10^8. Then about 1 ?J of output energy from the oscillator was amplified to 3.6 J. The main amplifier head had the four pumping LD modules which irradiated the Yb:YAG ceramics directly. This original angular pumping scheme ideally increases irradiation intensity and homogenizes irradiation pattern on the Yb:YAG ceramics due to superposition effect of all of the LD modules. A maximum peak power of 200 kW was generated by one LD module. When the output energy of the LD modules was 450 J, 1,086 of SSG at 2 pass was obtained. Stored energy density was evaluated to 0.49 J/cc when 170 J energy were stored in 346 cc of Yb:YAG ceramics. As a result, a 55-J output energy with 10 ns pulse duration was demonstrated at a pumping energy of 450 J. The optical-to-optical conversion efficiency which includes transmissivity of the LD modules was 12 %. The extraction efficiency was estimated to 32%.

10082-30, Session 6

1KHz, 96W pulse-bursts picosecond laser system with 6 equal amplitude and spacing pulses in a 4ns width burst

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An average power of 96W, 6 pulses in a burst picosecond Nd:YAG laser system at a 1 KHz repetition rate was reported. The 6 pulses in a burst have equal amplitude and pulse spacing, pulse spacing between each other was 800ps, which repetition rate was up to GHz, the beam quality of M^2 factor was less than 3.5, the stability for pulse to pulse rms was about 1%,beam pointing was approximately 40urad, pulse width was 38ps. In Nd:YVO4 mode-locked cavity,average power of 1W and pulse width of 23ps seed pulses were obtained with the 3W pumping light at 808nm,light conversion efficiency was up to 33%. A single pass volume-bragg-gratings(VBG) broadened these pulse width to 135ps. Next, beam splitter mirrors split and combined the pulse beam, making the single pulse divided into 6 pulses in the same interval time of 800ps. Then, the pulses was injected into the LD side-pump Nd:YAG regenerative amplifier, 6 pulses in a burst at 1KHz repetition rate was putout, the power was 11W, pulse width was compressed to 99ps and beam quality of M^2 factor was 1.4. Adjusting reflecting mirror, we made 6 pulses in a burst at the same amplitude. Finally, two stages of single passed high gain Nd:YAG amplifier enlarged the power to 96W and self-compressed the pulse width to 50ps, the beam quality of M^2 was about 3.5.

10082-31, Session 7

Novel pump head design for high energy 1064 nm oscillator amplifier system for Lidar applications

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Motivated by the growing need for high energy laser sources for Lidar applications, we demonstrate a 1064 nm laser and amplifier system that employs a novel head and pump cavity design. The gain medium consists of a composite Nd:YAG/Sm:YAG slab, wherein the Sm:YAG portion absorbs any parasitic 1064 nm oscillations that might occur in the pump axis, with ground surfaces limiting parasitics in the orthogonal axis. A pump cavity is built around the slab, consisting of angled gold coated reflectors which allow for multi-pass pumping from four locations around the slab. Pumping is performed directly with off-axis diode bars, allowing for compact design. This configuration allows for a highly homogeneous pump distribution throughout the slab, enabling high beam quality. This head design is employed for both the gain medium in the oscillator, and for the amplifier slabs, with the size being scaled in the two amplifier stages. Modeling and design of the system will be presented along with the final results of oscillator output and final amplified characteristics. Initial results from seeded q-switched linear oscillator are an output of 25 mJ at 250 Hz with a beam quality of Mx2 = 4.2 and My2 = 5.6.

10082-32, Session 7

New gain materials for high power laser applications

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For achieving highest peak powers in a solid state laser (SSL) system, significant energy output and short pulses are necessary. For mode-locked lasers, it is well-known from the Fourier theorem that the largest gain bandwidths produce the narrowest pulse-widths; thus are transform limited. For an inhomogeneously broadened line width of a laser medium, if the intensity of pulses follow a Gaussian function, then the resulting mode-locked pulse will have a Gaussian shape with the emission bandwidth/pulse duration relationship of ??pulse ≥ 0.44?02/c??. Thus, for high peak power SSL systems, laser designers incorporate gain materials capable of broad emission bandwidths. Available energy outputs from a phosphate glass host doped with rare-earth ions are unparalleled. Unfortunately, the emission bandwidths achievable from glass based gain materials are typically many factors smaller when compared to the Ti:Sapphire crystal. In order to overcome this limitation, a hybrid "mixed" laser glass amplifier – OPCPA approach was developed. The Texas petawatt laser that is currently in operation at the University of Texas-Austin and producing high peak powers uses this hybrid architecture. In this mixed-glass laser design, a phosphate and a silicate glass is used in series to achieve a broader bandwidth required before compression. Though proven, this technology is still insufficient for the future compact petawatt and exawatt systems capable of producing high energies and shorter pulse durations. New glasses with bandwidths that are two and three times larger than what is now available from glass hosts is needed if there is to be an alternative to Ti:Sapphire for laser designers. In this paper, we present new materials that may meet the necessary characteristics and demonstrate the laser and emission characteristics these through the internal and external studies.

10082-33, Session 7

Orthogonally polarized self-mode-locked Nd:YAG laser with tunable beat frequencies

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Orthogonally polarized dual-frequency laser sources are very attractive in many applications and can be achieved by inserting some birefringence elements or inducing the birefringence in an isotropic medium, such as Nd:YAG crystal, for splitting the central frequencies of the orthogonal polarizations. Recently, self-mode-locked (SML) operation, which means without any active or passive mode-locking elements except for the gain medium in the resonator, in Nd:YAG lasers has been reported. Therefore, it is of great interest to utilize Nd:YAG crystal as the gain medium for obtaining the orthogonally polarized SML output.

In this work, we thoroughly investigate the temporal dynamics of the polarization-resolved output intensity of a Nd:YAG laser with a short cavity. It is experimentally found that the SML operation can be realized in the two orthogonal polarizations along the principal axes simultaneously and then the central frequency difference between these two mode-locked components will lead to a beating in the polarization-resolved output intensity. The origin of the central frequency splitting is confirmed to be the thermal-induced birefringence in the Nd:YAG crystal. We believe the present finding can be developed as a promising approach for creating orthogonally polarized mode-locked lasers with tunable beat frequency.

10082-34, Session 7

Structured laser gain-medium by new bonding for power micro-laser

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The demand for compact high brightness micro-laser systems have increased during past years. The applications on frequency conversion, terahertz-wave generation and micromachining require over tens of mili-Joule of energy with pulse durations below several hundred picosecond. To obtains such energies master oscillator pulse amplification (MOPA) approach should be applied. In such systems, if increased pump power or high repetition rate operation are applied, the quality of the output beam easily deteriorates due to thermal effects in active media. Increased heating inside the gain crystal creates high temperature gradients in transverse and longitudinal directions of the crystal creating so called thermal lens with spherical aberrations which require additional modification of the system to compensate for. In addition, a depolarization loss will reduce the extracted energy out of the amplifier.

In this work we propose a new scheme for the end-pumped micro-laser amplifier where the heatsink and small sections of gain elements are combined in a periodic fashion thanks to the surface activated boding technology at room temperature. This design allows a basic pattern consisting of bonded Sapphire and Nd:YAG crystals to be repeated, up to four times in our investigation. Also Finite Element Analysis method was applied to confirm lower heat generation compared to the standard approach. Due to such design the flat temperature distribution along the crystal can be achieved. Also with the help of Sapphire heatsink the temperature gradient across the crystal is homogenized. The authors believe that this approach could boost up the output of conventional MOPA systems.

10082-35, Session 7

Wavelength tunable dual channel solid state laser for terahertz difference frequency generation

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The generation of narrowband terahertz (THz) radiation with tunable capabilities has shown much interest in recent years. THz systems are used for rotational-vibrational spectroscopy, nondestructive inspection, security screening and others. Monochromatic THz emission has been generated by means of THz parametric oscillation, nonlinear difference frequency generation, and quantum cascade lasers. Intracavity difference frequency generation (DFG) in the nonlinear crystal gallium arsenide (GaAs) has shown as an efficient way to generate a continuous wave THz radiation.

A novel high energy solid state resonator is presented with the use of volume Bragg grating (VBG) technology to create a dual channel system by spectral beam combination. The system consists of two separate Tm:YLF crystals and two VBGs for narrowband wavelength selection. At the end of the resonator both channels share common spherical mirrors, which provide feedback and focuses the beam for nonlinear purposes. This allows each channel to provide tunable power and wavelength, eliminating gain competition and allowing individual wavelength tunability. The VBGs are recorded in photo-thermo-refractive glass, which has a high damage threshold and can withstand the high intracavity power present in the resonator. Tunability of the system has shown spectral spacing from 5 to 20 nm, 0.4 - 1.7 THz, and intracavity continuous wave power levels from 80 to 100 W. By placing the GaAs crystal near the waist, THz radiation can be extracted from the cavity.

10082-36, Session 8

A review of state of the art CVD diamond: Synthesis, processing, and scalability

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Microwave plasma chemical vapour deposition (CVD) of diamond has enabled a multitude of optical applications due to its range of extreme properties. Transparency from the ultra-violet to the infra-red is complemented by the highest thermal conductivity of any bulk material, high laser damage threshold, low thermal expansion and chemical inertness. Looking forward these properties and more – such as high Raman gain coefficient and spin properties - make this an exciting material for emerging applications as an active material in laser systems and in quantum photonics.

Up until recently, modest progress has been made in integrating diamond into high performance and demanding optical applications due to limitations in size, scalability for manufacture and precision processing of polycrystalline and single crystal diamond. Element Six will review and summarize key progress made in state of the art diamond for a number of case studies, including high power laser optics, cooling in high power disk lasers, diamond Raman lasers and photonics applications.

The improvement of low loss single crystal is enabling engineers to access new wavelengths with excellent beam quality in the yellow part of the spectrum for medical use and mid-infrared wavelengths for eye-safe applications. Latest developments in increasing the size of low loss single crystal diamond (> 10 mm) will be reviewed as well as the processing capability of extremely smooth surfaces (Rz ≤ ?/10) and applying radius of curvature to optimize beam focus and minimize scatter.

10082-37, Session 8

Polarization-dependent angular distribution of the absorption behavior in Ytterbium-doped monoclinic LYB and LGB compounds

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Ytterbium-doped crystals have proven to be attractive laser media and are used in industrial laser systems. This is mainly due to the relatively small Stokes shift of these materials, which limits the heating effect during the laser process. Moreover, the absorption spectrum of the Ytterbium ion matches perfectly the emission wavelength of high power InGaAs laser diodes for pumping those laser crystals. Owing to the relatively large gain bandwidth depending on the host matrices Yb-doped crystals are suitable for ultrafast lasers and amplifiers down to the femtosecond regime. Curiously, many of the commonly used materials, as e.g. double-tungstates, belong to the monoclinic system, such low symmetry being known to show non trivial optical specificities.

In this contribution we show the absorption properties of two different Yb-doped monoclinic borate compounds under polarized light. The studied crystals are Li6(Gd)0.75Yb0.25(BO3)3 and Li6Y0.75Yb0.25(BO3)3, respectively, and were grown by the Czochralski method. We focused on the study of their absorption at the zero line transition as a function of the polarization direction of the incident light for two different crystal cuts of each compound. We will discuss the different frames that should be considered in these materials due to their monoclinic character, as well as the optimal crystal orientation for absorption and the potential influences when used as laser materials.

10082-38, Session 8

Enhancement of Fe diffusion in ZnSe/S laser crystals under Hot Isostatic Pressing

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Many organic molecules have strong and narrow absorption features in the middle Infrared (mid-IR) spectral range, also called the "molecular fingerprint" region. The ability to probe absorption characteristics of the molecules allows applications in non-invasive medical diagnosis, industrial processing and process control, environmental monitoring, and many others. Thus, there is a strong demand for lasers operating in mid-IR spectral

range. Transition metal ion (TM) doped II-VI semiconductors such as Fe/Cr:ZnSe/S are the material of choice for fabrication of mid-IR gain media due to favorable combination of properties: a four level energy structure, absence of excited state absorption , broad mid-IR vibronic absorption and emission bands. Despite the significant progress in post-growth thermal diffusion technology there are still some difficulties associated with diffusion of certain TM's in these materials. In this work we try to address the issue of poor diffusion of Fe in ZnSe/S polycrystals. It's well known with increase of the temperature the diffusion rate also increases. However, application of high temperatures is problematic for ZnSe/S crystals due strong sublimation. This can be suppressed by application of high pressures. Hot isostatic pressing was utilized as the means for application of high temperatures (1300 C) and high pressures (1000 atm and 3000atm). It was determined that the diffusion coefficient of Fe was improved by 13 times and 14 times in ZnSe and ZnS, respectively, as compared to the standard diffusion at 950 Celsius. The difference in diffusion coefficients can be due to difference in increase of the grain size of polycrystals.

10082-39, Session 8

Spectroscopy and laser operation of Indium-modified Yb:KLuW: a promising crystal for femtosecond lasers

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We report on the growth, spectroscopic and laser characterization of a novel monoclinic laser crystal, 3.5 at.% Yb, 5.5 at.% In:KLu(WO4)2 (Yb,In:KLuW). Single-crystals of high optical quality are grown by the TSSG method. The absorption, stimulated-emission and gain cross-section spectra are determined for this material at room temperature with polarized light and compared with those for Yb,In:KY(WO4)2 (Yb,In:KYW) , as well as singly Yb-doped KLuW and KYW crystals. Raman-active modes are determined for Yb,In:KLuW crystals. It is found that the introduction of In3+ ions results in a decrease of the transition cross-section and in a spectral broadening of the absorption and emission bands. For Yb,In:KLuW, the maximum ?abs is 9.9 ? 10-20 cm2 at 980.9 nm for E || Nm and the corresponding bandwidth of the absorption peak is 3.7 nm. The radiative lifetime for Yb3+ ions in Yb,In:KLuW is 237±5 μs. The stimulated-emission cross-sections are ?SE(m) = 2.4?10-20 cm2 at 1022.4 nm and ?SE(p) = 1.3?10-20 cm2 at 1039.1 nm corresponding to an emission bandwidth of >30 nm and >35 nm, respectively. A diode-pumped Ng-cut Yb,In:KLuW microchip laser generated 4.11 W at 1042-1048 nm with a slope efficiency of 78% in a TEM00 mode and a measured M2x,y < 1.15. Polarization-switching between the Nm and Np oscillating states is observed in the Yb,In:KLuW microchip laser at low output coupling. The Yb,In:KLuW crystal is very promising for sub-100 fs mode-locked lasers.

10082-40, Session 8

Highly-efficient multi-watt Yb:CaLnAlO4 microchip lasers

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Tetragonal rare-earth calcium aluminates, CaLnAlO4 where Ln = Gd or Y (CALGO and CALYO, respectively), are attractive laser host crystals due to their disordered structure and high thermal conductivity. In the present work, to the best of our knowledge, we report on the first highly-efficient power-scalable microchip lasers based on Yb:CALGO and Yb:CALYO. The Yb-ion doped CALGO (8 at.%) and CALYO (3 at.%) crystals were grown by the Czochralski method. The laser elements were a-cut. This orientation provided weak and positive thermal lens owing to the combined action of positive thermal expansion and negative dn/dT. The uncoated laser elements were mounted in a water-cooled Cu-holder and placed in a compact plano-plano cavity. The crystals were pumped by an InGaAs laser diode at 978 nm, the zero-phonon line. The 6 mm-long Yb:CALGO microchip laser generated 7.79 W at 1057–1065 nm with a slope efficiency of ? = 84% (with respect to the absorbed pump power) and an optical-to-optical efficiency of ?opt = 49%. The 3 mm-long Yb:CALYO microchip laser generated 5.06 W at 1048–1056 nm corresponding to ? = 91% and ?opt = 32%. Both lasers produced linearly polarized output (?-polarization) with an almost circular output beam profile and beam quality factors M2x,y <1.1. The output performance of the developed lasers was modeled yielding a loss coefficient for the Yb:CALGO and Yb:CALGO crystals as low as ? < 0.008 cm-1. The results indicate that the Yb3+-doped calcium aluminates are very promising for high-peak-power passively Q-switched microchip lasers.

10082-41, Session 8

Optimizing grain size distribution in Nd:YVO4 powder pellets for random laser action with high efficiency

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Random lasers are important in many diverse applications, such as speckle-free imaging in biology, remote-sensing, display technology, encrypting and distributed amplification. Low dimensional random lasers, such as Random Raman fiber Lasers and two-dimensional DFB lasers have already demonstrated high output powers. However, these low-dimensional random lasers are quite large and require sophisticated production methods, which are in stark contrast to the simplicity and practicality of the 3-D random laser production. Volumetric random lasers can be solid or liquid and can be fitted into almost any available space of volume less than 10-2 mm3.

Here we demonstrate the first volumetric random laser with a slope efficiency of 5.2%, which is comparable to lamp pumped YAG lasers. We use a 1.33 mol% Nd:YVO4 crystal, grind it and mix the particles into twelve different size distributions with mean particle sizes ranging from approximately 1 micrometer to 100 micrometers. After pressing into pellets, each of the twelve groups has its transport mean free path calculated from the distribution spectra and experimentally measured by means of its backscattering cone. We then calculate the fill fraction of each sample. The pellets are diode- pumped at 806.5 nm. Linewidth narrowing and output power are measured as a function of absorbed pump power. We demonstrate that the smaller particles, trapped between large particles, serve as gain centers whereas the large particles control the light diffusion into the sample. By optimizing diffusion and gain we achieve high slope efficiency.

10082-63, Session PTue

Continuous wave operation of Nd:CaYAlO4 and Nd:ScYSiO5 lasers with hot band diode-pumping

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Neodymium-ion doped laser gain media have been extensively studied due to their high power capabilities and efficiency. Recently, several studies have focused on diode-pumping of neodymium lasers at absorption lines with longer wavelengths such as, for example, 880 nm, 888 nm and 914 nm in Nd:YVO4. Such low quantum defect pumping schemes decrease thermal effects in the gain medium which is particularly advantageous for laser gain media with disordered structures. In this report, we demonstrate for the first time low quantum defect pumping at 914 nm of two gain media with disordered structure, Nd:ScYSiO5 (Nd:SYSO) and Nd:CaYAlO4 (Nd:CALYO). Two 5 mm-long 0.8 at. % doped Nd:SYSO crystals were used inside the laser cavity with 1.6% output coupling. A 20 mm-long Nd:CALYO crystal was used in a 3-mirror cavity with 5% output coupling. The output power achieved was 201 mW (centered at 1078.0 nm) with slope efficiency of 18.6% for the Nd:SYSO and 154 mW output (centered at 1074.9 nm) with 7.8% slope efficiency for the Nd:CALYO. The experimental results were limited by the low pump absorption in the crystals. The absorbed pump power was 3.3 W and 9.0 W for Nd:SYSO and Nd:CALYO, respectively. It is worth noting that the absorbed pump power can be increased further by using a higher doping concentration and longer crystals. High-power fiber-coupled laser diodes around 914 nm are widely used for pumping of Yb-doped fiber lasers and are readily available for power scaling experiments.

10082-64, Session PTue

Er:YAG crystal temperature influence on laser output characteristics

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The main goal of this work was to investigate the influence of the temperature of the Er:YAG active medium on laser properties in eye-safe spectral region for three various pump wavelengths. The tested Er:YAG sample doped by 0.5% of Er3+ ions had a cylindrical shape with 25 mm in length and 5 mm in diameter. The absorption spectrum of the Er:YAG active medium in the range from 1400 nm up to 1700 nm for temperatures 80 K and 300 K was measured. The crystal was placed inside the vacuum chamber of a liquid nitrogen cooled cryostat. The temperature was controlled within the 80 – 340 K temperature range. Three pump sources generating at 1535, 1452, and 1467 nm were applied. The first one was flash lamp pumped Er:glass laser (repetition rate 0.5 Hz, pulse duration 1ms, pulse energy 148 mJ) . The further two sources were fiber coupled laser diodes (repetition rate 10 Hz, pulse duration 10 ms, maximum pulse energies 106 mJ and 195 mJ). The semi-hemispherical laser resonator consisted of a pump curved mirror and output plan coupler with a reflectivity of 90% @ 1645 nm. The laser output characteristics were investigated in dependence on temperature of active medium for three laser pumping systems. The output energy has an optimum in dependence on active medium temperature and pump wavelengths. The maximal generated laser energies were 16.2 mJ (90 K), 28.7 mJ (120 K), and 33.2 mJ (220 K), for pump wavelengths 1452 nm, 1467 nm, and 1535 nm, respectively.

10082-65, Session PTue

Influence of random spectral phase noise on the temporal contrast of an ultra-high intensity laser pulse

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With the remarkable progress of the chirped-pulse amplification (CPA) technique, petawatt-class Ti:sapphire laser systems have been constructed worldwide and the laser focused intensity has reached 1020 – 1022 W/cm2 in small-scale laboratories. For such relativistic laser-matter interactions, increased peak intensities require a commensurate improvement in temporal contrast. The contrast is a very important factor in the application of an ultra-high intensity laser to solid-state experiments because prepulses can generate unwanted plasmas before the main pulse arrives on target.

In CPA lasers, the laser beam is expanded and spectrally resolved on the optics surfaces in a stretcher and a compressor. The surface quality of the grating has an influence on the spectral phase, which reduces the temporal coherence of the main pulse and generates a pedestal around the main pulse. We have evaluated the temporal contrast using the spectral random phase noise (SRPN) due to the surface roughness of the gratings.

Detailed analysis of the temporal contrast using a measured surface quality (~?/10) of compressor gratings shows tens of picosecond pedestal structure starting from the 10-7 level of the main pulse.

The SRPN can be explanation as one of the origins of the pedestal. As the ASE contrast gets even higher, for example, than 10^12 in experiments with the focused intensity of over 10^22 W/cm^2, the spectral noise factor becomes more important because the pedestal could exist for more than 100 ps around the main pulse.

10082-66, Session PTue

Efficient Q-switched operation in 1.64 μm Er:YAG tapered rod laser

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The in-band pumped Er:YAG laser operating at 1.64 ?m is promising for the next step in eye-safe range finding, eco monitoring and free space optical communication. We model output characteristics of the 1645 nm 8 mJ 10 ns 100 Hz Q-switched Er:YAG DPSSL. The laser is end pumped at a wavelength of 1532 nm. Fiber-coupled diode laser module was 10 nm FWHM, 12 W CW, 200 ?m, NA 0.22. Co2+:gamma-Ga2O3 spinel-based transparent glass-ceramics was used for passive Q-switch. We discuss the heat deposition process, the energy storage efficiency and the average power limitations for Q-switched regime of generation and amplification.

We numerically analyze tapered active rod configuration in the energy storage regime, and find that the maximum energy storage efficiency strongly varies with incident pump power for a given diameter of the pump area, the active rod length and the concentration of erbium. The maximum energy storage efficiency does not coincide with the maximum gain, and the optimal energy storage regime differs from the regime of oscillator and amplifier. The high average power operation is possible due to the low heat deposition for the in-band pump scheme and low impact of the thermo-optical effects in YAG. We find the system scalable to the high power operation. This is promising for such applications as long distance free space communication and ecological monitoring.

10082-67, Session PTue

Ultra-high intensity J-KAREN-P laser development at QST

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The J-KAREN-P laser system consists of two successive Ti :sapphire CPA stages linked by a saturable absorber, which acts as a nonlinear temporal filter. The first CPA stage consists of an oscillator, a stretcher, a small amplifier and a compressor. The second CPA stage consists of a stretcher, an OPCPA preamplifier, a preamplifier, a power amplifier, a booster amplifier-1 (BA1), a booster amplifier-2 (BA2), a deformable mirror and a compressor.

The output pulses with high temporal contrast of ~10^12 and uniform spatial profile from the power amplifier are up-collimated and enter BA1, which uses a 80 mm diameter Ti:sapphire crystal, pumped with ~47 J from two Nd:glass green lasers at a 0.1 Hz repetition rate. The output pulses from BA1 having ~23 J energy, ~50 nm (FWHM) bandwidth, and uniform spatial profile are amplified in BA2, which uses a 120 mm diameter Ti:sapphire crystal, pumped with ~92 J from four Nd:glass green lasers at 0.1 Hz. A maximum output energy of ~63 J from BA2 is demonstrated. A deformable mirror is installed to correct the wavefront distortion. The amplified pulses are up-collimated to ~250 mm diameter and finally compressed in the compressor consisting of four gratings of 565 x 360 mm^2. A compressed pulse duration of less than 30 fs (FWHM) is achieved. A focused intensity of 10^22 W/cm^2 is expected when an f/1.4 off-axis parabolic mirror is used.

As a first step, the J-KAREN-P laser system will be used for >100 MeV proton generation and ~keV ultra-short x-ray generation.

10082-68, Session PTue

Numerical simulations of 1 kHz, high-energy, broadband multipass amplification for a Ho:YLF chirped pulse amplification system

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We demonstrate high-gain amplification numerical simulations of two double-pass Ho:YLF amplifiers with high-energy seed pulses injection via a modified population inversion Frantz-Nodvik model. In the numerical simulations, 1 kHz, 21.5 mJ amplified pulses can be achieved after two double-pass amplification assuming an 1 kHz, 20 J, 40 nm (FWHM) seed injection. Because of gain narrowing, the spectrum of the amplified pulse appears a narrow spike of 4 nm (FWHM) which may destroy the optical components. To generate a flat spectrum of the amplified pulse, the spectrum of the seed is pre-shaped before injection. Final, under the same pump condition, the pulses are amplified to 12.5 mJ with a flat spectrum of 15 nm (FWHM) which is corresponding to the Fourier transform limit of 317 fs. The numerical simulations also shows that the seed pulses should be loaded before the pump is loaded on the gain medium, which can reduces the energy of initial amplified pulses for avoiding damage of the optical components.

10082-69, Session PTue

Impact of the ring-shape pump beam on thermal lensing and the performance of Nd:YVO4 lasers

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A diode-end-pumped solid state laser is one of the most popular laser configurations due to its excellent laser performance since the pump beam can be easily matched to the low-order modes in the laser resonator. However, power scaling whilst maintaining high efficiency and good beam quality is rather challenging due to the generated heat and its detrimental impact on laser performance, e.g. thermal lensing, thermal birefringence and thermal fracture. Many researchers have devoted much effort to develop an efficient cooling method for alleviating these problems and some innovative laser configurations, such as slab, thin-disk and fiber lasers, can extract the generated heat very efficiently achieving excellent laser performance over 1 kW power levels.

Here we investigate impact of a ring-shape pump beam on thermal lensing effects and the laser performance. Numerical calculation for temperature distribution in the laser medium shows that the pump beam with the ring-shape intensity distribution can reduce the temperature gradient dramatically in the center of the pumped region compared to the Gaussian or top-hat intensity distribution. In order to confirm this phenomenon, we constructed the MOPA configuration using Nd:YVO4 as a gain medium and measured thermal lensing effects for the Gaussian and ring-shape pump beam respectively. Moreover we constructed a Nd:YVO4 laser end-pumped by the ring-shape pump beam achieving a higher TEM00 mode output power. Various measures for the laser due to the ring-shape pump beam and the prospects for further improvement including the output power will be discussed.

10082-70, Session PTue

Highly stable RF signal from a mode-locked laser stabilized to multiple saturated absorption lines

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Mode-locked lasers are promising sources of high-purity radiofrequency (RF) signals. Nd:YVO4 mode-locked lasers with intracavity frequency doubling based on KTP crystals are of special interests and attract much attention as the locking can be achieve for lower intracavity intensities compared to the other passive mode-locking techniques. Mode-locked operation results from: i) the active medium Kerr nonlinearity; ii) cascaded chi(2) process in the frequency doubling crystal; iii) nonlinear selectivity of the frequency doubling crystal and output coupler combination. We control the output optical comb via changing the cavity length and its dispersion properties.

The laser output wavelength (532 nm) is in the range of the molecular iodine absorption spectrum. Doppler broadening of the absorption spectral lines can be suppressed by appropriate techniques. This would produce a homogeneously broadened line with a width of 1.5 kHz. We stabilize the two laser longitudinal modes frequencies on two narrow Iodine absorption lines.

Piezoelectric transducer was used for fast frequency modulation of the output spectrum. The third derivative of the absorption line was obtained by heterodyning the absorption signal with the third harmonic of the modulation signal. The resulting RF error signal was extracted and used to stabilize two longitudinal modes separated by 1.37 GHz. It results in highly stable RF signal.

10082-71, Session PTue

InGaN diode pumped Pr:SrF2 laser at 639 nm wavelength

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Praseodymium based laser systems attract a great attention for more than two decades because the energy level structure of the Pr3+ active ion offers several laser transitions throughout the visible spectral range. However, there are only few reports on the Pr:SrF2 laser systems. In this contribution, we report on InGaN laser diode pumped Pr:SrF2 laser system with the slope efficiency of 16,4 % at 639 nm wavelength, which is the highest slope efficiency reported so far from this crystal, to our best knowledge.

In our experiment, 0.3 at. % doped 6,9 mm thick Pr:SrF2 single crystal was used. No antireflection coating was applied to the crystal faces. As a pump source, 3.5W InGaN laser diode from the Nichia Corporation was utilized. The sample placed in the "V"-groove was passively cooled only by the surrounding air, therefore, the laser system was designed for operation in pulsed regime with 2 ms pulse duration and 100 Hz repetition rate to prevent crystal damage by overheating. Using 98% output coupler reflectivity at the designed laser wavelength, 6 mW of the mean output power at 639 nm was extracted from the Pr:SrF2 sample. The oscillation threshold was 30 mW of the absorbed mean power.

10082-72, Session PTue

Temperature influence on diode-pumped Tm:SrF2-CaF2 laser properties

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The goal of this work was an investigation of the temperature influence (in range 77 - 300 K) on laser properties of Tm:SrF2-CaF2 solid-solution, which is suitable as a gain medium for generation of radiation at 1.8-2 um. The tested Tm:SrF2-CaF2 sample (60 mol % CaF2, 38 mol % SrF2) was doped with 2 mol % of TmF3. The diameter of the grown boule was 10 mm. The sample was cut and optically polished parallel to growing axis. The polished sample thickness was 8.5 mm. It was fixed in temperature controlled cupreous holder, placed inside vacuum chamber of the liquid nitrogen cryostat. A fiber coupled laser diode, operating in pulsed regime (10 ms pulse length, 10 Hz repetition rate) at wavelength 764 nm, was used for longitudinal sample pumping. The 142 mm long semi-hemispherical laser cavity consisted of flat pumping mirror (HR @ 1.8-2.0 um, HT @ 0.77 um) and curved (r=150 mm) output coupler with a reflectivity of 92 % @ 1.8-2.0 um. From the results it follows that the temperature of the active medium has a strong influence on laser slope efficiency. The highest slope efficiency (42 %in respect to absorbed power), obtained for temperature 77 K, was more than five times higher than slope efficiency for 300 K. The threshold decreased twice with the temperature lowering from 300 to 77 K. Laser output power amplitude 5.5 W at wavelength 1856 nm was reached for absorbed power 15.8 W at 77 K.

10082-73, Session PTue

Influence of temperature on Yb:YAG/Cr:YAG microchip laser operation

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The goal of this work was an investigation of the temperature influence (in range from 80 up to 320 K) on the laser properties of Yb:YAG/Cr:YAG Q-switched diode-pumped microchip laser. This laser was based on monolith crystal (diameter 3 mm) which combines in one piece an active laser part (Yb:YAG crystal, 10 at.% Yb/Y, 3 mm long) and saturable absorber (Cr:YAG crystal, 1.36 mm long, initial transmission 90 % @ 1031 nm). The laser resonator pump mirror (HT for pump radiation, HR for generated radiation) was directly deposited on the Yb:YAG monolith part. The output coupler with reflection 55 % for the generated wavelength was placed on the Cr:YAG part. The microchip laser was placed in the temperature controlled cupreous holder inside vacuum chamber of the liquid nitrogen cryostat. For Yb:YAG part longitudinal pulsed pumping (pumping pulse length 2.5 ms, rep-rate 20 Hz, power amplitude 21 W) a fibre coupled (core diameter 400 um, NA =0.22) laser diode, operating at wavelength 933 nm, was used. The microchip laser mean output power, pulse duration, repetition rate, emission wavelength, and laser beam profile were measured in dependence on temperature. The generated pulse length was in range from 2.2 ns to 1.1 ns (FWHM) with the minimum at 230 K. The single pulse energy was peaking (0.4 mJ) at 180 K. The highest peak power (325 kW) was obtained at 220 K. The highest pulse repetition rate (38 kHz) and output mean power (370 mW) was reached for temperature 80 K.

10082-74, Session PTue

High energy regenerative amplifier based on Yb:CaF2

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We report an ultrafast amplifier based on Yb :CaF2 delivering 32mJ with a pulse duration of 400fs, at a repetition rate of up to 100 Hz, with a central wavelength of 1030 nm. The laser source consists in a femtosecond oscillator delivering pulses centered at 1030 nm and a repetition rate of 40MHz, stretched to approximately 700 ps for a spectrum of 10 nm, and seeded in the regenerative amplifier. The regenerative amplifier consists in a 2% doped Yb:CaF2 crystal with 1 mm thickness used in an active mirror configuration, pumped by a fiber-coupled laserdiode emitting 100 W @ 980 nm, with a pump duration of 2ms and a repetition rate ranging from 10 Hz to 100 Hz. The Yb:CaF2 gain module is inserted in a linear cavity, together with a low-loss Pockels cell based on RTP crystal, for its low quarter-wave voltage requirement. Pulses with spectrale bandwith of 5 nm centered at 1030 nm FWHM are obtained.

The extracted pulses are then sent in a high energy and high efficiency compressor.In our case, pulse duration is compressed up to 400 fs at 100 Hz .This laser source constitutes an ideal source for pumping nonlinear crystals through Optical Parametric Amplification or Optical rectification

10082-75, Session PTue

Pulse-burst Er:glass laser

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We demonstrate a pulse-bursting phenomenon in Yb:Er glass laser operating at 1.54 ?m. 1?10 mm active rod was pulsed pumped by 80 W laser diode bar at 940 nm with a total pump pulse duration of 5 ms. We use novel Co2+:?-willemite-based glass-ceramic passive gate to maintain Q-switching. Concentration of Yb3+ (2.5?1021 cm-3) in the active element was much higher than the concentration of Er3+ (5.0?1019 cm-3), what makes the pump absorption higher. Low threshold Co2+ transparent glass-ceramics containing Co2+:?-willemite (?-ZnSiO4) nanocrystals was used as a passive gate for pulse-burst operation. We present the results on the synthesis and optical properties of this material.

The bursts of pulses were 1.3 ms long and separated by 1 Hz (pulsed pump repetition rate). Unconventionally, the average burst profile was flat-top Gaussian in time. Each burst consisted of 40-55 pulses with 30-150 ?J energy per pulse and 1-5 ?s pulse width. The shortness of the pulse can be attributed to the fast 200-300ns passive gate recovery time. The separation between the pulses and their amplitudes were random and unique for each burst. It is reminiscent of the excitable dynamics.

We discuss the application of pulse-bursting phenomena to range finding and the perspective of signal processing with the high ambient noise level based on the random pulse timing structure in the bursts.

10082-76, Session PTue

Compact single-mode diode laser in the visible spectral range

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Modern optical metrology applications, such as interferometric distance measurement, would benefit from more compact single-mode lasers as light sources. While solid-state and gas lasers are fundamentally limited when it comes to miniaturization, semiconductor-based diode lasers are promising candidates for the realization of compact laser devices. One key element which currently prevents miniaturization is the Faraday isolator being mandatory in many applications. Cadmium Manganese Telluride (CdMnTe) is a new promising material [1] for the fabrication of compact isolators in the visible range, as this material provides a large Verdet constant due to the spin-spin exchange interaction and an excitonic enhancement of the semimagnetic properties close to the band-edge [2].

This work reports on a diode laser emitting at 633 nm based on an AlGaAs/AlGaInP structure with an integrated DBR surface grating. The optical feedback due to the grating enables single-mode operation over a large range of currents and temperatures. The diode laser is integrated into a micro-fabricated package, which also includes optics for beam shaping, optical isolation and single-mode fiber coupling. We discuss the performance and the technological challenges for this approach. Furthermore, we present prospects towards the integration of atomic reference cells into compact laser systems. This would enable the realization of absolute frequency-stabilized diode lasers that could be used in quantum technology devices.

[1] L. Kowalczyk et al., “CdMnTe single crystal for room temperature optical isolator”, phys. stat. sol. (c) 1, No 4, 985-988 (2004)

[2] P. Leisching et al., “Coulomb enhancement of Faraday rotation in semimagnetic semiconductors”, Phys. Rev. B 54, No 12, R8305-R8308 (1996)

10082-77, Session PTue

Temperature dependence of spectroscopic and electrical properties of Cr(Fe):ZnSe laser active materials

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Chromium and Iron doped II-VI semiconductors are proving to be good materials for developing high-power solid-state mid-IR lasers for 1.9-6 ?m spectral range with potential for electrical pumping. In this paper we report on thermal optical bistability, electrical conductivity and spectral broadening in chromium and iron doped ZnSe laser active materials. The pump wavelengths with zero sensitivity of the absorption coefficient to the crystal temperature were measured for chromium and iron doped ZnSe samples. It was demonstrated that for Cr:ZnSe crystals there are two wavelengths (2040 nm and 1650 nm) where absorption coefficient is approximately constant within the 77-385K temperature range. Optical pumping of Cr:ZnSe at these wavelengths should provide greater stability and lower noise operation. On the other hand, the absorption at 1530 and 1830 nm in Cr:ZnSe gain elements reveals the largest change as temperature increases. The temperature changes of the absorption cross sections (S) were measured to be (S)^-1*dS/dT=-1.6x10^-3K^-1 and (S)^-1dS/dT=2.9x10^-3K^-1 at 1830 nm and 1530 nm wavelengths, respectively. It was demonstrated that pumping of Cr:ZnSe gain element into the spectral region with high temperature sensitivity of the absorption should induce optical bistability starting from 20W of absorbed power. We also studied temperature dependence of the electrical conductivity in Cr(Fe):ZnSe samples and the optical absorption induced by electrical free-carriers in n-type ZnSe crystals. It was demonstrated that free-carriers absorption of n-type ZnSe samples with resistivity ~100 Ohm*cm resulted in an increase of the absorption coefficient at 2.4 ?m up to 2.5 cm^-1.

10082-78, Session PTue

Glass-ceramics with Co2+:Mg(Al,Ga)2O4 nanocrystals: novel saturable absorber for erbium lasers

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We report on passive Q-switching of a diode-side-pumped Er,Yb: glass laser by a novel saturable absorber (SA) based on transparent glass-ceramics (GC) containing Co2+:Mg(Al,Ga)2O4 nanocrystals. To prepare the GC, an initial magnesium aluminosilicate glass doped with Ga2O3 containing 0.1 mol% CoO was synthesized by a conventional melt-quenching technique and heat-treated at 750–1000 °C. The X-ray diffraction analysis of the GC confirmed the precipitation of Co2+:Mg(Al,Ga)2O4 crystals with spinel structure (6-7 nm in size) and Co2+-doped magnesium galliumaluminotitanate solid solutions. The feature of this GC is a long-wavelength shift of the absorption band related to the 4A2(4F)?4T1(4F) transition of Co2+ ions up to ~1.67 µm. Depending on the heat-treatment temperature, the saturation intensity for the GC measured at 1.54 ?m was in the 0.5...0.7 J/cm2 range and the recovery time was in the 240...335 ns range. The GC were tested in a compact Er,Yb:glass laser. A plane-concave resonator was used. The laser rod was side-pumped by a stack of three InGaAs laser diodes emitting at 940 nm; it was passively-cooled. The uncoated SA was placed at Brewster angle. Using the SA based on GC heat-treated at 900 °C for 6 h with an initial transmission of 87.8%, we generated stable Q-switched pulses 0.7 mJ in energy and 8.7 ns in duration, respectively. The laser wavelength was 1.54 ?m at a repetition rate of 1 Hz. The conversion efficiency with respect to the free-running mode reached 16%. The developed GC are promising for Q-switching of erbium lasers emitting at 1.5-1.7 µm.

10082-79, Session PTue

Tm:CaGdAlO4: spectroscopy, microchip laser and passive Q-switching by carbon nanostructures

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A 3 at.% Tm:CaGdAlO4 (Tm:CALGO) crystal is employed as active medium in a 4 mm-long microchip laser diode-pumped at 792 nm. In the continuous-wave (CW) operation mode, this laser generated 1.16 W at 1883-1893 nm with a slope efficiency of 32% with respect to the absorbed pump power. Using a special “bandpass” output coupler, vibronic CW laser operation at wavelengths as long as 2043 nm is achieved. The Tm:CALGO microchip laser is passively Q-switched by saturable absorbers (SAs) based on CVD-grown graphene containing few carbon layers and randomly-oriented (spaghetti-like) arc-discharged single-walled carbon nanotubes (SWCNTs) in a PMMA film. SWCNT-SA demonstrates superior performance as compared with graphene. With the SWCNT-SA in the microchip cavity, the laser generated a maximum average output power of 245 mW at 1844 nm and a slope efficiency of 9% and conversion efficiency with respect to the CW operation mode of 21%. This corresponded to the pulse energy and duration of 6 ?J / 138 ns at a repetition rate of 41 kHz. The maximum peak power from the SWCNT-SA passively Q-switched Tm:CALGO laser reached 43 W. For graphene-SA, 2.8 ?J / 490 ns pulses were achieved at a repetition rate of 86 kHz. The maximum average output power reached 237 mW at 1842 nm and the slope efficiency was 8%. The superior performance of the SWCNT-SA is related to higher fraction of the saturable losses in the small-signal absorption.

10082-80, Session PTue

10 kHz, 73 mJ Nd:YVO4/Nd:YAG MOPA burst mode laser

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Many applications in laser-based diagnostics such as particle image velocimetry(PIV), planar laser Mie scattering, and Planar Laser Induced Fluorescence(PLIF) can take advantage of high-repetition-rate, high-pulse-energy pulsed lasers. Most of commercially available systems combine several flash pumped Nd:YAG oscillators to obtain a high-pulse-energy, high-repetition-rate multi-channel laser pulses with a limited pulse number. Continuous pulse generation from laser-diode(LD) pumped lasers has been developed significantly, but it is difficult to achieve high average power in high-repetition-rate operation due to thermal effects. Burst-mode laser is capable of generating hundreds of millijoule per pulse together with high repetition rate up to 1MHz by grouping several pulses in short burst with a low average output power. The common method is to amplify a sequence of low energy pulses(~?J) from a modulated continuous wave master oscillator. It is difficult to get an efficient energy extraction due to the gap between seed laser energy and stored energy in the laser amplifier. It is beneficial to produce a ~mJ pulse-burst master oscillator at high repetition rate with a short pulse width and increase system energy extraction efficiency.

In this paper, we demonstrated a high-pulse-energy, high-repetition-rate pulse burst 1064 nm laser from a LD pumped Nd:YVO4/Nd:YAG master-oscillator power amplifier(MOPA). An acousto-optical(A-O) Q-switched Nd:YVO4 laser under pulsed 878.6nm LD pumping is utilized to produce pulse burst laser at repetition rates ranging from 10kHz to 100kHz in a duration up to 2 ms.. Laser diode arrays (LDA) side pumped Nd:YAG modules are employed as amplifier and different amplification structures are investigated to suppress amplified spontaneous emission and achieve high extraction efficiency. Finally, the single pulse energy in 10kHz pulse burst 1064 nm laser reaches ~73 mJ with a duration a 9.3 ns and a peak power of ~7.8MW.

10082-42, Session 9

375 W, 37.5 µJ, 170 fs laser system utilizing nonlinear pulse compression in fused silica

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We present a novel, robust and efficient scheme for nonlinear pulse compression at average powers of several 100 W, which is suitable for compressing sub-ps pulses with energies of several tens of µJ. While this parameter range is interesting to applications such as micromachining or (intracavity) high-harmonic generation, it is hardly accessible by established high-power nonlinear pulse compression schemes, which are inherently limited to significantly lower (<5 µJ for fused-silica fiber based schemes) respectively significantly higher (>100 µJ for gas-filled capillary based schemes) pulse energies.

Our scheme is based on self-phase modulation in a thin bulk nonlinear medium, e.g. fused silica, placed inside a multi-pass cell. The B-integral for spectral broadening is accumulated during multiple passes through the nonlinear medium, while each pass is followed by a long free-space propagation without nonlinearity. This way, pulses with peak powers exceeding the threshold for catastrophic self-focusing can be spectrally broadened and beam quality degradation due to the spatial action of the Kerr-effect is mitigated. For compression, the chirp of the spectrally broadened pulses is removed with a dispersive mirror compressor.

Experimentally, we utilize this scheme to compress the pulses of an Yb:YAG-Innoslab amplifier system (850 fs pulse duration, 10 MHz repetition rate, >400 W average power). At 375 W of output power, respectively 37.5 µJ output pulse energy, pulse durations <170 fs are obtained at almost diffraction limited beam quality. The efficiency of the compression unit exceeds 90%.

10082-43, Session 9

Mobile terawatt laser propagation facility

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This presentation will describe the design and construction status of a new mobile high-energy femtosecond laser systems producing 500 mJ, 100 fs pulses at 10 Hz. This facility is built into a shipping container and includes a cleanroom housing the laser system, a separate section for the beam director optics with a retractable roof, and the environmental control equipment necessary to maintain stable operation. The laser system includes several innovations to improve the utility of the system for “in field” experiments. For example, this system utilizes a fiber laser oscillator and a monolithic chirped Bragg grating stretcher to improve system robustness/size and employs software to enable remote monitoring and system control. Uniquely, this facility incorporates a precision motion-controlled gimbal altitude-azimuth mount with a coudé path to enable aiming of the beam over a wide field of view. In addition to providing the ability to precisely aim at multiple targets, it is also possible to coordinate the beam with separate tracking/diagnostic sensing equipment as well as other laser systems. This mobile platform will be deployed at the Townes Institute Science and Technology Experimental Facility (TISTEF) located at the Kennedy Space Center in Florida, to utilize the 1-km secured laser propagation range and the wide array of meteorological instrumentation for atmospheric and turbulence characterization. This will provide significant new data on the propagation of high peak power ultrashort laser pulses and detailed information on the atmospheric conditions in a coastal semi-tropical environment.

10082-44, Session 9

A 1 J, 0.5 kHz repetition rate picosecond laser

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We report the demonstration of a chirped pulse amplification laser system that produces high quality 1.5 J pulses at 0.5 kHz repetition rate and 0.75 kW average power. These pulses are subsequently compressed resulting in the production of 1 J, ~5 ps duration pulses at 500 Hz repetition rate. The 8-pass main amplifier consists of two diode-pumped, cryogenic-temperature Yb:YAG active mirrors cooled by a unique, high capacity cryogenic-cooling system based on a flowing, sub-cooled cryogenic liquid. This amplifier is quite efficient with an optical-to-optical efficiency of 37%. The amplified pulses have excellent beam quality with a measured M2 factor of about 1.3. Furthermore, this laser is quite stable. Under continuous operation for 30 minutes we measured a standard deviation of 0.75% over the nearly 1 million shots fired during this time period. This laser was employed to make the first demonstration of a compact, plasma-based EUV/soft x-ray laser operating at a repetition rate of 400 Hz. In this proof-of-principle demonstration, shaped, picosecond duration, 1 J pulses were focused onto a rotating molybdenum target at grazing incidence. The resulting plasma is collisionially ionized to the Ni-like ionic stage where a large, transient population inversion results in production of bright ? = 18.9 nm laser pulses. Other applications including driving ultrafast optical parametric amplifiers and the investigation of next generation lithography laser-produced-plasma sources will be discussed. Prospects for energy and repetition rate scaling will also be presented.

10082-45, Session 9

Mode-locked sub 200 fs laser pulses from an Er-Yb-Ce ZBLAN waveguide laser

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Compact waveguide based lasers are an emerging architecture that combine high-gain solid-state media with low-loss waveguides and can possess lower lasing thresholds and higher efficiency than their solid-state counterparts. Short length waveguide lasers are suited for high repetition rate mode-locked operation.

This paper is the first report of a 976 nm diode-pumped passively mode-locked Er-Yb-ZBLAN waveguide laser oscillator with large mode-area waveguides (~ 50 ?m diameter), thus decreasing the effect of non-linearity of the gain medium on mode-locked performance.

The glass substrate is Er and Yb co-doped ZBLAN glass. ZBLAN has high transparency in the short to mid-infrared regions, low phonon energies, and a broad gain bandwidth and is thus an excellent candidate for compact and efficient mode-locked waveguide lasers. Low-loss depressed-cladding waveguides are directly inscribed in the L = 13 mm chip by using ultrafast laser inscription (< 250 fs, 520 nm wavelength).

This passively mode-locked 156 MHz repetition rate waveguide laser oscillator produces ‘close-to’ diffraction-limited beam quality, and stable mode-locked pulses with >25 nm bandwidth (~ 4 mW). The broad twin-peaked spectrum of the emission is characteristic of the gain lineshape of Er doped ZBLAN; a numerical approach based on the Ginzburg-Laudau equation is consistent with the mode-locked output we observe.

Stable mode-locking at a higher repetition rate of 534.2 MHz (and 1.3 GHz) is also demonstrated, and we report two stable but different domains of mode-locked output: (1) ~ 433 fs transform-limited pulses and (2) < 250 fs pulses with ~18 nm spectral FWHM.

10082-46, Session 9

Dynamic fiber delivery of 3 W 160 fs pulses with photonic crystal hollow core fiber patchcord

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We report output characteristics from the FC/APC connectorized photonics crystal hollow core fiber when is subjected to coiling down to 50 mm radius, bending, torsion etc. We achieved coupling efficiency up to 75%, output average power 2 W and 24 nJ pulse energy. With proper coupling the depolarization could be as low as 7%. Torsion of the photonic crystal patchcord destroys the polarization and other pulse properties.

10082-47, Session 10

Investigation of the critical parameters for CEP stabilized high power 1.5μm OPCPA

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High power, optical parametric chirped-pulse amplification (OPCPA) above 10 W at short-wave IR wavelengths (SWIR, 1.4 – 3 μm) may be limited because of thermal heat dissipation in the nonlinear crystals [1]. Powers reaching 100 W are now possible because of the commercial availability of Yb-based solid-state lasers in the kilowatt regime. These pump lasers have already opened up the possibility of OPCPA exceeding the 100 W level; for example, a 100 W, tunable (720 – 900 nm) with 30 fs pulse duration in burst mode (100 kHz in a 800 μs burst at 10 Hz) was achieved [2]. Power scaling this laser to 100 W and higher in continuous mode has been investigated [3]. In this work we provide up-to-date measurements of the absorption coefficients of the nonlinear crystals used at SWIR wavelengths and simulations of the thermal effects on critical parameters. In particular, power scaling limits will be discussed.

1. M. Mero, et al., "High-average-power, 50 fs parametric amplifier front-end at 1.55 μm", Opt. Express 23, 33157—33163 (2015).

2. H. Höppner, et al., "An optical parametric chirped-pulse amplifier for seeding high repetition rate free-electron lasers," New J. Phys. 17, 053020 (2015).

3. R. Riedel, et al., "Thermal properties of borate crystals for high power optical parametric chirped-pulse amplification," Opt. Express 22, 17607—17619 (2014).

10082-48, Session 10

Kerr-lens mode locking of a high-power diode-pumped Yb:KGW laser

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Over the past few years there has been an extensive effort to demonstrate generation of high power femtosecond pulses directly from a laser oscillator. An uncomplicated design with a small number of optical components and good reliability would be highly desired features for such a laser. Mode-locked lasers based on semiconductor saturable absorbers (SESAM) generally provide self-starting operation and offer a flexible design procedure, but SESAMs are susceptible to damage and are costly. Kerr-lens mode locking (KLM) of a laser, on the other hand, offers a fast saturable absorber like loss modulation and results in a considerable pulse shortening. However, a KLM laser requires careful design procedure and mode locking is often not self-starting. Furthermore, high power operation can be strongly affected by a considerable thermal lensing effect. Pure KLM lasers have been reported in a variety of laser crystals, including Yb-doped and Cr-doped crystals, but only a few "watt-level" oscillators were demonstrated, for example in Yb:CaF2 and Yb:CALGO laser crystals. Unfortunately, in both of these cases the lasers were not directly diode-pumped which is another highly desirable feature. Among the Yb-doped materials, the crystal of Yb:KGW has shown its potential for generation of femtosecond pulses with high average powers. This crystal possesses fairly broad amplification bandwidth, high emission cross-section and relatively high thermal conductivity. In addition, the nonlinear refractive index of Yb:KGW is large which makes it attractive for pure Kerr-lens mode locking technique.

In this work, we investigated the development of a high-power diode-pumped pure KLM Yb:KGW laser. The laser delivered 235 fs pulses with 2.3 W of output power. Shorter pulses of around 120 fs with 1.2 W of average power were also generated. The self-starting operation of the oscillator was demonstrated. The limiting factor to the laser operation was the appearance of a strong continuous wave component in the mode-locked laser spectrum.

10082-49, Session 10

High power lasers for gamma source

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A high intensity Gamma source is required for Nuclear Spectroscopy, it will be delivered by the interaction between accelerated electron and an intense laser beams. Those two interactions lasers are based on a multi-stage amplification scheme that ended with a second harmonics generation to deliver 200mJ, 3.5ps pulses at 515nm and 100Hz.

A t-pulse oscillator with slow and fast feedback loop implemented inside the oscillator cavity allows the possibility of synchronization to an optical reference. A temporal jitter of 120fs rms is achieved, integrated from 10Hz to 10MHz.

Then a regenerative amplifier, based on Yb:YAG technology, pumped by fiber-coupled QCW laser diodes, delivers pulses up to 30mJ. The 1nm bandwidth was compressed to 1.5ps with a good spatial quality: M2 of 1.1. This amplifier is integrated in a compact sealed housing (750x500x150cm), which allows to achieve a pulse-pulse stability of 0.1% rms, and a long-term stability of 1,9% over 100 hours (with +/-1°C environment).

The main amplification stage uses a cryocooled Yb:YAG crystal in active mirror configuration. The crystal is cooled at 130K via a compact and low-vibration cryocooler, avoiding any additional phase noise contribution, 340mJ in 6 pass was achieved, with 0.9 of Strehl ratio. The trade off to the gain of a cryogenic amplifier is the bandwidth reduction, however the 1030nm pulse was compressed to 4ps. For risk mitigation, a booster amplification stage is planned, to allow higher bandwidth at the same energy. Both amplifier stages would also be integrated in a compact sealed housing.

10082-50, Session 10

High power Yb:CALGO ultrafast regenerative amplifier for industrial application

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Laser sources offering high peak power in combination with relatively high repetition rate are extremely interesting for industrial applications as they allow a considerable reduction in the manufacturing throughput time. Lately, Yb:CaAlGdO4 (Yb:CALGO) has been shown as a very promising laser gain material for high power ultrashort pulse generation. Today this active

medium is mature enough to be exploited in industrial products.

Here we report a single-crystal, Yb:CALGO system able to deliver about 50 W in CW operation at room temperature in a near-diffraction-limited beam. The final goal of this project is to develop a power-scaled double crystal cavity.

The laser is based on a 8-mm long, 2%-doped crystal pumped by a 110-W, fiber-coupled diode laser.

At 95 W absorbed power, we extracted 50 W at 1042 nm from the CW resonator. The slope efficiency was 65%.

In the Q-switching regime at full pump power, the system generates a 11 nm broad spectrum centered at 1043 nm at 500 kHz.

We seeded the regenerative amplifier based on this resonator design with a single prism SESAM mode-locked Yb:CALGO oscillator able to generate a 9 nm broad optical spectrum continuously tunable between 1035 and 1060 nm. At full pump power, the regenerative amplifier generates as much as 34 W of average output power, at a repetition rate of 500 kHz. The compressed pulses were 141 fs long. This corresponds to 53 ?J pulse energy and 330 MW peak power.

We plan to power scale our system using a double-crystal cavity setup.

10082-51, Session 10

Mode-locking in Ti:sapphire oscillators with ultra-low intra-cavity pulse intensity

Mallachi-Elia Meller, Avi Pe'er, Bar-Ilan Univ. (Israel)

High repetition rate mode-locked lasers (in the GHz range), are desired for frequency comb spectroscopy. A major obstacle that currently impedes high repetition mode-locking is the inevitable subsequent reduction of the single pulse energy, which reduces the efficiency of the nonlinear Kerr effect in the cavity, eventually precluding mode-locking. The standard methods to overcome this restriction is to try to maintain the intra-cavity peak intensity in spite of the reduction of the single pulse energy, by tightening the focus of the intra-cavity beam on the crystal, or by enhancing the output coupler reflectivity and increasing the pump power. This standard approach is however limited since these actions also provide better conditions for CW operation, which reduces the ML robustness, and eventually spurs the laser to operate in CW. We demonstrate a fresh attack on this problem: instead of aiming to preserve the peak intensity by tightening the focus and lowering the OC loss, we enhance the nonlinearity inside the cavity to compensate for the reduction in intra-cavity peak intensity. We harness the enhanced nonlinearity to specifically target the intra-cavity peak intensity and explore its limits and effects. With an additional nonlinear window in the cavity we enhanced the Kerr nonlinearity by an order on magnitude compared to the standard Ti:S, allowing to maintain mode-locking with an output coupler reflectivity as low as R=55% and record-low intra-cavity peak intensity (10GW/cm2, 50 times less than without enhanced non-linearity). Our results provide an important new knob for high-repetition rate mode-locking.

10082-52, Session 11

FULAS: Design and test results of a novel laser platform for future LIDAR missions

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Spaceborne atmospheric LIDAR instruments enable the global measurement of aerosols, wind and greenhouse gases like CO2, Methane and Water.

These LIDAR instruments require a pulsed single frequency laser source with emission at a specific wavelength. Pulse energies in the 10 mJ or 100 mJ range are required at bandwidth limited pulse durations in the multi-10 ns range. Pulse repetition rate requirements are typically around 100 Hz but may range from 10 Hz to some kHz. High efficiency is mandatory.

Building complex laser sources providing the performance, reliability and lifetime necessary to operate such instruments in space has been recognized to be still very challenging.

To overcome this, in the frame of the FULAS technology development project - funded by ESA and supported by the German Aerospace Center DLR - a versatile platform for LIDAR sources has been developed. For demonstration the requirements of the laser source in the ATLID instrument have been chosen.

The design is based on a single frequency seeded, actively Q-switched, diode pumped Nd:YAG laser oscillator and an Innoslab power amplifier with frequency tripling. The laser architecture pays special attention on Laser Induced Contamination by avoiding critical organic and outgassing materials. Soldering technologies for mounting and alignment of optics provide high mechanical stability and superior reliability.

The FULAS infrared section has been assembled and integrated into a pressurized housing. The optical performance at 1064 nm has been demonstrated successfully and thermal vacuum tests have been carried out providing relevant data for the French-German climate mission MERLIN.

10082-53, Session 11

Tunable Q-switched solid state laser for methane detection

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Growing interest in precise measurements of methane concentration and distribution in the Earth's atmosphere is stimulating efforts to develop LIDAR systems in the spectral region of 1.65 μm utilizing Path Differential Absorption techniques. The key element of such systems is a tunable high energy transmitter operating in the vicinity of a methane absorption line.

We developed a novel laser source meeting these system needs using in-band pumping Q-switched solid state laser (SSLs) based on Er-doped yttrium gallium garnet. Unique spectral properties of active media are potential lasing transition near 1651nm and wide gain spectrum of this transition allowing to realize a tuning of spectral position in wide spectral range. The implemented in-band pumping of SSL allows shifting a significant portion of the system thermal load from the gain medium to the pump diodes, thus greatly reducing gain medium thermal distortions deleterious to SSL power scaling with high beam quality. Narrow spectral line and tuning of spectral position, which are required for methane detection, were reached by an utilizing of injection seeding approach.

We shown that potential tuning range can be >1.5nm. We demonstrated output pulse energy >750uJ at 2kHz repetition rate at injection seeding conditions. We reported a feasibility to measure methane line at 1651nm by developed laser transmitter.

10082-54, Session 11

10-50 kHz laser for airborne LIDAR applications

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Northrop Grumman Cutting Edge Optronics (NGCEO) has developed a new laser specifically for airborne LIDAR applications. The TEM00 laser operates at a nominal output power of 20-40W over a repetition rate range of 10-50kHz with a tailorable pulse width of ~ 1ns. The laser produces a jitter of < 100ps, allowing it to produce accurate measurements across a range of LIDAR applications.

The laser is based on a semiconductor master oscillator, Yb-doped fiber amplifiers, and a final-stage Nd:YVO4 amplifier. Further design details are

discussed, as is the laser's suitability for use in an airborne environment (e.g. 28 VDC input power, air/EGW cooling). In addition, data is presented over a range of operating temperatures and other environmental conditions.

10082-55, Session 11

A single-frequency Ho:YLF pulsed laser with spectral stability better than 500 kHz

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For space based measurement of the global atmospheric CO_2 trace-gas concentration with the differential absorption lidar technique, single-frequency laser pulses at a wavelength around 2051 nm provide a preferred option. The requirements on spectral stability of the center wavelength are very challenging. Moreover, to reduce mass and complexity for a beam source for a prospective space-borne system it is advantageous if the required pair of laser pulses is generated in only one optical assembly.

A Q-switched Ho:YLF laser oscillator with a bow-tie ring resonator, specifically designed for high-spectral stability, is reported. It is pumped by a Tm:YLF laser at 1.9 µm. The ramp-and-fire stabilization of the oscillator to a narrow-linewidth seed laser is employed for generating single-frequency emission. The linewidth of the seed laser is approximately 500 kHz and the optical power used for seeding is approximately 10 mW. At a repetition rate of 50 Hz, single frequency single pulses and double pulses with temporal separation of 750 µs are generated. The stability of the emission wavelength of the laser pulses of 2051 nm with respect to the seed laser is measured with the heterodyne technique. With a pulse energy of 2 mJ and a pulse duration of 15 ns the Allan-deviation of the center wavelength of the pulse laser is measured to be approximately 500 kHz for single pulses and approximately 50 kHz over 10 seconds. To our knowledge this is the highest stability reported for such a laser.

10082-56, Session 11

Demonstration of a 100mJ OPO/OPA for future LIDAR applications and LIDT-testing of optical components for MERLIN

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In the field of atmospheric research LIDAR is a powerful technology to measure remotely gas or aerosol concentrations, wind speed or temperature profiles. For global coverage spaceborne systems are advantageous. To achieve highly accurate, longitudinal resolved measurements pulse energies in the 100 mJ range are required. The measurement of gas concentrations, like CH_4 or CO_2, requires output wavelengths in the IR-B, which can be addressed by optical parametric frequency conversion.

An OPO/OPA frequency conversion setup was designed and built as a demonstration module to address the 1.6 µm range. The pump laser is a Nd:YAG-MOPA system consisting of a stable oscillator and two subsequent InnoSlab-based amplifier stages, delivering up to 500 mJ of output pulse energy at 100 Hz. The OPO is inherited from the OPO concept for the CH_4 lidar instrument on the French-German climate satellite MERLIN. In order to address the 100 mJ regime the OPO output beam is amplified in a subsequent multistage OPA.

With KTP as nonlinear medium the OPO/OPA obtained more than 100 mJ of output energy at 1645 nm from 450 mJ of the pump and a pump pulse duration of 30 ns. This corresponds to a quantum conversion efficiency of about 25 %.

Beside the demonstration of optical performance for future LIDAR systems, this laser will be part of a LIDT test facility, which will be used for the qualification of optical components especially for the MERLIN mission.

10082-57, Session 12

Extending solid state laser performance

Edward J. Miesak, Lee Laser, Inc. (United States)

Lee Laser, headquartered in Orlando Florida, produces solid state, medium to high repetition rate, high powered lasers predominantly for industrial applications. Primary wavelengths produced include 1064nm, 532nm, and 355nm. Other wavelengths produced include 1320nm, 1500nm, and 1600nm. Pulse widths range from several hundred nanoseconds to 6 picoseconds.

Depending on customer requirements the laser operating parameters (average power, pulse width, repetition rate, etc.) can be adjusted to optimize it for a particular application. Laser parameters are often cross-coupled such that adjusting one may change some or all of the others. Customers often request one or more parameters to be changed without changing any of the remaining parameters. Lee Laser has learned how to accomplish this successfully with rapid turn-around and minimal cost impact. The experience gained by accommodating customer requests has produced a textbook of cause and effect combinations of laser components to accomplish almost any parameter change request. A review of these cause and effect combinations provides valuable insight into lasing effects allowing designers to extend laser performance beyond what is currently available. Understanding the relationship between combination of cause and effect components has led to several break through products at Lee Laser, for instance >150W average power 355nm, >60W average power 6ps 1064nm, pulse lengths longer than 400ns at 532nm with average power >100W, >400W 532nm with pulse lengths in the 100ns range. Laser component combination cause and effect will be presented in this paper as a tutorial to provide a practical understanding of these types of lasers.

10082-58, Session 12

High-energy DPSS lasers for Ti:sapphire pumping

Ryan Feeler, Christopher J. Briggs, Wade Collins, Jay Doster, Faming Xu, Northrop Grumman Cutting Edge Optronics (United States)

A new generation of diode-pumped solid-state lasers has been developed that enables ultra-stable Ti:Sapphire pumping at high energies (1-5 J/pulse) and/or high repetition rates (tens to hundreds of Hz). Data for several lasers is presented to demonstrate performance over the parameter space. First, a 4J, 527nm, 10Hz, injection-seeded Nd:YLF laser is presented. Second, a 2J, 532nm, 10Hz, injection-seeded Nd:YAG laser is presented. Last, data from several green lasers operating at > 150mJ and > 100Hz is presented. All of these lasers feature flat-top beams in the near field to improve their performance in Ti:Sapphire pumping applications. A synopsis of the suitability of these lasers for Ti:Sapphire pumping is discussed, as are design details and the path to higher pulse energies and repetition rates. Particular attention is paid to the pulse-to-pulse energy stability measurements obtained from these lasers, as diode pumping allows for much greater stability than traditional lamp-pumped lasers. Life test data for the pump diodes is also presented.

10082-59, Session 12

Narrow line-width UV sources at 257nm

Brian J. Cole, Lew Goldberg, Chris McIntosh, Vernon King, Alan D. Hays, U.S. Army RDECOM CERDEC NVESD (United States)

Ultraviolet laser sources are commonly used for Raman spectroscopy and materials processing. To enable compact systems, we have implemented three types of passively Q-switched, 1030nm lasers for 257 nm fourth harmonic generation (FHG). All sources used Cr:YAG saturable absorbers for passive Q-switching and a VBG cavity mirror to produce the narrow linewidth (0.1nm FWHM) required for efficient FHG and Raman spectroscopy.

In the first implementation, an end-pumped Yb:YAG laser produced a 250 μJ pulse train with an average 1030nm power of 3.7 W. Using a 10mm LBO crystal (70% efficiency), followed by a 7mm BBO crystal (45% efficiency), 1.1W at 257nm was generated yielding an overall FHG efficiency of 30%, which is a record for a compact UV laser source.

The second implementation was a side-pumped Q-switched Yb:YAG laser, pumped by a 100 W diode bar that offers the advantage of a simple, compact resonator design. A 5mm KTP crystal followed by a 6mm BBO crystal resulted a 15% FHG conversion efficiency. The UV emission was in a form of 1-5Hz PRF, 2ms long burst of 0.2mJ pulses with 35kHz intra-burst PRF. Within the 2ms pulse window, a UV peak power of 6W was generated.

The final implementation used a fiber laser source that employed a 20μm-core Yb-DCF. The laser generated 2.4W in a 110μJ pulse train at 1030nm. FHG was achieved using a 10mm LBO crystal, followed by an 8mm BBO crystal, and generated 325mW of 257nm power. This paper will address the merits of each approach for realizing a man-portable laser suitable for ultraviolet Raman explosives detection.

10082-60, Session 12

Compact UVC laser modules for wavelengths near 220nm

Tim M. Smeeton, Karl P. Welna, Edward A. Boardman, Rishane Pereira, Sarah Mitchell, John Sandford-O'Neill, Valerie Berryman-Bousquet, Sharp Labs. of Europe Ltd. (United Kingdom)

Solid-state miniature frequency-doubled laser modules with UVC emission wavelength near 220nm have been developed, characterised and deployed. The laser modules are based on second harmonic generation from ~440nm wavelength light emitted from InGaN laser diodes and are operable in continuous wave (cw), quasi-cw and pulsed modes, providing an emission wavelength between 218nm and 227nm with maximum optical output power exceeding 0.1 mW. The modules occupy less than 40cm?, have an extremely wide operating temperature range (0°C-50°C needing no warmup time) and operate directly at low voltage. Continuous operating lifetimes exceeding several thousand hours have been demonstrated. Owing to their high output power, small size, robustness and practical operating conditions, these modules are the first laser sources with wavelength near 220nm that are suitable for widespread use and thereby enable new classes of sensors based on absorption, fluorescence and scattering of deep UVC light. The accessible wavelengths coincide with strong and characteristic absorptions from proteins, other organic molecules and inorganic molecules which are required for new sensor applications in medical, life science, water quality monitoring and gas sensing sectors. The performance of the laser modules throughout long-term deployment in sensors operated in-the-field demonstrates the excellent stability and reliability of the technology. In this paper we will describe the structure, properties and results of application trials of this new laser module technology all for the first time.

10082-61, Session 12

Compact, quasi-continuous wave, single-frequency, polarization maintaining, single stage Yb-doped fiber amplifier

Enkeleda Balliu, Magnus Engholm, Mid Sweden Univ. (Sweden); Gunnar Elgcrona, Peter Jänes, Håkan Karlsson, Cobolt AB (Sweden)

We demonstrate a compact, CW/QCW, single frequency, polarization maintaining, fiber amplifier (MOFA) at 1064 nm, which can find use in e.g. compact additive manufacturing applications. The amplifier is developed by using only one amplification stage, few optical components, allowing to reduce the overall complexity and cost. The system is based on a hybrid solid state laser (SSL)/fiber amplifier where a key component is a compact ring-cavity Nd:YAG SSL operating in single frequency (10 kHz linewidth). The SSL provides up to 3 W with a PER > 30 dB. The single stage fiber amplifier is constructed by using PM fiber optic components with relatively small core/cladding dimensions of 10/125 um. A short (< 1.5 m), custom made, highly Yb-doped PM fiber with high photodarkening resistance is used, allowing for the reduction of non-linear effects (SBS). In the present configuration, a (2+1) x 1 PM combiner and two wavelength stabilized pump diodes at 976nm (2 x 60W) provides SBS free CW output power levels up to 80 W at 1064nm with a PER of more than 25dB. The amplifier can be run in QCW mode by allowing the pump diodes to operate with up to 3 times the rated CW average power for sub-millisecond pulses (< 10 % duty cycle), increasing in this way the flexibility of the laser system. Furthermore, single-pass, frequency conversion to 532 nm in both CW and QCW mode is demonstrated by using different non-linear crystals (KTP and PPLN) with conversion efficiencies > 20 %.

10082-62, Session 12

100 J UV glass laser for dynamic compression research

Jason S. Zweiback, Logos Technologies, Inc. (United States); Scott F. Fochs, Jake Bromage, Douglas Broege, Robert H. Cuffney, Univ. of Rochester (United States); Zachary Currier, Logos Technologies, Inc. (United States); Christophe Dorrer, Brian Ehrich, Univ. of Rochester (United States); Jim Engler, Logos Technologies, Inc. (United States); Mark J. Guardalben, Univ. of Rochester (United States); Nick Kephalos, Logos Technologies, Inc. (United States); John A. Marozas, Richard G. Roides, Jonathan D. Zuegel, Univ. of Rochester (United States)

A 100-J, 351-nm laser has been designed and built. This laser is for the Dynamic Compression Sector located at the Advanced Photon Source. This user facility will employ the laser to drive shocks in solid-state materials which will be probed by picosecond x-ray pulses available from the synchrotron source. Using proven technology, the laser is designed for reliability and ease of use. A state-of-the-art fiber front end provides pulse lengths up to 20 ns with pulse shapes tailored to optimize shock trajectories. A diode-pumped Nd:glass regenerative amplifier is followed by a four-pass, flash-lamp-pumped rod amplifier. The regenerative amplifier produces up to 20 mJ with better than 1% RMS stability. The passively multiplexed four-pass amplifier produces 1.7 J to 1.9 J depending on the pulse shape. The final amplifier uses a 15-cm Nd:glass disk amplifier in a six-pass configuration. Over 200 J of infrared energy is produced by the disk amplifier. A KDP Type-II/Type-II frequency tripler configuration converts the 1053-nm laser output to a wavelength of 351 nm and the ultraviolet beam is image relayed to the target chamber. Output energy stability is better than 3%. Smoothing by Spectral Dispersion and polarization smoothing have been optimized to produce uniform shocks in the materials to be tested. A distributed phase plate and aspheric lens produce a highly uniform 500-micron diameter (FWHM), super-Gaussian far-field spot. Custom control software collects all diagnostic information and provides a central control for all aspects of laser operation. Performance and operational aspects of the laser will be discussed.

Conference 10083: Fiber Lasers XIV: Technology and Systems

Monday - Thursday 30–2 February 2017

Part of Proceedings of SPIE Vol. 10083 Fiber Lasers XIV: Technology and Systems

10083-1, Session 1

12 mJ pulse energy 8-channel divided-pulse ultrafast fiber laser system

Michael Müller, Marco Kienel, Arno Klenke, Thomas Gottschall, Evgeny Shestaev, Friedrich-Schiller-Univ. Jena (Germany); Marco Plötner, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Jena Limpert, Friedrich-Schiller-Univ. Jena (Germany); Andreas Tünnermann, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

State-of-the-art ultrafast fiber lasers currently are limited in peak power by excessive nonlinearity and in average power by modal instabilities. Coherent beam combination in space and time is a successful strategy to continue power scaling by circumventing these limitations. Following this approach, we demonstrate an ultrafast fiber laser system featuring spatial beam combination of 8 amplifier channels and temporal combination of a pulse burst comprising 4 pulses. Active phase stabilization of this 10-armed interferometer is achieved using LOCSET and Hansch-Couillaud techniques. The system delivers 1 kW average power at 1 mJ pulse energy being limited by pump power and delivers 12 mJ pulse energy at 700 W average power being limited by optically induced damage. The system efficiency is 91% and 78%, respectively, which is due to inequalities of nonlinearity between the amplifier channels and to inequality of power and nonlinearity between the pulses within the burst. In all cases, the pulse duration is ~260 fs and the M?-value is better than 1.2. Further power scaling is possible using more amplifier channels and longer pulse bursts.

10083-2, Session 1

Multi-mJ energy extraction using Yb-fiber based coherent pulse stacking amplification of femtosecond pulses

John M. Ruppe, Hanzhang Pei, Siyun Chen, Morteza Sheikhsofla, Univ. of Michigan (United States); Russell B. Wilcox, Lawrence Berkeley National Lab. (United States); John A. Nees, Almantas Galvanauskas, Univ. of Michigan (United States)

We report multi-mJ energy (>5mJ) extraction from femtosecond-pulse Yb-doped fiber CPA using coherent pulse stacking amplification (CPSA) technique. This high energy extraction has been enabled by amplifying 10's of nanosecond long pulse sequence, and by using 85-µm core Yb-doped CCC fiber based power amplification stage. The CPSA system consists of 1-GHz repetition rate mode-locked fiber oscillator, followed by a pair of fast phase and amplitude electro-optic modulators, a diffraction-grating based pulse stretcher, a fiber amplifier chain, a GTI-cavity based pulse stacker, and a diffraction grating pulse compressor. Electro-optic modulators are used to carve out from the 1-GHz mode-locked pulse train an amplitude and phase modulated pulse burst, which after stretching and amplification, becomes equal-amplitude pulse burst consisting of 27 stretched pulses, each approximately 1-ns long. Initial pulse-burst shaping accounts for the strong amplifier saturation effects, so that it is compensated at the power amplifier output. This 27-pulse burst is then coherently stacked into a single pulse using a multiplexed sequence of 5 GTI cavities. The compact-footprint 4+1 multiplexed pulse stacker consists of 4 cavities having rountrip of 1 ns, and one Herriott-cell folded cavity - with 9ns roundtrip. After stacking, stretched pulses are compressed down to the bandwidth-limited ~300 fs duration using a standard diffraction-grating pulse compressor.

10083-3, Session 1

mJ range all-fiber MOPA prototype with hollow-core fiber beam delivery and fiber beam shaping designed for large scale laser facilities seeding

Florent Scol, Pierre Gouriou, Arnaud Perrin, Jean-François Gleyze, Commissariat à l'Énergie Atomique (France); Constance Valentin, Géraud Bouwmans, Ctr. National de la Recherche Scientifique (France); Emmanuel Hugonnot, Commissariat à l'Énergie Atomique (France)

The Laser megajoule (LMJ) is a French large scale laser facility dedicated to inertial fusion research. Its front-ends are based on fiber laser technology and generate highly controlled beams in the nanojoule range. Scaling the energy of those fiber seeders to the millijoule range is a way explored to upgrade LMJ's architecture.

We report on a fully integrated narrow line-width all-fiber MOPA prototype at 1053 nm designed to meet stringent requirements of large-scale laser facilities seeding. We achieve 750 µJ temporally-shaped pulses of few nanoseconds at 1 kHz. Thanks to its original longitudinal geometry and its wide output core (26µm MFD), the Yb-doped tapered fiber used in the power amplifier stage ensures a single-mode operation and negligible spectro-temporal distortions. The transport of 30 kW peak power pulses (from tapered fiber) in a 17 m long large mode area (39µm) hollow-core (HC) fiber is presented and points out frequency modulation to amplitude modulation conversion management issues. A S? measurement of this fiber allows to attribute this conversion to a slightly multimode behavior (< 13dB of extinction between the fundamental mode and higher order modes). Other HC fibers exhibiting a really single-mode behavior (>20 dB) have been tested and the comparison will be presented in the conference. Finally, fiber spatial beam shaping from coherent Gaussian beam to coherent top-hat intensity profile beam in the mJ range with a specifically designed and fabricated fiber will also be presented.

10083-4, Session 1

Coherent pulse stacking with delay lines

Henrik Tünnermann, Akira Shirakawa, The Univ. of Electro-Communications (Japan)

Temporal coherent beam combining of pulsed fiber lasers has gained a lot of interest as it could pave the way for fiber lasers to compete with bulk lasers in terms of pulse energy. We purpose to stack up the symmetric output of an oscillator by phase and polarization switching. This way we can avoid the effects of gain dynamics and are able to utilize all the seed power as opposed to regular pulse picking approaches.

We used a 47 MHz femtosecond fiber oscillator centered at 1558 nm (5 nm bandwidth). Feeding the pulse train into a Mach Zehnder interferometer and adding electro optic modulators (EOMs) in both optical paths, we imprint a ϖ phase shift in one path on every other pulse. We then use a polarization beam splitter to combine the two beams and stabilize the resulting polarization with a unity gain significantly lower than MHz. Therefore after the two beams are combined, the ϖ phase shift stays intact and neighboring pulses have their polarization flipped. In a following PBS horizontal and vertically polarized pulses are separated. The vertical polarized pulses are delayed and combined with the next pulse. This halves the repetition rate basically acting like a pulse picker but without discarding 50% of the output power. The efficiency of the experiment was so far limited by linear losses in the PBS and linear losses due to the pickups for the photodiodes. We will give an update un the latest results and our plans to go forward.

10083-5, Session 1

Efficient and compact nonlinear compression for medium energy high repetition rate and average power lasers

Tino Eidam, Active Fiber Systems GmbH (Germany); Steffen Hädrich, Friedrich-Schiller-Univ. Jena (Germany) and Active Fiber Systems GmbH (Germany); Armin Hoffmann, Active Fiber Systems GmbH (Germany); Jens Limpert, Friedrich-Schiller-Univ. Jena (Germany) and Active Fiber Systems GmbH (Germany)

Ultrashort laser pulses are routinely employed in a variety of scientific and industrial applications. Kilowatt level systems based on Yb-doped laser media have gained huge interest, since they can help improving signal-to-noise-ratios or reduce processing times in industrial applications. However, there is growing interest in shorter pulse durations both in science and industry. The established approach to achieve this is to utilize a concept called nonlinear compression whereby spectral broadening is achieved via the nonlinear effect of self-phase modulation followed by temporal compression. Typically, the spectral broadening part is achieved in a waveguide that enhances the interaction length and also eliminates spatial chirp. For years there was a gap in the 10 µJ to 100 µJ, which couldn't be addressed due to either damage (solid fiber) or high losses (capillaries). In recent years, Kagome fibers have been utilized, since they provide low loss propagation for rather small cores and can be filled with noble gas for spectral broadening. However, recent studies showed that also higher order modes propagate, which might lead to difficulties in high average power operation. Here, we present an alternative approach that builds on proven capillaries for nonlinear compression at 100 µJ level pulse energies. Utilizing short capillaries with a high pressure filling allows for efficient compression with a small footprint. We demonstrated the compression of a 16W, 80 µJ, 330fs laser to 12 W, 60 µJ, sub-50 fs in a 20 cm long capillary filled with 23 bar of krypton.

10083-6, Session 2

Femtosecond coherent beam combining of a large number of fiber amplifiers: First results

Jeremy Le Dortz, Thales Research & Technology (France); Anke Heilmann, Ecole Polytechnique (France); Marie Antier, Thales Optronique S.A.S. (France); Jérôme Bourderionnet, Christian Larat, Thales Research & Technology (France); Ihsan Fsaifes, Louis Daniault, Ecole Polytechnique (France); Severine Bellanger, Lab. pour l'Utilisation des Lasers Intenses, Ecole Polytechnique (France); Christophe Simon Boisson, Thales Optronique S.A.S. (France); Jean-Cristophe Chanteloup, Ecole Polytechnique (France); Arnaud Brignon, Eric Lallier, Thales Research & Technology (France)

We previously demonstrated that interferometric phase measurement is compatible with the Coherent beam combining (CBC) of thousands of fiber amplifiers in continuous regime. For some applications such as particle accelerations femtosecond operation will be required with both high energy and high repetition rate. As a proof of concept, the X-CAN project carried out by Thales and the Ecole Polytechnique aims at developing a highly scalable ultrafast laser system based on that principle. To alleviate the remaining technical challenges, a demonstrator implying the coherent addition of 61 amplifier chains is under work, with a targeted delivery of 10 mJ, 350 fs pulses at 50 kHz repetition rate.

In a first experiment, 300fs pulses (chirped to 200ps) are split in 19 passive fibers. In a hexagonal tile aperture combining scheme, we successfully demonstrate the coherent combination of femtosecond pulses with the interferometric technique. In closed loop, the measured residual phase shift errors are below ?/60 rms. We obtain a FWHM pulse duration of 310 fs for the combined beam by assuming a Gaussian pulse shape.

In a second experiment, the phase locking of two fiber amplifiers was investigated. The amplifiers were driven at the final targeted peak power, leading to the same amount of non-linear effects (B-integral). Successful phase locking was demonstrated with a residual phase shift error of ?/30 rms. The power spectral density noise of the relative phase between two amplifiers without and with phase control loop was measured.

Detailed results will be presented for these two experiments.

10083-7, Session 2

Divided-pulse amplification with fiber-coupled electro-optic modulators

Henning Stark, Michael Müller, Friedrich-Schiller-Univ. Jena (Germany); Marco Kienel, Arno Klenke, Friedrich-Schiller-Univ. Jena (Germany) and Helmholtz Institute Jena (Germany); Jens Limpert, Andreas Tünnermann, Friedrich-Schiller-Univ. Jena (Germany) and Helmholtz Institute Jena (Germany) and Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

The development of high-power ultrafast lasers in the last years has enabled a variety of different applications, e.g. material processing and laser particle acceleration. Power scaling constantly faces technological and fundamental physical limitations, such as nonlinear effects and material damage. Promising techniques to overcome those boundaries are spatial coherent beam combining and divided-pulse amplification.

In this contribution, we demonstrate in a proof-of-principle experiment spatial combination of two amplifier channels and temporal combining of up to 8 pulses using a mostly fiber-coupled divided-pulse amplification setup. The pulses to be combined are taken directly from a high-repetition rate laser oscillator, which cancels the need for pulse division via optical delay lines. Electro-optic modulators are applied to achieve temporal combination in free-space delay lines. The mostly fiber-integrated structure reduces the impact of environmental perturbations and hence increases stability. The temporal combining of 4 pulses results in a high combining efficiency of about 94% and great temporal contrast of above 25 dB for a variety of input pulse train energies. The relative intensity noise at the system output is below 0.5% in the frequency interval from 1 Hz to 100 kHz, indicating stable operation. For the combining of 8 pulses about 90% efficiency is achieved. This technique is further scalable via combination of even more pulses and could be used in high-power setups. In addition to that, phase- and amplitude-shaping of each pulse is possible and potentially allows to compensate for amplifier saturation and for nonlinear phase differences to the 0th order, yielding the highest possible combining efficiencies.

10083-8, Session 2

MW peak power diffraction limited monolithic Yb-doped tapered fiber amplifier

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Denisov, Mikhail M. Bubnov, Fiber Optics Research Ctr. of the Russian Academy of Sciences (Russian Federation); Denis S. Lipatov, Alexander Y. Laptev, Alexey N. Guryanov, Institute of Chemistry of High-Purity Substances of the Russian Academy of Sciences (Russian Federation); Elena A. Anashkina, Sergey V. Muravyev, Alexey V. Andrianov, Arkady V. Kim, Federal Research Ctr. Institute of Applied Physics of the Russian Academy of Sciences (Russian Federation) and N.I. Lobachevsky State Univ. of Nizhni Novgorod (Russian Federation); Mikhail E. Likhachev, Fiber Optics Research Ctr. of the Russian Academy of Sciences (Russian Federation)

A novel operation regime of Yb-doped tapered fiber amplifier, that allows one to achieve ultimately high peak power (0.5-0.8MW directly from amplifier) is predicted theoretically and demonstrated experimentally in this study. The amplifier utilizes a relatively long fiber (2.2m) of improved design (clad absorption of 23.5dB/m @ 976nm, maximum core D is 67μm). Calculations showed that utilization of 976nm pump power and signal centered at 1065nm realize regime when input signal stays almost unchanged in the most part of tapered fiber and rapidly amplifies in the output 70cm of the tapered fiber having ultimately high mode field diameter. In this case estimated stimulated Raman scattering threshold should be at high level of about 0.7MW for 30ps pulses.

During the first experiment we have amplified 2mW 30ps pulses with spectrum peaked at 1055nm (Δ?=17.5nm) and repetition rate of 0.55MHz up to 8.6W of average power and 15.6μJ in energy, corresponding to peak power of 0.5MW directly from the amplifier. These pulses were compressed with grating compressor down to about 350fs with 50% efficiency, resulting in estimated peak power of ~24MW. In order to obtain better results we placed spectral filter in scheme that gave us ~9ps pulses with center wavelength at 1064nm and FWHM of 6nm. These pulses were amplified up to 4.6W of average power and ~0.8MW of peak power. Maximum achieved power level was limited by luminescence instead of SRS or FWM in the case.

10083-9, Session 2

Figure-of-eight bismuth doped fiber laser operating at 1.3 microns in dissipative soliton regime

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An ultrafast lasers at 1.3 microns are of great interest due to existence of transmission window of living tissues in this very range of optical spectrum. At present time there are not so many devices capable to generate a femtosecond pulses in this region, especially fiber lasers.

In this work we present an all-fiber ultrafast dissipative soliton (DS) laser based on phosphosilicate fiber doped with bismuth working in the region of 1.3 microns. The setup uses figure-of-eight laser scheme with nonlinear optic loop mirror and yields pulses as short as 11.3 ps assuming sech profile with average power of ~6 mW and pulse energy of ~1.7 nJ. The cavity of the laser has large positive net dispersion that allows reaching DS regime. As most of the silica based fibers have quite small dispersion in this region, we used high-germanium (HiGe) optical fiber to provide needed net dispersion. At the same time HiGe fiber increases nonlinearity of the loop mirror. The pulses from the cavity were amplified using bismuth fiber amplifier up to ~30 mW of average power level that corresponds to pulse energy of 8.5 nJ and then compressed with couple of diffraction gratings down to 530 fs.

To achieve best results we investigated dependence of fiber gain on bismuth active centers concentration in phosphosilicate fibers and obtained that maximum gain (~0.2 dB/m) is reached at active bismuth concentration corresponding to absorption level between 0.55 and 1.2 dB/m at 1.3 um. Increase of bismuth concentration leads to outrunning growth of unsaturable losses.

10083-10, Session 3

High-average power 4 GW pulses with sub-8 optical cycles from a Tm-doped fiber laser driven nonlinear pulse compression stage

Martin Gebhardt, Christian Gaida, Fabian Stutzki, Friedrich-Schiller-Univ. Jena (Germany); Steffen Hädrich, Active Fiber Systems GmbH (Germany); Cesar Jauregui-Misas, Jens Limpert, Andreas Tünnermann, Friedrich-Schiller-Univ. Jena (Germany)

We demonstrate the nonlinear compression of ultrashort pulses from a high repetition rate Thulium-based fiber CPA system using a nitrogen gas-filled hollow capillary. Pulses with 4 GW peak power, 46 fs FWHM duration and an average power of 15.4 W have been achieved. Based on this result, we discuss the next steps towards a 100 W-level, GW-class few-cycle mid-IR laser.

10083-11, Session 3

Towards sub-100 fs multi-GW pulses directly emitted from a thulium-based fiber CPA system

Christian Gaida, Friedrich-Schiller-Univ. Jena (Germany); Martin Gebhardt, Friedrich-Schiller-Univ. Jena (Germany) and Helmholtz Institute Jena (Germany); Fabian Stutzki, Cesar Jauregui-Misas, Friedrich-Schiller-Univ. Jena (Germany); Jens Limpert, Helmholtz Institute Jena (Germany) and Friedrich-Schiller-Univ. Jena (Germany) and Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Andreas Tünnermann, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany) and Helmholtz Institute Jena (Germany) and Friedrich-Schiller-Univ. Jena (Germany)

Experimental demonstrations of Tm-based fiber amplifiers (typically in CW- or narrow-band pulsed operation) span from about 1700 nm to well beyond 2000 nm wavelength. Thus, it should be possible to obtain a bandwidth of more than 100 nm enabling sub-100 fs pulse duration in an efficient, linear amplification scheme. In fact, this would enable pulses with less than 20 optical cycles directly from a Tm-based fiber system, something that seems to be extremely challenging for other dopants in a fused silica fiber. In this contribution, we summarize the current development of our Thulium-based fiber CPA system, demonstrate preliminary experiments for further scaling and discuss important design factors for the next steps. The current single-channel laser system presented herein delivers a pulse-peak power of 2

GW and a nearly transform-limited pulse duration of 200 fs in combination with 28.7 W of average power. Special care has been taken to reduce the detrimental impact of water vapor absorption by employing the whole system in a dry atmosphere housing (<0.1% rel. humidity) and utilizing a sufficiently long wavelength (1920-1980 nm). The utilization of a low-pressure chamber in the future will allow for extension of the amplification bandwidth. Preliminary experiments demonstrating a broader amplification bandwidth that supports almost 100 fs pulse duration and average power scalability to > 100W have been performed. Based on these results, a Tm-based fiber CPA with sub-100 fs pulse duration, multi-GW pulse peak power and >100 W average power can be expected in the near future.

10083-12, Session 3

Self-protecting nonlinear compression in a solid fiber for long-term stable ultrafast lasers at 2 μm wavelength

Fabian Stutzki, Christian Gaida, Martin Gebhardt, Cesar Jauregui-Misas, Jens Limpert, Andreas Tünnermann, Friedrich-Schiller-Univ. Jena (Germany); Ioachim Popzea, Max-Planck-Institut für Quantenoptik (Germany)

Nonlinear pulse compression in an solid core fiber is very simple and elegant way for the generation of shortest pulses durations. However, small energy fluctuations of the input pulses can lead to devastating destruction of the fiber by the fundamental self-focusing. We theoretically predict and experimentally verify the existence of a safe operation regime, which is characterized by a distinct peak power maximum at the point of best pulse compression. The laser system delivers 23 W, 18 MW and 40 fs pulses around 2 μm wavelength.

10083-13, Session 3

Dispersion tailored non-PM and PM fibers for 2 microns ultrafast fiber lasers

Clémence Jollivet, Daniel Jeannotte, Peyman Ahmadi, Adrian L. Carter, Kanishka Tankala, Nufern (United States)

One of the current challenges towards the development of ultrafast 2 microns all-fiber laser systems delivering transform-limited pulses is to manage dispersion and nonlinearities which are well-known limiting factors in fiber-based systems due to their negative impact on pulse duration and shape.

Here, we present what we believe to be, to the best of our knowledge, the first all-solid step-index dispersion tailored fiber designed with anomalous dispersion around 2 microns. This all-solid, step-index ultra-high numerical aperture (UHNA) fiber offers an efficient and simple alternative compared to existing approaches such as free-space optical systems or micro-structured fibers that are complex to manufacture and handle. The combination of highly Ge-doped core with a small core diameter allows tailoring the material and waveguide components of the dispersion to reach the anomalous dispersion required by the application.

In this work, details will be provided using experimental and calculated values via the example of a non-PM UHNA fiber with 2.45 microns core and 0.34 NA. This fiber was designed to achieve anomalous dispersion of -45 ps/(nm.km) at 2 microns. It will be shown that the UHNA fiber design can be further tuned to achieve specific values of anomalous dispersion and dispersion slope. The fiber performances were confirmed using a 2 microns chirp-pulsed fiber amplifier where the pulse duration was measured at 24 ps and 4.3 ps without and with the UHNA fiber respectively. A PM-UHNA fiber design is currently being developed and will be characterized and tested following a similar fashion.

10083-14, Session 3

Mode-locked tunable thulium-doped fiber laser

Wenyan Tian, Eric D. Park, Q-Peak, Inc. (United States)

Tunable CW thulium-doped fiber lasers have been investigated in the past decade due to their applications in medicine, optical sensing, spectroscopy, and nonlinear frequency conversion. Ultrashort pulse thulium-doped fiber lasers at 2 μm wavelength are very attractive as pump sources for mid-infrared (Mid-IR) optical parametric oscillators and Mid-IR supercontinnum generation. So far, passively mode-locked fiber lasers based on semiconductor saturable absorber mirrors (SESAMs), graphene, and carbon nanotubes have been demonstrated. Recently, an all-fiber, actively mode-locked thulium-doped fiber laser at 1980 nm based on a 10-GHz bandwidth electro-optic intensity modulator and a 1550-nm fiber laser as a pump source has been demonstrated. Kneis et al. reported a free space coupled, actively mode-locked, tunable, thulium-doped fiber laser based on an acousto-optic modulator and diffraction grating. However, stability will be an issue in its application due to the free space components. Here, we present what we believe to be the first report on an all-fiber, actively, mode-locked, tunable, thulium-doped fiber laser based on a 20-GHz bandwidth electro-optic intensity modulator (EOM) and a voltage driven 2-μm, custom designed, intra-cavity, fiber coupled, Fabry-Perot tunable filter (FFP-TF). The thulium-doped fiber is cladding-pumped at 793 nm. The repetition rate of output pulses was 47 MHz for fundamental mode-locking and the shorted measured output pulse width was 445 ps limited by the damage threshold of the FFP-TF. The tuning range is continuous from 1954 to 2042 nm and exhibits an output spectral bandwidth ≤0.14 nm with a signal-to-noise ratio over 55 dB.

10083-15, Session 4

1940 nm all-fiber Q-switched fiber laser

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We present development of a Q-switched 1940 nm Tm-doped fiber laser with 45 W average power and 10 kW peak power and discuss preliminary demonstration of the system utilized as a precision surgical tool. The laser has a Master-Oscillator-Power-Amplifier design. The master oscillator operates at 1 W average power with pulse repetition rate (PRR) between 30 – 100 kHz. At the lowest PRR the pulse width is about 120 ns. Two amplification stages increase the average power to 45 W. Polarization insensitive isolators are installed between amplification stages to ensure stable operation of the laser. The laser output is delivered with a 2 meter fiber and collimated to a beam size of 5 mm.

Medical surgery is a field of application where such a laser may be able to improve clinical practice.

Tm-doped fiber lasers have the unique advantage of conventional fiber delivery and high tissue removal rates with excellent beam quality compared with traditional surgical lasers such as CO2. Fiber delivery expands potential applications for laparoscopic surgeries, where the laser used for cutting tissue needs to be delivered to locations through small-sized incisions in the body. The laser together with scanning galvanometer mirrors was used to cut precisely around small footprint vessels in tissue phantoms. The focused laser beam effectively removed tissue without leaving visible residual thermal damage. Another common surgical application of cutting up to but sparing sensitive tissue structures (e.g. nerves) was also explored. We conclude that this laser has promising potential in the laser surgery application space.

10083-16, Session 4

Simulation and design of a multistage 10W thulium-doped double clad silica fiber amplifier at 2050nm

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A careful comparison of experiment and theory is important both for basic research and systematic engineering design of Thulium fiber amplifiers operating in the 2 μm region for applications such as LIDAR or spectroscopy (e.g. CO2 atmospheric absorption at 2051.4 nm). In this paper we report the design and performance of a multistage high-power PM Tm-doped fiber amplifier, cladding pumped at 793 nm. The design is the result of a careful comparison of numerical simulation, based on a three level model including ion-ion interactions, and experiment. Our simulation model is based on precise measurements of the cross sections and other parameters for both 6 and 10 μm core diameter fibers. Good agreement for several single and multistage amplifier topologies and operating conditions will be presented. Origins of the difference between theory and experiment are discussed, with emphasis on the accuracy of the cross sections and the cross relaxation parameters. Finally based on our simulation tool, we will demonstrate a design with an output power greater than 10 W for a multistage amplifier with a single-frequency signal at 2050 nm. The power stage was constructed with a 6 μm active fiber showing a 64 % optical slope efficiency. The output power is found to be within 5% of the simulated results and is limited only by the available launched pump power of ~24 W. No stimulated Brillouin scattering is observed at the highest output power level for an active fiber well thermalized.

10083-17, Session 4

Design optimization of Tm-doped large-mode area fibers for power scaling of 2 microns lasers and amplifiers

Clémence Jollivet, Kevin F. Farley, John Edgecumbe, Adrian L. Carter, Kanishka Tankala, Nufern (United States)

High efficiency Double-clad large-mode area (LMA) Thulium-doped fibers (TDF) used in 2 microns lasers and amplifiers are designed with high doping concentration to favor the cross-relaxation process when pumping at 79X nm. It is common to design a pedestal layer around the core to effectively lower the core NA and to limit the number of transverse modes offering the possibility to achieve diffraction-limited beam quality. However, the pedestal also acts like a guiding region for parasitic light from coupling loss or bend-induced loss limiting the performances of the system.

In this work, the influence of the pedestal design on the system performances is studied by measuring the change in refractive index in the vicinity of fusion splices using a fiber index profilometer. The fraction of light coupled in the core and pedestal of the LMA TDF is evaluated using mode-overlap integrals and beam propagation calculations on the measured fiber index profiles. Two LMA TDF designs are compared; both fibers have 400 microns cladding and 0.11 core NA, one is 25 microns diameter core with pedestal-to-core ratio (B/A) of 1.7 and the other is 20 microns with B/A = 3. Splice analysis confirm the need for splice optimization and suggest that fiber with larger B/A are more resistant to splicing conditions, increasing the LP01 mode coupling efficiency from 42% to 99%. The most recent results on a new LMA TDF with 25 microns core, 400 microns clad and B/A = 3 will be provided as well as additional pedestal design considerations.

10083-18, Session 4

Extreme temperature operation of thulium-doped silica fiber lasers

Benjamin R. Johnson, Daniel J. Creeden, Scott D. Setzler, BAE Systems (United States)

We investigate thulium-doped silica fiber lasers operating from 80 K – 370 K. Using an ASE source and a spectrum analyzer we characterize the spectroscopic behavior of a standard commercial thulium-doped silica fiber over a ~300K temperature range. We show a reduction in inhomogeneous broadening at cryogenic temperatures that reduces the width of the 3H4-3H6 absorption feature allowing for efficient lasing in the ~1800nm region. Greater than 17 W of output power was generated at ~1850 nm by 793 nm diode-pumping a free-running single-mode thulium oscillator under cryogenic cooling conditions. We also discuss the advantages of cryogenic cooling short-wavelength thulium fiber lasers and amplifiers for non-linear frequency conversion and telecommunications.

10083-19, Session 4

Nonlinear processes associated with the amplification of MHz-linewidth laser pulses in single-mode Tm:fiber

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This work will study the accumulated nonlinearities when amplifying a narrow linewidth 2053 nm seed in a single mode Tm:fiber amplifier. A <2 MHz linewidth CW diode seed is externally modulated using a fiberized acousto-optic modulator. This enables independent control of repetition rate and pulse duration (>50 ns). The pulses are subsequently amplified and the repetition rate is further reduced using a second acousto-optic modulator. It is well known that spectral broadening occurs in such fibers for peak powers of 100's of watts due to SPM, FWM, and modulation instability. In addition to enabling a thorough test bed to study such spectral broadening, this system will also enable the investigation of SBS thresholds in the same system. This detailed study of the nonlinearities encountered in 2 μm fiber amplifiers is important in a range of applications from telecommunications to the amplification of ultrashort laser pulses.

10083-20, Session 4

Linewidth-narrowed 2-μm single-frequency fiber laser based on stimulated Brillouin scattering effect

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Single-frequency fiber laser around 2 μm have drawn much intense interest due to the attractive characteristics in terms of low noise, narrow linewidth and the resulting long coherence length for the potential applications in such areas as high-resolution spectroscopy, coherent LIDAR and free-space optical communications. The narrow-linewidth 2 μm single-frequency sources are in great demand to improve the detection ranges and resolutions for the aforementioned applications.

In this paper, a 2-μm linear-polarized single-frequency Brillouin-Thulium fiber laser has been experimentally investigated for linewidth narrowing, where a piece of Thulium-doped fiber was employed in the ring cavity to serve as the gain media for both the Brillouin pump and Stokes light. In the experiment, a fiber laser with 34 kHz linewidth was pre-amplified to act as

the Brillouin pump. The Brillouin-Thulium fiber laser operates at 1925.08 nm, which is upshifted by 0.10 nm from the Brillouin pump. The threshold for the Brillouin pump is ~ 200 mW. The experiment confirms that the function of the Brillouin pump is to excite the SBS and the Tm-doped fiber in the ring cavity is mainly used to amplify the power of Stokes light. The linewidth of the fiber laser has been narrowed for ~8 times, from 34 to 4.6 kHz. The measured RIN of the BTFL is <-150 dB/Hz for frequency above 2 MHz, which approaches the shot noise limit. Furthermore, the linewidth of the laser can be further narrowed to several hundred Hertz through the optimization of the Brillouin ring cavity.

10083-21, Session 5

Transverse mode instability analysis in fiber amplifiers *(Invited Paper)*

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Theoretical models of transverse modal instability (TMI) so far consider the interaction of two propagating modes and study the power exchange between the modes and TMI threshold either though STRS static or dynamic mode interactions. In this work, we take a different approach in studying TMI. We start with the paraxial wave equation for the fundamental mode (FM) under the slowly-varying envelope approximation, accounting for the effects of both the inversion and thermal load on the fiber refractive index. A TMI condition is derived by considering the stability of the amplified FM. For a given pump power, the electric field, inversion and thermal distribution are perturbed from their steady-state values and the stability of this transverse perturbation is studied, using a standard perturbation technique. We observe that population inversion contribution to instability gain is dominant at low powers and high inversion. Under high powers and low inversion (high amplifier saturation) the thermal effects dominate the instability behavior. A simple and easy to interpret TMI power threshold (Pth) formula is derived for the first time. Pth is inversely proportional to the quantum defect (qD) and the saturated amplifier gain (gs). It is proportional to (?0/D0)^2, in good agreement with experimental data. The explicit dependence of Pth on ?0, qD and gs results in similar TMI power thresholds for Yb- and Tm-doped amplifiers, despite the larger qD of the latter.

10083-22, Session 5

The impact of core co-dopants on the mode instability threshold of high-power fiber laser systems

Cesar Jauregui-Misas, Hans-Jürgen Otto, Christoph Stihler, Friedrich-Schiller-Univ. Jena (Germany); Jens Limpert, Friedrich-Schiller-Univ. Jena (Germany) and Helmholtz Institute Jena (Germany) and Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Andreas Tünnermann, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany) and Friedrich-Schiller-Univ. Jena (Germany)

Transverse mode instabilities (TMI) have become a very serious problem for the further scaling of the average power of fiber laser systems. Recently the strong impact that photodarkening (PD) has on the TMI threshold of Yb-doped fiber laser systems has been revealed. This is a remarkable finding since it opens the door to a significant increase of the average power of fiber laser systems in the near future. The key to achieve this is to reduce the amount of PD losses in the fiber, which can be done with an optimization of the glass composition in the fiber. In this work we perform a theoretical study on the impact that co-dopants such as Al and P have on PD and on the TMI threshold. This analysis tries to find the optimum glass composition from the point of view of TMI. It is shown that in a short rod type fiber, changing the glass composition only leads to a modest increase of the TMI threshold due to the degradation of the cross-sections. This demonstrates that the optimization of the glass cannot be done attending only to the PD losses at the cost of the laser cross-sections. In spite of this, changing the glass composition can bring benefits in pulsed operation in terms of the stored energy. Additionally, other fiber geometries different from the rod-type can benefit in a greater degree by introducing co-dopants in the glass.

10083-23, Session 5

Understanding regime dependence of photo-darkening-induced modal degradation in high power fiber amplifier

Johan Boullet, Cyril Vincont, Alain Jolly, ALPhANOV (France)

Thermally induced transverse modal instabilities (TMI) have attracted these five years an intense research efforts of the entire fiber laser development community, as it represents the current most limiting effect of further power scaling of high power fiber laser. Anyway, since 2014, a few publications point out a new limiting thermal effect: fiber modal degradation (FMD). It is characterized by a power rollover and simultaneous increase of the cladding light at an average power far from the TMI threshold together with a degraded beam which does not exhibit temporal fluctuations, which is one of the main characteristic of TMI.

We report here on the first systemic experimental study of FMD in a high power photonic crystal fiber. We put a particular emphasis on the dependence of its average power threshold on the regime of operation. We experimentally demonstrate that this dependence is intrinsically linked to regime-dependent PD-saturated losses, which are nearly three times higher in CW regime than in short pulse picosecond regime. We make the hypothesis that the existence of these different PD equilibrium states between CW regime and picosecond QCW pulsed regime is due to a partial photo-bleaching of color centers in picosecond regime thanks to a higher probability of multi-photon process induced photobleaching (PB) at high peak power. This hypothesis is corroborated by the demonstration of the reversibility of the FMD induced in CW regime by simply switching the seed CW 1064 nm light by a short pulse, picosecond oscillator.

10083-24, Session 5

Controlling mode instabilities at 628 W average output power in an Yb-doped rod-type fiber amplifier by active modulation of the pump power

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The phenomenon of transverse mode instabilities (TMI) is currently the most limiting effect for the scaling of the average output power of fiber laser systems with near diffraction limited beam quality. Thus, it is of high interest to develop efficient mitigation strategies to further enhance the performance of fiber laser systems. By actively modulating the pump power of an Yb doped rod-type fiber amplifier it was possible to weaken the thermally-induced refractive index grating along the fiber, and thus to mitigate TMI to a large extent. A function generator connected to the pump

diode driver was utilized to achieve the modulation. With this setup we were able to extract a stabilized beam with an average output power of 628 W, which is more than three times higher than the free-running TMI threshold of that particular fiber under identical conditions (e.g. seed power). This is the highest average output power reported from a single channel rod-type fiber amplifier with a high-quality stabilized beam, to the best of our knowledge.

10083-25, Session 5

Virtual long term testing of high-power fiber lasers by simulation of mode instabilities and photodarkening-induced degradation of laser power

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The power scaling of high power fiber lasers has decelerated recently, due to transverse mode instability (TMI) and photodarkening (PD).

The origin of TMI is a power transfer from the fundamental mode of the fiber to higher transverse modes due to self-induced thermo-optical long period gratings. The excitation of higher modes can lead to temporal instability and a bend-loss-induced reduction of the laser power.

Over the lifetime of a fiber laser, the TMI threshold is decreased due to photodarkening of the fiber. Many investigations have been made to model both effects, but the microscopic mechanisms both of TMI and PD are not yet fully understood. The existing models are either comprehensive, but very slow and therefore limited to the simulation of short fibers, or reduced models that do not take transverse effects into account. Furthermore, these models have been applied only to single-pass fiber amplifiers so far.

We present a hierarchical numerical approach that allows to first pre-calculate the transverse distribution of the photodarkening losses, and then apply the precalculated data to a scalar coupled-mode model of the fiber laser. As a result, it is possible to perform virtual long term tests simulating several 10 000 hours of laser operation in a few hours. The transverse distribution of photodarkening losses in the fiber and the mode coupling gain can be analysed at any cross section along the fiber.

The simulation results are compared to experimental data, which also gives rise to a refinement of the existing models.

10083-26, Session 5

Experimental investigation of transverse mode instabilities in a double-pass Yb-doped rod-type fiber amplifier

Christoph Stihler, Hans-Jürgen Otto, Cesar Jauregui-Misas, Friedrich-Schiller-Univ. Jena (Germany); Jens Limpert, Andreas Tünnermann, Friedrich-Schiller-Univ. Jena (Germany) and Helmholtz Institute Jena (Germany) and Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

The phenomenon of transverse mode instabilities (TMI) is currently the most limiting effect for the scaling of the average output power of fiber laser systems with nearly diffraction limited beam quality. Even though a significant amount of knowledge on TMI in single-pass fiber amplifiers has been generated in the last years, relatively little is known about this effect in multi-pass amplifiers and oscillators. In this contribution TMI is experimentally investigated in a double-pass fiber amplifier, for the first time to the best of our knowledge. The TMI threshold was found to be significantly lower in the double-pass configuration than in the single-pass arrangement. Furthermore, the investigations unveiled a complex dynamic behavior of the instabilities in the double-pass fiber amplifier.

10083-27, Session 6

Numerical investigations of self- and cross-phase modulation effects in high-power fiber amplifiers *(Invited Paper)*

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The development of high-power fiber lasers is of great interest due to the advantages they offer relative to other laser technologies. Currently, the maximum power from a reportedly single-mode fiber amplifier stands at 10 kW. Though impressive, this power level was achieved at the cost of a large spectral linewidth, making the laser unsuitable for coherent or spectral beam combination techniques required to reach power levels necessary for airborne tactical applications. An effective approach in limiting the SBS effect is to insert an electro-optic phase modulator at the low-power end of a master oscillator power amplifier (MOPA) system. As a result, the optical power is spread among spectral sidebands; thus raising the overall SBS threshold of the amplifier. It is the purpose of this work to present a comprehensive numerical scheme that is based on the extended nonlinear Schrodinger equations that allows for accurate analysis of phase modulated fiber amplifier systems in relation to the group velocity dispersion and Kerr nonlinearities and their effect on the coherent beam combining efficiency. As such, we have simulated a high-power MOPA system modulated via filtered pseudo-random bit sequence format for different clock rates and power levels. We show that at clock rates of ≥30 GHz, the combination of GVD and self-phase modulation may lead to a drastic drop in beam combining efficiency at the multi-kW level. Furthermore, we extend our work to study the effect of cross-phase modulation where an amplifier is seeded with two laser sources.

10083-28, Session 6

The first experimental observation of long-term mode degradation in high peak power Yb-doped amplifiers

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In the present work, we report the first experimental observation and investigation of a new theoretically predicted detrimental effect – gradual and irreversible output mode shape degradation. This effect occurs during a long-term operation of a high peak power pulsed ytterbium-doped fiber lasers based on large mode area fibers. As in the case of so-called Mode Instability (MI) mode shape degradation is caused by power transfer from fundamental mode (FM) to first high order mode (HOM) LP11 occurring on long-period refractive index grating (LPG). But in contrast to MI, LPG is formed in active fiber core as a result of local photodarkening process taking place at positions of local electric field minima of modal interference pattern produced by FM and HOM.

The effect has been observed during operation of typical picosecond master oscillator power amplifier system with average power of 3 watts that final stage was based on different (glass matrix, cutoff wavelength, geometrical dimensions) few-mode LMA step-index fibers. Total degradation time lied in range of 70-1500hrs. System restart and power reducing had no effect on output mode shape. Further investigation reveals that absorption spectrum for FM in degraded fibers exhibit LPG-like bands structure. Excitation of FM with small signal centered at bands maximum wavelength leads to

registering HOM at the fibers output. Exposure to green light, that is known to reverse photodarkening-induced color-centers, allowed to bleach almost all induced absorption and mitigate the effect of FM degradation for small signal.

10083-29, Session 6

Modal-field spectra analysis of pump absorption efficiency in double-clad rare-earth doped fibers

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High-power fiber lasers became important devices in many industrial and health care fields. The key for high-power operation of fiber lasers is the double-clad fiber technology transforming lower-brightness pumps into high-brightness laser beams. Efficient pump absorption in the active core of the double-clad fiber is crucial for reliable and economic operation of high power fiber lasers. In our recent work we extensively studied the dependence of the pump absorption efficiency on bending and twisting of the fiber. For the first time we theoretically predicted and later experimentally demonstrated significant enhancement of pump absorption efficiency by simultaneous bending and twisting of the double-clad fiber.

In this contribution we provide extension of our previous theoretical studies using beam propagation model incorporating laser rate equations. The effect of bending and twisting on signal amplification in the double-clad fiber is analyzed for different input signal powers, and moreover, pump field modal spectra are evaluated. The results show that in correspondence with pump absorption efficiency the gain of the amplifier is enhanced under the conditions of simultaneously bent and twisted fiber. The key to understand the effect of bending and twisting on pump absorption efficiency consists in modal spectra of pump field propagating in the first clad of the double clad fiber. Three cases of straight, bent only, and simultaneously bent and twisted fiber are compared. The comparison shows that bending causes increase of the spectral range of propagating modes, but does not bring about mode-mixing. Substantial mode-mixing is established only in simultaneously bent and twisted fiber.

10083-30, Session 6

SBS suppression and coherence properties of a flat top optical spectrum in a high power fiber amplifier

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Suppression of stimulated Brillouin scattering (SBS) is typically achieved using a radio-frequency (RF) noise source to drive a phase modulator in order to increase the optical bandwidth of the laser and decrease the effective Brillouin gain. Previously, using a filtered pseudo-random bit sequence (PRBS) RF source has shown to give the largest SBS enhancement factor for a given coherence length at 90% visibility. Recently, it has been suggested that generating a flat top optical spectrum through phase modulation is ideal for suppressing SBS, although no experimental results in kilowatt class amplifiers have been demonstrated.

This paper generates a 5 GHz FWHM flat top optical spectrum using an arbitrary waveform generator. The optical spectrum consists of a number of discrete spectral lines within the 5 GHz bandwidth, ranging from 16 to 256 lines and corresponding to a spacing of 333 MHz to 20 MHz. These discrete lines correspond to a PRBS pattern of n = 4 to n = 8. The SBS threshold and coherence properties of the flat top spectrum are measured and compared to that of the PRBS in a kilowatt class fiber amplifier. It is experimentally demonstrated that for large frequency comb spacing, the flat top spectrum significantly outperforms the corresponding filtered PRBS, but as the line spacing is decreased to less than the Brillouin bandwidth the two noise sources have similar enhancement factors due to crosstalk between neighboring frequency components.

10083-31, Session 7

Optimizing the noise characteristics of high-power fiber laser systems

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The noise characteristics of high-power fiber lasers, unlike those of other solid-state lasers such as thin-disk lasers, have not been systematically studied up to now. However, novel applications for high-power fiber laser systems with carrier-envelope offset (CEO) stabilization, such as attosecond pulse generation, set stringent limits to the maximum noise level of these sources. Besides, it is known that mode instabilities can be seeded by amplitude noise. Therefore, in order to address these applications and issues, a detailed knowledge and understanding of the noise characteristics and its behavior in a fiber laser system is required. In this work we have carried out a systematic study of the propagation of the relative intensity noise (RIN) along the amplification chain of a state-of-the-art high-power fiber laser system. The most striking feature of these measurements is that the RIN level is progressively attenuated after each amplification stage. In order to understand this unexpected behavior, we have simulated the transfer function of the RIN in a fiber amplification stage (~80μm core) as a function of the seed power and the frequency. Our simulation model shows that this damping of the amplitude noise is related to saturation. Additionally, we show, for the first time to the best of our knowledge, that the fiber design (e.g. core size, glass composition, doping geometry) can be modified to optimize the noise characteristics of high-power fiber laser systems. This study opens the path towards the development of high-power fiber laser systems with unprecedented low-noise performance.

10083-32, Session 7

Power scaling of a hybrid microstructured Yb-doped fiber amplifier

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Hybrid microstructured fibers, utilizing both air holes and high index

cladding structures, provide important advantages over conventional fiber including robust fundamental mode operation with large core diameters (>30 ?m) and spectral filtering (i.e. ASE and Raman suppression). This work investigates the capabilities of a hybrid fiber designed to suppress stimulated Brillouin scattering (SBS) and modal instability (MI) by characterizing these effects in a counter-pumped amplifier configuration as well as interrogating SBS using a pump-probe Brillouin gain spectrum (BGS) diagnostic suite. The fiber has a 35 ?m annularly gain tailored core, the center doped with Yb and the second annulus comprised of un-doped fused silica, designed to optimize gain in the fundamental mode while limiting gain to higher order modes. A narrow-linewidth seed was amplified to an SBS-limited 724 W, with near-diffraction-limited beam quality, an effective linewidth < 1 GHz, and a pump conversion efficiency of 82%. No sign of MI was observed at the highest power level. Based on preliminary pump-probe measurements a Brillouin gain coefficient, gB, of 1.9?10-11 m/W was estimated. The primary gain peak occurred at 15.9 GHz; corresponding to the Yb-doped region of the core. A much weaker BGS response with a secondary peak occurring at 16.3 GHz was also observed; corresponding to the pure silica annulus. The low SBS response of the latter indicates that the fundamental mode overlaps weakly with the silica annulus of the core.

10083-33, Session 7

3 kW single stage all-fiber Yb-doped single-mode fiber laser for highly reflective and highly thermal conductive materials processing

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A 3 kW single stage all-fiber Yb-doped single-mode fiber laser with bi-directional pumping configuration has been demonstrated. Our newly developed 915-nm-high-power LD modules are employed for a high available pump power of 4.9 kW. The length of the delivery fiber is 20 m which is long enough to be used in most of laser processing machines. An output power of 3 kW is achieved at a pump power of 4.23 kW. A slope efficiency is 70%. SRS was able to be suppressed at the same output power by increasing ratio of backward pump power. The SRS level is improved by 5 dB when 57% pump ratios is adopted compared with the case of 50%. SRS is 35 dB below the laser light power at the output power of 3 kW even with a 20-m delivery fiber. The M-squared factor is 1.3. Single-mode beam quality is obtained. To evaluate practical utility of the single-mode fiber laser whose output power is 3 kW, A Bead-on-Plate (BoP) test onto a pure copper plate is executed. The BoP test onto a copper plate is made without stopping or damaging the laser system, which indicates our high power single-mode fiber lasers can be used practically in processing of materials with high reflectivity and high thermal conductivity.

10083-34, Session 7

Single mode low-NA step index Yb-doped fiber design for output powers beyond 4kW

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Fiber amplifiers are representing one of the most promising solid state laser concepts, due to the compact setup size, a simple thermal management and furthermore excellent beam quality. In this contribution, we report on the latest results from a low-NA, large mode area single mode fiber with a single mode output power beyond 4?kW without any indication of mode instabilities or nonlinear effects and high slope efficiency. Furthermore, we quantify the influence of the bending diameter of our manufactured low NA fiber on the average core loss by an OFDR measurement and determine the optimal bending diameter in comparison to a second fiber with a slightly changed NA. The fibers used in the experiments were fabricated by MCVD technology combined with the solution doping technique. The investigation indicates the limitation of the step index fiber design and its influence on the use in high power fiber amplifiers. We demonstrate, that even a slightly change in the core NA crucially influences the minimum bending diameter of the fiber and has to be taken into account in applications. The measured output power represents to the best of our knowledge the highest single mode output power of an amplifier fiber ever reported on.

10083-35, Session 7

5kW monolithic continuous wave near diffraction-limited fiber laser directly pumped by laser diodes

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We report a monolithic continuous wave (CW) fiber laser source at 1080 nm, producing > 5 kW average laser power. The laser consists of a CW fiber laser oscillator and one double cladding (DC) fiber amplifier in the master oscillator-power amplifier (MOPA) configuration. The oscillator is a linear cavity fiber laser with a pair of fiber Bragg gratings (FBG) centered at the wavelength of ~1080 nm. The active fiber utilized in the laser oscillator is ~ 20 meters 20/400 ?m (diameter of the core/inner cladding) double cladding ytterbium-doped fiber. The numerical aperture (NA) is 0.06/0.46 (core/inner cladding). The oscillator can produce ~ 500 W laser power with ~ 700 w launched pump power, provided by fiber coupled laser diodes at ~976 nm. One fiber amplifier was built to boost the average power of the seed laser. A piece of double cladding ytterbium-doped fiber with 30?m core was utilized as the active medium in the fiber amplifier. The fiber amplifier was directly pumped by fiber coupled laser diodes at ~976 nm. >5kW laser power was achieved when ~5352 W pump power was launched into the amplifier. The optical-to-optical conversion efficiency of the fiber amplifier with respect to the launched pump power reach 86.5%. The beam quality factor was measured to be <1.6. This is the first demonstration of the >5 kW monolithic near diffraction-limited fiber laser directly pumped by laser diodes and no any tandem pumping technique was adopted.

10083-36, Session 8

~1 kilowatt Ytterbium-doped all-solid photonic bandgap fiber laser

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Transverse mode instability (TMI) has been recognized as a major limit to average power scaling of single-mode fiber laser besides the optical nonlinear effects. One key to mitigate TMI is to suppress the higher-order

modes (HOMs) propagation in the optical fiber. By implementing additional cores in the optical fiber cladding, HOMs can be resonantly coupled from the main core to the surrounding cladding cores, leading to better HOMs suppression. Here, we demonstrate an Yb-doped multiple-cladding-resonant all-solid photonic bandgap fiber with a ~60μm diameter core for high power fiber lasers. The fiber has a multiple-cladding-resonant design in order to provide better HOMs suppression. Maximum laser power of 910w is achieved for a direct diode-pumped fiber laser without TMI with a 9m long fiber at 60cm coil diameter, breaking the TMI threshold of 800w that has been observed in large-mode-area PCFs with ~40μm core. This result is limited by fiber end burning due to the un-optimized thermal management. Later experiment demonstrates maximum laser power of 1050w with 90% lasing efficiency versus absorbed pump power in a 8m long fiber coiled at 80cm diameter, limited by the pump source. However, the fiber bending condition needs to be optimized in order to produce a better laser beam quality.

10083-37, Session 8

Design and characterisation of SRS filtering optical fibre for pulsed fibre laser beam delivery

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We report on a design and fabrication of stimulated Raman scattering (SRS) filtering fibre in high average (kW level) or high peak (>200kW) optical power delivery applications. The specifications require negligible loss (<0.1dB/m) at the signal wavelength and >100dB total loss at the Raman wavelength. Previous design of SRS filtering fibres was based on the resonant rings surrounding a solid core and index-matching at the Raman wavelength. However, this approach suffered from undesired couplings to ring modes, which dramatically reduce the transmission window and induce very high tolerance requirements for the fibre's structural parameters. Here, we introduce the novel geometry based on the series of circularly arranged rod resonators in the fibre cladding, which break the azimuthal symmetry of the resonant ring. Thus, importantly, no rod-mode crosses the dispersion curve of the fundamental mode near the designed operating wavelength. The extensive numerical modelling was carried out to identify suitable fibre design parameters within the refractive index and dimension bounds imposed by the commercially available materials. The fabricated fibre demonstrated excellent agreement with the numerical simulations. The fibre characterization revealed wide transmission window with small loss at signal wavelength and large loss at the Raman wavelength. Furthermore, the fibre performance for pulsed fibre laser beam delivery was evaluated with respect to SRS filtering. Preliminary measurements show not only effective SRS filtering, but also high output beam quality.

10083-38, Session 8

Three layer fiber with high stimulated Brillouin scattering threshold

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A new method of management stimulated Brillouin scattering (SBS) spectrum and increase of SBS threshold has been proposed. The method is based on fabrication of few concentric layers with a different compound using modified chemical vapor deposition technology. Optical fiber preform with step-index core (NA=0.24) consisting of three layers with different Al2O3 and GeO2 concentrations has been fabricated. The layers were deigned to have identical part of optical power at operating wavelength near 1550 nm (the core was designed to have cut-off wavelength near 1500 nm, clad diameter - to be 125 μm). Fibers with outer diameter of 80 μm, 100 μm, 125 μm and 135 μm were drawn. SBS gain spectrum of those fibers was measured using pump-probe technique. Correlation between electric field distribution over the layers and relative SBS gain peaks amplitudes has been demonstrated. It has been shown that peaks amplitudes in the SBS spectra become almost equal when fiber parameters (cut-off wavelength) approaches to the designed value. Thus it is possible to design fiber with any required parameters (core NA, cut-off wavelength) by appropriate chose of the layers width. SBS threshold of said fibers was measured directly by launching 500 ns single frequency pulses into the fiber with lengths of 75 m and measuring back scattered light. To compare fibers with different MFDs the dependence on power density in the core was compared. Increase of SBS threshold by 6.4 dB relative to that of SMF-28 has been demonstrated for fiber with outer diameter of 135 μm.

10083-39, Session 8

Yb-doped large mode area tapered fiber with depressed cladding and dopant confinement

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A polarization-maintaining Yb-doped double-clad fiber featuring depressed-index inner cladding layer and confinement of rare-earth dopants has been drawn in the form of a long tapered fiber, starting from a preform fabricated through conventional MCVD and solution doping process. The fiber has a core/cladding diameter of 35/250 μm in the narrow end and 56/400 μm in the wide end. The refractive index profile features a small depression at the inner portion of the 1st cladding layer such as to enhance higher-order modes bending loss. The effective mode area is predicted to scale from approximately 500 μm2 in the narrow end to over 1000 μm2 in the wide end, from finite-difference analysis using index profile measured through refracted near-field method. The confinement factor of Yb dopant in the core (about 2/3) yields near optimal differential mode overlap. The fiber was tested up to approximately 100 W average power, with near diffraction-limited output as the beam quality factor M2 was measured < 1.2. Suppression of higher-order modes has been further investigated through offset launching of incident mode-matched beam for both loosely and tightly coiled narrow end section. The recorded beam profiles unequivocally show that as single-mode guidance is effectively enforced in the first section due to enhanced bending loss, subsequent adiabatic transition of the mode field in the taper section preserves single-mode amplification towards the larger end of the fiber.

10083-40, Session 8

Numerical optimisation of pump absorption in doped double-clad fiber with transverse and longitudinal perturbation

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The fiber laser industry now demands higher and higher efficiency lasers, which require further optimization while keeping ease of manufacture and simplicity. As such, maximum pump photon absorption is needed and therefore optimization of the cladding shape and of fibre layout (longitudinal variation). Here, using a Beam Propagation Method based on azimuthal harmonic expansions and the so-called "superformula" to describe complex shape with a limited number of parameters, both aspects are investigated.

In our model, the fiber core diameter is 16.2 micron with a 0.06 NA, while the equivalent cladding diameter is 125 micron with a 0.44 NA. The pump light is injected through the fiber end and after some scrambling it reaches a 0.15 NA, typical of commercial pump diode. Subsequently it propagates over 4 m of doped shaped fibre set in either straight, circular or figure-of-eight layout. In the latter two cases the fiber bend radius is 4 cm which is a realistic value. The results show that for straight fiber (without longitudinal mode mixing), the pump absorption saturates quickly with fiber length for all type of cladding shapes. The best absorption is achieved with the lowest number of sides, becoming worst with increasing number of sides. We found that circular layout improves the pump absorption while the figure-of-eight layout improves even further the absorption to reach the Beer-Lambert limit for all non-circular cladding shaped fibers. With this method, other parameters can be investigated to optimize much more complex fibre structures such as pedestal fiber or core shape.

10083-41, Session 8

All normal dispersion fiber with large mode area at 2 micron wavelength

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Large mode area fiber design structures have considerable attention in recent years and which have significant importance at the wavelength of 2 micron. The fiber lasers have the great importance in high power lasers because of its excellent quality, reliability and compact size. In large core fibers, the structure supports several higher order modes. To avoid the power in unwanted modes it is required to suppress the higher order modes and with large Aeff. To suppress the higher modes leaky channel fibre is the good technique. Soliton formation and modulation instability are also the limiting effects in large mode are fiber, and in-order to avoid such effects it is very important to operate the fibers in normal dispersion regime. We have designed leaky fiber structure it consists of a large core with low doped germanium and the core is surrounded with hexagonal shape arranged rods. The rods designed with high doped germanium material and the clad is pure silica material. We have designed this structure at 2 micron wavelength and the structure leaks all higher order modes with 5cm in bend. The fiber design shows all normal dispersion from 1850 nm to 2000nm and the structure shows a very low dispersion around 2000nm wavelength. We have also calculated the large mode area of fiber by controlling the fiber design parameters. We have fabricated the present fiber with optimized parameters.

10083-73, Session PTue

Dual wavelength SOA based fiber ring laser

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In this paper we present a novel dual wavelength SOA based fiber ring laser. The ring consists of a wide band SOA as the gain medium with gain spectrum extending between 1460 nm and 1660 nm, a FP tunable filter with 1 nm spectral width, a polarization controller, an output PM coupler and PM fiber ring. By setting the tunable filter at the edge of gain spectrum and due to positive feedback effect in the ring lasing action occurs. The gain starving effect at the edge of the gain spectrum insures that the output is single mode which is verified by monitoring the beating on an optical detector connected to an RF spectrum analyzer. By changing the polarization state in the PM fiber ring using the in-loop polarization controller dual wavelength output can be obtained which is monitored on an optical spectrum analyzer. The ring laser combines the effect of SOA gain starving at the edge of the gain spectrum and the polarization state in the PM fiber ring to generate the dual wavelength laser.

10083-74, Session PTue

A switchable fiber laser based on an all-fiber Fabry-Perot filter

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In this experimental manuscript, a switchable Erbium-doped fiber ring laser based on an all-fiber Fabry-Perot filter was demonstrated. The filter is composed by several air micro-cavities formed into a section of a single-mode fiber splice joints with special hollow-core photonic crystal fiber. These micro-cavities are formed by air and silica, which produces several reflections generated at each silica-air-silica interfaces. Using this experimental setup we obtain a very high stable triple-laser emission at 1529.450nm, 1549.100nm and 1555.350nm with a linewidth of 0.2nm and a side-mode suppression ratio of 32dB, 37dB and 29dB respectively. These laser emission show a maximal peak power fluctuation around 0.4dB, 1.5dB and 2.6dB, with 0.025nm of wavelength oscillations. These results were observed after monitoring the laser cavity during an hour by recording the data each three minutes. By appropriately adjusting of transversal load applied over the Fabry-Perot filter between 0g and 550g, the ring laser cavity can be operated in double- wavelength, triple- wavelength, or quadruple- wavelength states. For this analysis, the all-fiber Fabry-Perot filter was set between a metal layer (below) and a thin glass layer (above) where transversal load was applied, here uniform load distribution over all the Fabry-Perot filter structure is achieved, as a result, the air intra-cavities that conform the filter are affected and the gain-losses profile is modified into the laser arrangement. The lasing emissions obtained in this work have a side-mode suppression ratio greater than 30dB. This ring laser cavity design offers a compact, simple and low-cost implementation and can be used in different applications where a very stable double, triple or quadruple laser lines are required.

10083-75, Session PTue

Tunable and non-reciprocal dual-wavelength SOA-fiber ring laser

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Dual-wavelength fiber lasers provide a low cost and simple method for the optical generation of microwave and THz radiation over the electrical techniques. The main reported technique for this purpose is based on the

use of FBGs with two different and close wavelengths allowing these two wavelengths only to oscillate within a laser cavity comprising EDFA or SOA gain medium, where the latter provides much less homogeneous line-broadening and improved stability. Non-conventional FBGs and filtering mechanisms were reported all based on unidirectional configuration, where the two wavelengths propagate in the same direction in the ring laser. In this work, we report a tunable dual-wavelength ring laser including non-reciprocal circulators connected back to back providing uncommon path and allowing for having each wavelength rotating in a different direction in the ring. This technique provides the flexibility of controlling each of the wavelengths separately in terms of tunability, polarization and losses. Two tunable Fabry-Perot filters are inserted in the uncommon path and the wavelength of the CW and the CCW waves are controlled independently. Polarization controllers are used in the ring to achieve better stability and achieve single longitudinal mode of operation. For a given settings of the filters, the wavelength of the CW wave is 1485.2 nm while the CCW wave wavelength is 1488.5 nm. The generation of tunable dual wavelength laser is demonstrated by tuning of either of the Fabry-Perot filters. For instance, the CCW wave was tuned from 1532.2 nm to 1534.1 nm while holding the CW at 1535.2 nm. The results demonstrate the generation of tunable dual-wavelength laser output in the proposed non-reciprocal ring, which allows for tunable THz generation.

10083-76, Session PTue

Compact, highly efficient, athermal, 25W, 2051nm Tm-fiber based MOPA for CO2 trace-gas laser space transmitter

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There is significant interest in narrow linewidth 2051nm laser transmitters for atmospheric CO2 remote sensing. It is generally recognized that 2 um has stronger absorption lines, and trade studies have identified performance benefits at this wavelength compared to 1.57 um. NASA is highly interested in maturing the technology readiness of 2051nm laser transmitters to TRL-6. NASA has successfully demonstrated CO2 integrated path absorption (IPDA) LIDAR system in an airborne platform using a ~0.1W 2051nm CW Ho:YLF single frequency laser. An all fiber, higher power, and highly efficient version of the transmitter is targeted for a space-based satellite measurement system with global coverage. A compact, (10x20x20 cm) 4U cubsat, form factor significantly increases the number of pathfinder NASA missions that can be supported by the transmitter. Achieving power scaling and compact form factor for the transmitter requires high efficiency and high gain performance for the transmitter.

A cladding-pumped PM Tm fiber based amplifier optimized for high efficiency and high power operation at 2051nm is presented. The two stage amplifier has been demonstrated to achieve 25W average power, >16dB PER out of a single mode PM fiber with <50MHz linewidth and ~43dB gain. The power amplifier's optical conversion efficiency was 53%. An internal efficiency of 58% is calculated after correcting for passive losses. The two stage amplifier sustains its highly efficient operation for a temperature range 5-40C. The absence of SBS for the narrow linewidth amplification shows promise for further power scaling. Demonstrated fiber types and components are compatible with a compact CubeSat form factor.

10083-77, Session PTue

Thulium-doped fiber laser using two FOLMs with a high birefringence fiber in the loop

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With the development of fiber components compatible for laser generation at 2 ?m, Thulium-doped fiber lasers (TDFL) have been of growing interest for application in diverse research areas such as medicine, optical instrumentation and light detection and ranging (LIDAR). We report a linear cavity all-fiber Thulium-doped fiber (TDF) laser with tunable narrow linewidth operating near to the 2 μm wavelength. The cavity is delimited by two fiber optical loop mirrors (FOLM) with high birefringence fiber in the loop (Hi-Bi FOLM) with different periodical wavelength-dependent reflection periods. A long period Hi-Bi FOLM is used for the generated laser line wavelength tuning in a range of ~44 nm and a narrow-band Hi-Bi FOLM determines the generated laser line spectral width. The generated laser wavelength exhibits a linewidth less than 0.05 nm. Discrete wavelength tuning is achieved by wavelength reflection displacement of the narrow-band Hi-Bi FOLM by temperature variation on the high birefringence fiber loop. We present the use of the Hi-Bi FOLM as a reliable optical filter for laser wavelength generation with narrow linewidth and wide wavelength tuning range of TDF lasers at the 2 μm region.

10083-78, Session PTue

Investigation of ASE and SRS effects on short-wavelength Yb-doped fiber laser

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Short wavelength Yb-doped fiber laser can be widely used for tandem-pumped fiber laser system in 1 ?m regime because of its high brightness and low quantum defect (QD). High power, high brightness short wavelength fiber laser under 1030nm can also be pump sources for tandem pumped system due to its high efficiency and low quantum defect compared with LD pump sources(i.e.~915nm and 976nm). The small quantum defect of 1018nm pumping mitigates the thermal problems. In order to achieve short wavelength Yb-doped fiber laser with high output power, a steady-state rate equations considering the amplified spontaneous emission (ASE) and Stimulated Raman Scattering (SRS) have been investigated. We theoretically analyzed the ASE and SRS effects in short wavelength Yb-doped fiber laser, and how the ASE is the main restriction rather than SRS for high power short wavelength Yb-doped fiber laser, especially for the laser with the wavelength below 1040nm. To achieve high power output with high signal-to-noise ratio for short wavelength fiber laser, we should shorten the active fiber length by using 976nm pump sources and the Yb3+-doped fiber with larger absorption cross section at 976nm. Compared with increasing the reflectivity of OC-FBG to suppression ASE, choosing suitable fiber parameters is more important. In our simulation, 2m gain fiber and the OC-FBG reflectivity of 0.1 are optimized for the investigated 1018nm fiber laser.

10083-79, Session PTue

KW-level tandem pumped Yb-doped fiber amplifier with a single pump port

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We present our experimental results of high-power tandem pumped Yb-doped fiber amplifier with single port pump source. we combined 1750W tandem pump applicable source via 7 individual self-made 1018 nm engineering all fiber lasers. All engineering all fiber lasers' output power is 1810.8W, that all combined into a custom-built 7?1 signal combiner, and then

the output fiber spliced with a pump port of (6+1)?1 pump combiner. Finally, we got 1677W amplified 1080nm through a single stage fiber amplifier from 80W seed power. The optical-optical conversion efficiency is more than 88%.

10083-80, Session PTue

Mode locking of a fibre laser with a matrix-less carbon nanotube film

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Carbon nanotubes (CN) are widely used in fibre lasers for passive mode locking. Saturable absorbers fabricated from CN may be divided into two types: those embedding CN into host matrices (for example, polymer-based) and those not relying on such matrices. A host matrix makes it possible to fabricate a CN-containing film, which is further placed into the cavity of a fibre laser as a separate element. A CN-impregnated polymer matrix is a weak component of the saturable absorber because its properties undergo changes over time under the action of laser radiation and the ambient environment. Matrix-less absorbers on the basis of CN necessitate deposition of CN onto the surface of some element inside the cavity of a fibre laser, a generally difficult technological operation.

This work for the first time reports experimental results on Er fibre laser mode-locked with saturable absorbers based on single-walled matrix-less CN films fabricated by aerosol method. Nearly transform-limited output pulses had duration of 2.7 ps and average power of 1 mW. Measured high-contrast RF output spectra (noise suppression over 70 dB in 1-GHz band) confirm high quality of achieved mode locking. Discussed are details of the aerosol method of matrix-less CN film fabrication and parameters of studied mode-locked fibre laser. Application of matrix-less CN films for mode locking and Q-switching of fibre and other laser types are analysed.

10083-81, Session PTue

Mode instability in a Yb-doped stretched core fiber

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Recent years, a stretched (or rectangular) core fiber has been proposed for its ability of effective mode area scaling by simply increasing a waveguide width and effective heat dissipation as compared to a conventional circular core fiber. Therefore, the rectangular core fiber appears to have the potential to further increase the output power beyond the circular counterpart. In particular, the efficient heat dissipation in the rectangular core fiber is expected to suppress the mode instability which has been identified as a limit for the power scaling in rare earth doped large mode area fiber lasers and amplifiers. In this paper, we theoretically investigate, for the first time to our knowledge, the mode instability in the rectangular core fiber by employing the moving thermal grating model in the beam propagation method (BPM). Our simulation reveals that the rectangular core fiber can suppress the maximum temperature along fiber by up to 35% as compared to the circular core fiber. However, contrary to the expectation, the reduced temperature does not help to suppress the mode instability. The mode instability starts much earlier than the circular core fiber by up to 69%. We show that the unexpected results are originated from overlap ratios of LP11 to LP01 with a doping area and gain saturation effect.

10083-82, Session PTue

Selective generation of two pulse modes in a single all normal dispersion fiber laser oscillator and analysis of their optical characteristics

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Fiber based ultrafast pulse laser sources have been tried to apply to high precision metrology applications in recent years because of their useful optical characteristics such as short temporal coherence length related to measuring resolution and high spatial coherence related to measuring area and distance. Mode-locked pulses are guaranteed laser sources for long distance and large area surface metrology with high precision due to their excellent temporal and spatial coherence characteristics, but there is still more to be proven for higher precision low coherence interferometry applications because of a limitation of temporal coherence length due to high-order dispersion and nonlinearity difficult to compensate. Meanwhile, noise-like pulses which can be generated by controlling polarization and intra cavity power in fiber oscillators have attempted to apply to high precision surface metrology applications such as OCT and semiconductor inspection instead of mode-locked pulses due to their beneficial coherence characteristics without dispersive effects. In this research, we develop an ytterbium doped fiber laser with all normal dispersion and 1030 nm center wavelength which can selectively generate two types of pulses, mode-locked pulses and noise-like pulses, by a turn-key system including polarization control and selective detection parts. The spectral and temporal characteristics of two different pulses generated from the oscillator are analyzed and compared with each other through optical spectrum, radio frequency spectrum and autocorrelation. Moreover, temporal and spectral coherence characteristics of two pulses are verified to be appropriate for precision metrology applications through analyzing interference signals generated by balanced and unbalanced arm interferometers.

10083-83, Session PTue

Narrow line width semiconductor optical amplifier based random laser

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We demonstrate a novel random fiber laser based on Fabry-Perot configuration with outstanding characteristics and a rather simple design solution. Semiconductor optical amplifier (SOA) is the gain medium of the laser. A standard single mode fiber of length 1 Km acts as a distributed mirror. It provides the Rayleigh backscattering that is amplified through the SOA to seed the laser oscillation. An optical bandpass filter of bandwidth 1 nm is inserted stabilize the lasing wavelength. The operating wavelength is 1550 nm. The laser threshold current was found to 140 mA, while the slope efficiency was calculated to be 0.06143 W/A. The laser operates in a single longitudinal mode with narrow linewidth. The minimum linewidth was measured to be 6.5 KHz at SOA bias current (170 mA) that is close to the laser threshold current. As the bias current of the SOA increases, the linewidth of the proposed random laser increases. The laser linewidth and optical power were measured to be 13.5 KHz and 4 mW, respectively, at the rating current (200 mA) of the SOA driver. The optical signal to noise ratio (OSNR) was measured to be 34 dB at SOA bias current 180 mA.

10083-84, Session PTue

High energy actively Q-switched pulsed MOPA at 1.064μm using large core Yb-doped active fibers

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Here we present an actively Q-switched all fiber master oscillator power amplifier at 1.064 μm with a cladding pumped fiber seed source and dual stage amplifier. The system is capable of delivering more than 0.8 mJ of pulse energy in a clean Gaussian shaped pulse of 107 ns pulse width at 10 kHz repetition rate through distortion less amplification using large core Yb-doped active fibers. In the system a pre-amplifier has been used after the seed source to primarily scale up the pulse average power and energy before feeding it to the second stage amplifier. The core diameter of the active fiber was increased in each stage to scale up the pulse energy. The seed source active fiber is having a core diameter of 12 μm and the pre-amplifier is having a core diameter of 15 μm. In the final stage amplifier a large core active fiber of 36 μm core diameter, which is having a high core to clad ratio has been used to increase the amount of saturation energy so more pulse energy can be extracted without temporal or spectral pulse distortion due to gain saturation effect or fiber nonlinearity. The final stage amplifier delivered a gain of 9.17 dB and the average power achieved was more than 8 W with 7.7 kW peak power suitable for laser marking and engraving applications. The final output pulse signal to noise ratio was measured to be > 30 dB over a very weak Raman peak and amplifier spontaneous emission generated noise.

10083-85, Session PTue

Laser stimulated grain growth in 304 stainless steel anodes for reduced hydrogen outgassing

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Metal anodes in High Pulsed Power Electromagnetic (HPEM) devices erode during operation due to hydrogen outgassing and plasma formation, both of which are thermally driven phenomena generated by the electron beam impacting the anode's surface. This limits the lowest achievable pressure in an HPEM device reducing its efficiency. Laser surface melting the anodes of 304 stainless steel by a continuous wave Yb Fibre laser with no post-processing showed a reduction in hydrogen outgassing by a factor of ~4 under 50 keV electron bombardment compared to that from untreated stainless steel. This is attributed to an increase in the grain size (from 10 - 3500 m2) effectively reducing the number of grain boundaries that serve as trapping sites for hydrogen by 16 %, making such laser treated metals excellent candidates for use in high pulsed power electromagnetic devices.

10083-86, Session PTue

Adjustment of TruMicro laser parameters to process driven requirements

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Adjustment of TruMicro laser parameters to process driven requirements

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The matchless properties of ultra short laser pulses, such as the enabling of cold processing and non-linear absorption, pave the way to numerous novel applications. Ultrafast lasers arrived in the last decade at a level of reliability suitable for the industrial environment. Within the next years many industrial manufacturing processes in several markets will be replaced by laser based processes due to their well-known benefits: These are non-contact wear-free processing, higher process accuracy or an increase of processing speed and often improved economic efficiency compared to conventional processes. Furthermore, new processes will arise by novel sources, accessing previously unsolved challenges. One technical requirement for these exciting new applications will be to optimize the large number of available parameters to the requirements of the application.

In this work we present an ultrafast laser system distinguished by its capability to combine high flexibility and real time process inherent adjustments of the parameters with industry ready reliability.

The industrial ready reliability is ensured by its all fiber MOPA (Master oscillator power amplifier) CPA (Chirped pulse amplification) laser architecture and patented technology. The pulses are generated in a mode-locked fiber oscillator enabling flexible bursts with 20 ns pulse separation.

Furthermore an external AOM (Acousto-optical modulator) enables linearization and patented quad-loop stabilization the output power of the laser [1].

Beyond these stabilization aspects these acoustic optical modulators as well as other opto electronically/mechanically modules combined with smart laser control software enable process-driven adjustments of the parameters (e.g. repetition rate, burst functionalities, pulse energy) by external signals, which will be presented in this work.

[1] O. Heckl, S. Weiler, R. Fleischhaker, R. Gebs, A. Budnicki, M. Wolf, J. Kleinbauer, S. Russ, M. Kumkar, D. Sutter, "Industry-grade High Average Power Femtosecond Light Source," Proc. Of SPIE Vol. 8972, March 2014

10083-87, Session PTue

A method for determining the direction of rotation in ring laser gyroscope based on fiber ring cavity and semiconductor optical amplifier

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Conventional RLGs are based on He-Ne laser; which requires ultimate quality laser cavities, very high performance mirrors with high reflectivity and low scattering, precise alignment of the cavity mirrors and high power to pump the laser. These constraints result in high cost, heavy weight and large power consumption. On the other hand, the optical fiber technology is much cheaper and allows several novel cavity architectures more easily with lower cost and less effort. As a result, Ring Laser Gyroscope (RLG) based on fiber ring cavity and a semiconductor optical amplifier (SOA) has recently attracted the researchers due to their simple structure, lightweight, low power consumption and low cost . Moreover, the fiber ring cavity can provide larger cavity with low propagation and scattering losses enhancing the gyros sensitivity. A method for determining the direction of rotation was not disclosed before in such RLGs based on fibers and semiconductor optical amplifier. In this work, a simple and straightforward method is illustrated and experimentally demonstrated . The method depends on creating a virtual rotation in a certain direction using an acousto-optic modulator placed outside the ring laser cavity, therefore do not add extra losses, and thus do not affect the cavity's finesse. The ring cavity supports two counter propagating beams sharing the same SOA gain medium. The main idea is to shift one of the two counter propagating beams with an initial frequency shift with respect to the other. This corresponds to a virtual rotation in a certain direction, and then if the RLG actually rotates in the same direction of this virtual one, then the shift in frequency between the two counter propagating beams will increase. On the other side if the RLG rotates in the opposite direction to this virtual rotation, then this frequency shift will decrease.

10083-88, Session PTue

Experimental study on all Yb-doped photonic crystal fiber laser

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In this paper, we demonstrated an experiment of the all Yb-doped photonic crystal fiber laser using free space optical paths method. The laser gain medium of the seed laser and the amplifier are the same Yb-doped photonic crystal fibers that are fabricated by non-chemical vapor deposition (Non-CVD) technology. The seed laser cavity is a Fabry-Perot cavity. The amplifier is pumped by back-end method. They are coupled each other by lens and dichroic mirrors on the optical table. The experimental results have a good reference value for the photonic crystal fiber laser research in the future.

10083-42, Session 9

Recent progress in 3 micron class dysprosium-doped fluoride fiber lasers

(Invited Paper)

Matthew Majewski, Stuart D. Jackson, Macquarie Univ. (Australia)

Recent progress in our work on the development of three micron class dysprosium-doped ZBLAN fiber lasers will be presented. A novel in-band pumping scheme was employed for the work which involves use of an erbium-doped fiber laser as the pump source. This system represents small quantum defect, leading to the demonstration of a linear resonator operating at a maximum 51% slope efficiency which to our knowledge is a record for three micron class fiber lasers and shows distinct potential for power scalability in this spectral region. This concept is extended to a resonator design incorporating a diffraction grating for wavelength tuning. The laser emission for this configuration is shown to be tunable over 400nm of the mid-infrared with an extreme wavelength of 3.35 microns. These experimental results are compared with a numerical model based on the laser rate equations. Intrinsic fiber loss and energy transfer processes are identified as possible limiting factors on the current performance of these dysprosium-based fiber laser systems. Previous work in dysprosium fiber lasers based on alternate pumping schemes and cavity arrangements are also examined with a numerical modelling effort to allow for discussion of system optimization and future potential.

10083-43, Session 9

High power, ultra-broadband supercontinuum source based on highly GeO2 doped silica fiber

Deepak Jain, DTU Fotonik (Denmark); Raghuraman Sidharthan, Nanyang Technological Univ. (Singapore); Peter Morten Moselund, NKT Photonics A/S (Denmark); Seongwoo Yoo, Darly Ho, Nanyang Technological Univ. (Singapore); Ole Bang, DTU Fotonik (Denmark)

We demonstrate a 74 mol % GeO_2 doped fiber for mid-infrared supercontinuum generation. Experiments ensure a highest output power for a broadest spectrum from 700nm to 3200nm from this fiber, while being pumped by a broadband 4 stage Erbium fiber based MOPA. The effect of repetition rate of pump source and length of Germania-doped fiber has also been investigated.

Further, Germania doped fiber has been pumped by conventional Silica based photonic crystal fiber supercontinuum source. At low power, a considerable broadening of 200-300nm was observed. Further broadening of spectrum was limited due to limited power of pump source. Our investigations reveal the unexploited potential of Germania doped fiber for mid-infrared supercontinuum generation. This measurement ensures a possibility of Germania based photonic crystal fiber or a step-index fiber supercontinuum source for high power ultra-broad band emission being pumped a 1060nm or a 1550nm laser source. To the best of our knowledge, this is the record power, ultra-broadband, and all-fiberized SC light source based on Silica and Germania fiber ever demonstrated to the date.

10083-44, Session 9

Coherent combining of fiber-laser-pumped 3.4 μm frequency converters

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Coherent beam combining (CBC) by active phase control could be useful for power scaling fiber-laser-pumped optical frequency converters like optical parametric oscillators (OPOs). However, a phase modulator operating at the frequency-converted wavelength would be needed, which is a non-standard component.

Fortunately, nonlinear conversion processes rely on a phase-matching condition, correlating not only the wavevectors of the coupled waves, but also their phases. It is therefore possible to control the phase indirectly, using more standard phase modulators.

Feasibility of this technique was previously demonstrated for second harmonic generators (SHG). Controlling the phase of the fundamental wave, excellent harmonic wave combining efficiency was achieved in both cases of phase matching and quasi phase matching, with lower than ?/30 residual phase error.

In this paper, coherent combining of difference frequency generators (DFG) is experimentally tested. Even if DFG is more challenging than SHG as it implies handling three waves instead of two, phase control of the sole 1-μm pump waves is sufficient to combine the 3.4-μm waves generated.

The mid-infrared DFG crystals are pumped and signal-seeded with standard all-fiber sources at 1 μm and 1.5 μm respectively. Phase control is performed with an electro-optic phase modulator which is a standard all-fiber component operating at 1 μm.

CBC of mid-infrared DFG modules is a first step towards combining continuous wave OPOs. The capability to perform combination of 1-μm pumped mid-infrared OPOs is finally investigated.

10083-45, Session 9

A passively mode-locked sub-picosecond Ho3+,Pr3+-doped fluoride fiber laser operating at 2.86 μm

Sergei Antipov, Macquarie Univ. (Australia) and Ctr. for Ultrahigh bandwidth Devices for Optical Systems (Australia); Stuart D. Jackson, Macquarie Univ. (Australia); Michael J. Withford, Alexander Fürbach, Macquarie Univ. (Australia) and Ctr. for Ultrahigh bandwidth Devices for Optical Systems (Australia)

We demonstrate a passively mode-locked holmium-praseodymium co-doped ring fiber laser that produces an estimated 950 fs pulsewidth and peak power of 4.3 kW at a pulse repetition rate of 74 MHz. The measured center wavelength was 2.86 μm which overlaps more strongly with liquid water whilst better avoiding atmospheric water vapor which overlaps more strongly with previously reported ultrafast Er3+ fiber lasers operating at 2.8. Thus the present system should display better long term stability compared to the Er3+-based system and at the same time, be a more practical tool for interaction with biological tissues.

The laser was constructed using a 1.2 m long double-clad fluoride fiber doped with Ho3+ and Pr3+ ions and arranged into a unidirectional ring resonator that was resistant to instabilities associated with back reflections. Two semiconductor 1150 nm laser diodes with the maximum combined output of 7.5 W were used to pump the fiber. Mode-locking was achieved using the combination of two techniques: sub-picosecond pulses were produced by nonlinear polarization evolution after longer pulses were initially obtained using an in-cavity GaAs saturable absorber having a modulation depth of 90% and a relaxation time of 10 ps. A standard arrangement employing two waveplates and an optical isolator was introduced into the resonator to carry out nonlinear polarization rotation. The average power of the mode-locked laser reached 350 mW after the 50% outcoupling mirror. The RF signal-to-noise ratio reached 67 dB for the first peak at the resolution bandwidth of 10 kHz.

10083-46, Session 9

Energy loss in gas lasers operating in hollow-core optical fibers

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The output of solid core fiber lasers is constrained in the mid-infrared due to the absorption properties of silica. Optically pumped gas lasers can reach the mid-infrared but require long path lengths for interaction between the pump light and gain medium. Optically pumped gas lasers where the gain medium is contained in a hollow-core optical fiber may provide a robust and compact platform that combines advantages of fiber and optically-pumped gas lasers. Experimental demonstrations of gas-filled-fiber lasers have been reported. The energy output of a molecular gas laser operating in a hollow-core optical fiber is computationally modeled using rate equations. The rate equations include terms for various physical processes including molecular self-collisions, molecular collisions with the fiber walls, and fiber attenuation. The rate equations are solved for a one-dimensional fiber model with an acetylene gain medium that lases along rotation-vibrational transitions. The energy output and losses are computed for multiple experimentally-feasible configurations. Model correspondence with reported experiments is shown. The computed energy losses due to backwards propagating light, fiber losses, and molecular collisions are applied to pulsed, continuous wave, and synchronously pumped gas lasers operating in hollow-core optical fibers. Energy losses due to molecular collisions are used to estimate heating in the gain medium.

10083-47, Session 10

Pulse-to-pulse wavelength switching of diode based fiber laser for multi-color multi-photon imaging

Matthias Eibl, Univ. zu Lübeck (Germany); Sebastian N. Karpf, Univ. of California, Los Angeles (United States); Hubertus Hakert, Daniel Weng, Torben Blömker, Robert A. Huber, Univ. zu Lübeck (Germany)

We present an entirely fiber based laser source for non-linear imaging with a novel approach for multi-color excitation. The laser is a master oscillator fiber power amplifier (MOFPA) where the output of a narrowband 1064 nm laser diode is actively modulated to adjustable 50ps- 5ns pulses and amplified in an ytterbium fiber amplifier up to kWs of peak power. By combining different fiber types and lengths, we achieve non-linear wavelength conversion in the delivery fiber itself and can switch between 1064nm, 1122nm, and 1186nm on-the-fly by tuning the pump power of the fiber amplifier.

We propose that a combination of Stimulated Raman Scattering and Four-Wave Mixing is the underlying process of this coherent wavelength shifting and show that the spectral and temporal characteristics of the initial pulses are maintained. Furthermore, we show pulse to pulse shifting between two wavelengths from one fiber output.

To evaluate the performance of the laser for multi-photon imaging, we coupled it in a commercial two photon microscope and compared it with the standard laser, a Ti:Sa with OPO. We found that the overall image quality is the same for same excitation parameters.

Fiber amplified laser diode sources have high potential for endoscopic two photon imaging, however, they inherently lack spectral flexibility. With the presented novel multi-color approach of shifting the excitation light in the delivery fiber itself it is possible to implement various new wavelengths to make those laser sources more flexible in two photon imaging.

10083-48, Session 10

Tunable Yb-doped fiber laser based on a FBG array and a theta ring resonator ensuring a constant repetition rate

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Fiber lasers provide the perfect basis to develop broadly tunable lasers with high efficiency, excellent beam quality and user-friendly operation as they are increasingly demanded by applications in biophotonics and spectroscopy. Recently, a novel tuning scheme has been presented using fiber Bragg grating (FBG) arrays as fiber-integrated spectral filters containing many standard FBGs with different feedback wavelengths. Based on the discrete spectral sampling, these reflective filters uniquely enable tailored tuning ranges and broad bandwidths to be implemented into fiber lasers. Even though the first implementation of FBG arrays in pulsed tunable lasers based on a sigma ring resonators works with good emission properties, the laser wavelength is tuned by a changing repetition rate, which causes problems with applications in synchronized environments.

In this work, we present a modified resonator scheme to maintain a constant repetition rate over the tuning range and still benefit from the advantages of FBG arrays as filters. With a theta ring cavity and two counter propagating filter passes, the distributed feedback of the FBG array is compensated resulting in a constant pulse round trip time for each filter wavelength. Together with an adapted gating scheme controlling the emission wavelength with a modulator, the tuning principle has been realized based on a Ytterbium-doped fiber laser. We present first experimental results demonstrating a tuning range of 25nm, high signal contrast and pulse

durations of about 10ns. With the prospect of tailored tuning ranges, this pulsed fiber-integrated laser may be the basis to tackle challenging applications in spectroscopy.

10083-49, Session 10

All-fiber widely tunable optical parametric oscillator laser system

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Stimulated Raman Scattering requires an extremely quiet, widely wavelength tunable laser, which, up to now, is unheard of in fiber laser systems. We present a compact all-fiber optical parametric oscillator based on degenerate four-wave mixing (FWM) in an endlessly single-mode photonic crystal fiber. We employ an all-fiber frequency and repetition rate tunable laser, which is tunable in the range of 1015 to 1065 nm. After amplification and subsequent conversion in the all-fiber OPO, the signal and idler radiation can be tuned between 785 and 960 nm and 1177 and 1500 nm. Thus, all biochemically relevant Raman shifts between 910 and 3030 cm-1 may be addressed. An additional output provides a low noise high-repetition rate output to enable SRS imaging. We measure the relative intensity noise of the Stokes beam at the modulation frequency of the SRS pump at 4.75 MHz to be -150 dBc, which is quiet enough to enable high-speed SRS imaging with a good signal-to-noise ratio. Combining FWM based conversion, with all-fiber Yb-based fiber lasers allows for the first extremely compact, turn-key and widely tunable optical parametric oscillator. This source could very well be the missing key instrument to propel CRS imaging to real world applications.

10083-50, Session 11

High peak-power fiber laser based on a non filamented-core fully-aperiodic large pitch fiber

Aurélien Benoit, Marie-Alicia Malleville, XLIM Institut de Recherche (France); Romain Dauliat, XLIM Institut de Recherche (France) and Leibniz-Institut für Photonische Technologien e.V. (Germany); Dia Darwich, Raphaël Jamier, XLIM Institut de Recherche (France); Stephan Grimm, Jens Kobelke, Kay Schuster, Leibniz-Institut für Photonische Technologien e.V. (Germany); Philippe Roy, XLIM Institut de Recherche (France)

Fiber lasers have witnessed an exponential power scaling during the last two decades. This evolution of the extracted power was made possible by the development of very large mode area aiming at delivering high peak power and high energy. However, the expansion of the fiber core has led to the evidencing of a new limitative phenomenon, called transverse modal instabilities (TMI). Due to the heat load deposited in the fiber core, the transverse refractive index profile is modified, ensuring the re-confinement of higher-order modes (HOM) and leading a dramatic degradation of the beam quality. In order to reduce the modal content in the fiber core and push away the threshold of TMI, aperiodic cladding structure have been proposed to optimize the delocalization of HOM out of the gain region and enhance the amplification of the fundamental mode. A first CW emission has been recently demonstrated with this kind of fiber.

We report on high peak power fiber laser composed of a 50 μm non-filamented core fully-aperiodic large pitch fiber manufactured by the REPUSIL method which is based on the sintering and vitrification of micrometric doped-silica powders. In amplifier configuration, an average output power of 95 W at 1030 nm has achieved with an available pump power of 175 W. The emitted peak power reaches 35 kW with pulse duration of 200 ps at a repetition rate of 13.5 MHz. This is the first demonstration in pulsed regime with such fiber. As for beam quality, preliminary M2 measurements are around 1.3.

10083-51, Session 11

Short-pulse MOPA fiber laser with kilowatt average power and multi-megawatt peak power, applying advanced XLMA fiber amplifiers

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In solar-panel, machine tool and automotive industry many ablation or surface treatment applications are most efficiently done with short-pulse lasers. Short-pulse fiber lasers with fiber beam delivery are smart solutions for those applications because of their low investment cost, very high wall plug efficiency, robustness, compactness, no mirror alignment, simple cooling, maintenance free operation etc.

We have demonstrated a short-pulse high peak- and average- power fiber laser with selectable pulse durations between 10 ns and 100 ns where more than 150 mJ pulse energy has been achieved at a repetition rate of 10 kHz. To avoid the generation of undesired optical nonlinearities, pulse shape capabilities are applied and flexible extra-large-mode-area (XLMA) step index fibers above 100 μm core diameter - drawn from optimized preforms made by powder-sinter technology - are used as gain fibres. As an example, for 30 ns pulses, an average output power of more than 1 kW and a peak power of up to 3.5 MW have been achieved with negligible optical nonlinearities. To the authors´ knowledge, it is the first time that this type of gain fiber is applied in short-pulse lasers with kilowatt average output power.

Stable and safe operation of the fiber-laser has been shown with power densities up to 3 GW/cm? in the gain fiber, carefully controlled and clearly set below fiber damage threshold. For various temporal pulse shapes, results of different ablation applications with various process fiber core geometries will be presented.

10083-52, Session 11

Picosecond MOPA with ytterbium doped tapered double clad fiber

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The technology of high-power picosecond and femtosecond fiber picosecond master oscillator – power amplifiers (MOPA) is developing very quickly to date. Currently, there are two basic approaches for ultrafast MOPA's buster amplifiers: either using of large pitch photonic crystal fibers (LPF or rod-type fiber) or large mode area (LMA) fibers. The MOPA systems with LPF have only lack– they are contains relatively long (1.2m) unbendable rod-type fibers resulting in bulky and cumbersome optical scheme. Nevertheless, the technology of industrial micro-machining requires a simple, all-fiber MOPA system delivering pulses with high peak power and mJ-level energy. MOPAs comprising LMA fibers usually are more compact but allow reaches energy only up to 50μJ.

We proposed to use an active tapered double-clad fiber (T-DCF) as a buster amplifier for ultrafast MOPA systems. Using an active T-DCF on the one hand enables exploiting fiber with a very large MFD (100 μm or even more) and, simultaneously, using the advantages of doping concentration management. The use of T-DCF allows making a system compact (T-DCF is easily coiled with a 35cm diameter and reduce the thermal stresses and influence of non-linear effects).

In this paper, we demonstrate a further development of earlier proposed approach for amplification of ultrashort pulses by T-DCF with a large core diameter (100 μm). The developed MOPA has 60 ps pulses with 0.3 mJ pulse energy and 5 MW peak power with perfect beam quality (M2=1.25).

10083-53, Session 11

Realization and optimization of a 1 ns pulsewidth multi-stage 250 kW peak power monolithic Yb doped fiber amplifier at 1064 nm

Bertrand Morasse, Estéban Plourde, CorActive High-Tech Inc. (Canada)

High peak power pulsed fiber laser are often realized using bulky and expensive air-silica holey fiber. In this paper, we present a simple way to achieve and optimize hundreds of kW peak power pulsed output using a monolithic amplifier chain based on solid core double cladding fiber tightly packaged. A fiber pigtailed current driven diode is used to produce nanosecond pulses at 1064 nm. We present how to optimise the use of Fabry-Perot versus DFB type diode along with the proper wavelength locking using a fiber Bragg grating. The optimisation of the two pre-amplifiers with respect with the pump wavelength and Yb inversions is presented. We explain how to manage ASE using core and cladding pumping and by using single pass and double pass amplifier. ASE rejection within the Yb fiber itself and with the use of bandpass filter is discussed. Maximizing the amplifier conversion efficiency with regards to the fiber parameters, glass matrix and signal wavelength is described in details. We present how to achieve high peak power at the power amplifier stage using large core/cladding diameter ratio highly doped Yb fibers pumped at 976 nm. The effect of pump bleaching on the effective Yb fiber length is analysed carefully. We demonstrate that counter-pumping brings little advantage in very short length amplifier. Dealing with the self-pulsation limit of stimulated Brillouin scattering is presented with the adjustment of the seed pulsewidth and linewidth. Future prospects for doubling the output peak power is discussed.

10083-54, Session 11

High peak power picosecond pulse generation from a Yb-doped phosphate fiber amplifier

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We demonstrate an all fiber picosecond laser with megawatt-level peak power based on highly ytterbium-doped phosphate fiber. The phosphate fiber used in the power amplifier stage has the cladding absorption 50 dB/m at 976 nm. The length of the gain fiber in the main amplifier is only 34 cm, which will effectively reduce the nonlinear effect during the process of picosecond pulse amplification. The core diameter of the gain fiber is 25 ?m with numerical aperture of 0.04, which is helpful to obtain high beam quality laser. The pulse energy of the seed is 0.2 ?J at repetition rate of 25 kHz, which is amplified to 21 ?J with the pulse width of 20 ps and the peak power is 1.05 MW. High beam quality is also demonstrated with M2 factor measured at highest pulse energy of 1.4 in the both X and Y directions. This kind of laser source with high peak power and high beam quality has a wide range of applications in the field of material processing.

10083-55, Session 12

High energy 1.5 μm 3-color pulsed fiber laser with high coherence length and precise wavelength control for LIDAR applications

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We developed a core pumped, 3-color pulsed fiber laser with 40W average output at 1550 nm with a pulse duration of 5 ns at PRF of 1 MHz corresponding to 8kW peak power. The enabling technology for this high power laser was 1480 nm core pumping of a Polarization Maintained Very Large Mode (PM-VLMA) Er-doped fiber amplifier with ~50 μm mode field diameter. Optical pulses from modulated seed sources were pre-amplified to 1W average power and injected into the PM-VLMA core pumped with a 100W, 1480 nm Raman Fiber Laser. The fiber laser was free from any non-linearity due to Stimulated Brillion Scattering or Four-wave mixing.

10083-56, Session 12

115 W, 10 GHz, femtosecond pulses from a very-large-mode-area Er-doped fiber amplifier

Jeffrey W. Nicholson, Raja Ahmad, Anthony M. DeSantolo, OFS Fitel LLC (United States); Zolton Varallyay, Furukawa Electric Institute of Technology Ltd. (Hungary)

We demonstrate high average power, high peak power amplification of 10 GHz, picosecond and femtosecond pulses in a Very-Large-Mode Area (VLMA), Er-doped fiber with an effective area of ~1050 square microns. A high power, single-mode Raman fiber laser with up to 183 W of power at 1480 nm served as a pump source. 130 femtosecond pulses with an average power of 115 W, peak power of 88 kW, and M2 of 1.18 were achieved. Simulations that take into account pair-induced quenching give excellent agreement with measurements.

10083-57, Session 12

57.6 fs L-band amplifier similariton generation from Er-doped fiber lasers and pulse kinetics

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In this paper, we demonstrate the realization of L-band amplifier similariton (AS) operation from a normal dispersion Er-doped fiber laser (ND-EDFL) with the help of two types of EDFs with different parameters of peak absorption and dispersion for controlling the gain and dispersion in the cavity. The laser can deliver sub-60 (57.6) fs AS pulses with a repetition rate of 36 MHz and the pulse energy of 1.3 nJ centered at the wavelength of 1.6 ?m. As far as we know, this is the shortest pulse with highest pulse energy yet reported of an EDFL operating in L-band. Furthermore, we also show experimentally and numerically, the remarkable transition between

dissipative soliton (DS) and AS solutions of generalized Ginzburg-Landau equation via spectral filtering of frequency-chirped pulses in ND-EDFLs. DSs and ASs can coexist and they can switch to each other via solely altering the filter bandwidth in the cavity. The laser favors DSs operation for large filter bandwidth and it jumps to ASs operation along with reducing the filter bandwidth. The results put forwards directional ideas on realizing switchable DS-AS fiber lasers and they are helpful to get insight into the physical mechanisms in various mode-locked regimes in NDFLs.

10083-58, Session 12

High power pump source at 1535 nm based on multimode Er-doped fiber

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Compact high-power multimode pump laser at 1532 nm is presented in this work. The key feature of the laser is a specially-developed double-clad Er-doped fiber (EDF). The fiber has core/cladding diameter of 100/125 μm and NA of 0.15 thus being compatible with standard pump combiners. Core composition of the fiber core was optimized by numerical modeling to maximize pump conversion efficiency of the fiber. Novel MOPA scheme was proposed to realize the laser. It consisted from cavity based on short piece of single-mode double-clad Er-doped fiber and pair of fiber Bragg gratings (FBGs) at 1532 nm that was spliced to multimode fiber described above. About 6% of pump was absorbed in the short cavity and generate seed signal at 1532 nm with efficiency 44%. The rest 94% of pump was absorbed in multimode fiber where the seed signal was amplified. In such a scheme a single bunch of 980 nm pump sources was used for both seed laser and amplifier thus decreasing number of required components. Utilization of single mode FBGs resulted in rather narrow spectrum compare to that of multimode FBG-based lasers. As a result, ~15 W of multimode radiation at 1532 nm was generated with slope efficiency of 37 %.

After that, developed laser was tested as a pump source for MOPA based on a new single-mode Er-doped fiber. The fiber was coated by Teflon that demonstrates low loss at 1532 nm region. Output power of 7 W with 50 % efficiency was obtained.

10083-59, Session 12

Experimental and numerical analysis of high power Er:Yb co-doped fiber amplifiers

Julia R. Limongelli, Daniel J. Creeden, Scott D. Setzler, BAE Systems (United States)

We created a model to predict the behavior of high power Er:Yb-doped fiber amplifiers, which has shown excellent correlation to experimental results. The rate equations for Er and Yb fibers are generally well-known; however, within the co-doped system, there are two transfer coefficients, which determine the energy transfer rates to and from the Yb and Er ions. These coefficients are not well publicized in literature, particularly for silica glass, which was used in our experimentation. Determination of these parameters is critical to the accuracy of the model. To determine the appropriate values for these rates, we ran our model with a range of energy transfer coefficients and compared to the experimental data at two different pumping wavelengths, 940nm and 976nm, for a commercially available 25/300 Er:Yb-doped fiber. Experimentally, we have shown 50.5% amplifier slope efficiency for a 5m fiber length under 940nm pumping, while pumping at 976nm for a 1.3m fiber length yielded a 40.2% slope efficiency. These results allowed us to directly anchor our model to measured experimental results under fixed conditions. In doing so, we were able to determine fixed values for both energy transfer rates which give us excellent correlation to the experimental data, regardless of fiber length or pump wavelength used. This determination of the transfer coefficients and excellent correlation to experimental data allows us to accurately predict Er:Yb-doped fiber amplifier performance.

10083-60, Session 12

Clad-pumped Er-nanoparticle-doped fiber laser

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Erbium-doped fiber lasers are attractive for directed energy weapons applications because they operate in a wavelength region that is both eye-safer and a window of high atmospheric transmission. For these applications a clad-pumped design is desirable, but the Er absorption must be high because of the areal dilution of the doped core vs. the pump cladding. High Er concentrations typically lead to Er ion clustering, resulting in quenching and upconversion. Nanoparticle (NP) doping of the core overcomes these problems by physically surrounding the Er ions with a cage of Al and O in the NP, which keeps them separated to minimize excited state energy transfer. A significant issue is obtaining high Er concentrations without the NP agglomeration that degrades the optical properties of the fiber core. We have developed the process for synthesizing stable Er-NP suspension which have been used to fabricate EDFs with Er concentrations >90 dB/m at 1532 nm. Matched clad fibers have been evaluated in a core-pumped MOPA with pump and signal wavelengths of 1475 and 1560 nm, respectively, and efficiencies of ~72% with respect to absorbed pump have been obtained. We have fabricated both NP- and solution-doped double clad fibers, which have been measured in a clad-pumped laser testbed using a 1532 nm pump. The 1595 nm laser efficiency of the NP-doped fiber was 47.7%, which is high enough for what is believed to be the first laser experiment with the cladding pumped, NP-doped fiber. Further improvements are likely with a shaped cladding and new low-index polymer coatings with lower absorption in the 1500 – 1600 nm range.

10083-61, Session 13

Effects of coating thickness on high power metal coated fibre lasers *(Invited Paper)*

Jae M. O. Daniel, Aether Photonics (Australia) and Defence Science and Technology Group (Australia); Nikita Simakov, Defence Science and Technology Group (Australia) and Univ. of Southampton (United Kingdom); Alexander V. Hemming, Defence Science and Technology Group (Australia); W. Andrew Clarkson, Univ. of Southampton (United Kingdom); John Haub, Defence Science and Technology Group (Australia)

We investigate the effects of coating thickness on scattering losses of metal coated fibre. Metal coated active fibres offer a promising route to power scaling of high power fibre lasers. By replacing the typical polymer coating with a metal one, significant increases in temperature handling and heat removal can be achieved. However, metal coated optical fibres tend to show higher propagation losses in comparison to polymer coated fibre. This increased loss can be understood as an increase in scattering losses due to the increased rigidity of metals in comparison to polymers. From a power scaling perspective, this scattering loss plays an important role in determining laser beam quality and is also expected to play an important part in modal instability thresholds. In this submission we investigate the effects of metal coating thickness on scattering losses of metal coated active fibre. A 20 m length of ytterbium doped, metal coated, active fibre is placed in an etchant solution whilst measuring propagation loss as a function of time. By utilising in-situ coating resistance measurements we are able to correlate propagation losses with coating thickness. Experimentally we find a linear dependence on coating thickness and propagation loss with losses reducing from a maximum of 1.3dB (~25%) down to near negligible values when the coating is sufficiently thin. We will present the results of this work providing useful parameters for high power metal coated laser design.

10083-62, Session 13

Temperature measurement of acrylate coated optical fibers during high power operation

Thomas Theeg, Arthur Krüger, Hakan Sayinc, Laser Zentrum Hannover e.V. (Germany); Ludger Overmeyer, Laser Zentrum Hannover e.V. (Germany) and Institut für Transport- und Automatisierungstechnik (Germany); Jörg Neumann, Dietmar Kracht, Laser Zentrum Hannover e.V. (Germany)

The knowledge of the temperature of double clad optical fiber coatings during laser operation is very important for coating reliability and laser performance. However, the measurement of the fiber coating temperature is very challenging since each physical contact with a measuring sensor (e.g. thermocouples) results in significant temperature measurement error. To overcome this problem a non-contact measurement can be realized by measuring the thermal radiation of the fiber, e.g. with a high local resolution thermographic camera. A prerequisite for accurate temperature measurements is the knowledge of the emissivity of the fluoroacrylate-based coating in dependence of the measurement wavelength and coating temperature. Since double-clad fibers typically consists of two coating layers – the primary (low index coating) and secondary coating (for mechanical protection) – the emissivity of the two-layer coating system has to be considered. We investigated in detail the emissivity of typically used primary and secondary coatings in dependences of the thermal radiation wavelength and the coating temperature. Based on our experimental results we can provide – to the best of our knowledge for the first time – important guidelines for fiber coating temperature measurement in practice. One conclusion that can be drawn from the results is that a ribbon emissivity of 0.95 (7.5 to 13.0 μm) is a suitable value for the measurement of the fiber coating temperature between 20°C and 180°C. Moreover, based on fiber amplifier experiments, we will discuss the error of the measured coating temperature due to additional thermal radiation from the surface of the fused silica fiber cladding.

10083-63, Session 13

Interferometric modal content measurements in fibers

Michael Steinke, Christian Bremauer, Omar de Varona Ortega, Jörg Neumann, Dietmar Kracht, Peter Wessels, Laser Zentrum Hannover e.V. (Germany)

We report a novel approach for fast measurements of the modal content in few-mode fibers with an interferometric setup based on a scanning Michelson interferometer. A first experimental proof-of-principle is presented which allows us to re-construct the corresponding modes of the fiber under test by evaluating the numerical Hilbert transformations of the experimentally obtained interferograms. Furthermore, the novel interferometric approach is compared to the spatially and spectrally (S2) resolved imaging approach in terms of acquisition speed. It has a great potential to enable real-time measurements by using all-optical instead of numerical Hilbert transformations and state-of-the-art CCD or CMOS cameras. Furthermore, the proposed all-optical Hilbert transformations are not limited by the Nyquist theorem since the transformations are analog and the fringes must not be resolved, which is an additional major benefit in terms of speed. Thus, the interferometric approach will enable for example real-time monitoring of the higher-order mode suppression during the manufacturing of fiber devices and components.

10083-64, Session 13

Photodarkening kinetics in a high-power YDFA versus CW or short-pulse seed conditions

Alain Jolly, ALPhANOV (France) and Commissariat à l'Énergie Atomique (France); Cyril Vincont, Johan Boullet, ALPhANOV (France)

We demonstrate significant variations of the rate and kinetics of photodarkening in a high - power YDFA, depending upon seed conditions. Given the same output power, the comparison of experimental data provided with short - pulse and CW seeds at 1064nm evidences specific penalties. First, measurement results are referred to already published results of interest for analysis. Second, we give an interpretation of the phenomena thanks to an interplay between the different species of the ytterbium content, by considering bulky defects and charge transfer phenomena between aggregated trivalent ions and divalent ions. Multiphoton absorption, which does not apply to basically trivalent ytterbium ions, is discussed as a representative route in the case of aggregates to enable direct excitation of the color centers in the UV band from infrared photons. This is done by comparison with gradual excited state re - absorption throughout defect - related color centers, either structural or due to impurities. Third we develop a comprehensive numerical model with the suitable spatial resolution all along the active fiber. Competing photodarkening and photobleaching effects are involved, starting from a given density and distribution of the defects and of aggregates which operate as activators and precursors. Finally, inherent benchmark limitations and remaining approximations in the model will be discussed in view of more complete validation of the possible modelling options. Further directions are also proposed, as a contribution to currently open discussions in the community, to help for deeper understanding and optimizing the operating conditions of highly - doped fibers.

10083-65, Session 14

Dual wavelength pumping scheme for resonantly core-pumped Holmium doped fiber lasers

Saniye Sinem Yilmaz, Laser Zentrum Hannover e.V. (Germany) and Bilkent Univ. (Turkey); Okan Isik, Christoph Ottenhues, Katherina Hausmann, Hakan Sayinc, Laser Zentrum Hannover e.V. (Germany); Fatih Ömer Ilday, Bilkent Univ. (Turkey); Jörg Neumann, Dietmar Kracht, Laser Zentrum Hannover e.V. (Germany)

The compact fiber laser sources operating in the 2 μm wavelength range have attracted considerable attention recently. The Ho-doped fiber lasers which are pumped by high brightness Tm-doped fiber lasers is an attractive scheme to high output power and pulse energy with a low quantum defect around the wavelength range of 2 μm. Recently, we have developed resonantly core-pumped holmium fiber lasers primarily for high power laser applications in the 2 μm spectral region by all-fiber truly single mode Tm-doped fiber lasers combined with WDM cascade. Despite the higher threshold for nonlinear effects at longer wavelengths, scaling the power of the Ho-doped fiber amplifier with Tm-doped fiber lasers still has limitations. Thermal loading, which limits the average power can be minimized by using low-doped, longer gain fibers, whereas the presence of nonlinear effects requires the use of high doped, shorter fibers to maximize the average or peak power of the system. We propose the use of two different pump wavelengths with different absorption coefficient along the gain fiber as an analogy to doping management to circumvent these opposing requirements. As a first implementation, we developed a fiber amplifier system which composed of Ho-doped fiber pumped by Tm-doped fiber lasers at the wavelengths of 1920 nm and 1950 nm. We obtained an average power of 9 W from the Ho-doped amplifier resulted in an efficiency of 68 %. Our results show that a dual wavelength pumping scheme can be employed to manipulate the temperature of the fiber coating.

10083-66, Session 14

Spontaneous laser-line sweeping in Ho-doped fiber laser

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Spontaneous laser-line sweeping (SLLS) refers to fiber laser instabilities with regular laser wavelength sweeping within a broad range that may exceed 10 nm; narrow-linewidth and sustained relaxation self-pulsing. So far, the SLLS was observed in Yb, Er, Tm and Bi-doped fiber lasers. In this paper we provide report on the first experiment with SLLS in holmium doped fiber laser emitting at around 2100 nm. Several laser cavity configurations, holmium-doped fibers with different concentrations of holmium and various lengths of the fibers were tested. The holmium-doped fiber lasers were pumped by thulium-doped fiber lasers at ~2030 nm (ring-fiber laser built in house) and 1940 nm (commercial fiber laser). The SLLS regime was observed in Fabry-Perot cavity configuration low reflectivity of the output mirror of 3.5 %. The other mirror was formed by the highly-reflective fiber-loop mirror made of 3 dB coupler with flat spectral transmission characteristics around 2 micrometers. The holmium-doped fiber was single mode at 1940 nm and beyond and its peak absorption was 40 dB/m at 1950 nm. We observed SLLS with 3-5 nm span of laser wavelength sweeping at around 2100 nm and the sweeping rate was typically 0.7-0.9 nm/s. However, the SLLS regime did not exhibit long term stability, probably due to the effect of heating of the active medium. The SLLS disappeared in several minutes. In the contrary, the SLLS regime of Yb-doped fiber lasers can be readily established with excellent long-term stability. Therefore, the SLLS in Ho-doped fiber lasers require further optimization of the laser cavity and understanding of the heating processes that occur within the Ho-doped fiber and limit the SLLS operation.

10083-67, Session 14

Single frequency distributed Bragg reflector Nd-doped silica fiber laser

Wei Shi, Qiang Fang, Yang Xu, Shijie Fu, Tianjin Univ. (China)

Three-level Nd-doped silica fiber lasers (using the 4F3/2-4I9/2 transition) can produce coherent emissions in the spectral range of 900 nm - 945 nm, which can be used for frequency doubling to obtain the pure blue light. we report a CW single frequency DBR fiber laser at 930 nm, using a short length commercial highly Nd-doped double cladding silica fiber, which was core-pumped by a single mode fiber coupled laser diode at 808 nm. This single frequency fiber laser cavity was fabricated by cleaving the high-reflection FBG and the partial reflection FBGs very close to the index modulation region and directly splicing to a ~2.5 cm-long commercial highly Nd3+-doped silica fiber. The output power of the single frequency Nd-doped fiber laser was measured using a sensitive thermal power sensor (818P-001-12, Newport Inc.). ~1.9 mW output power was achieved when ~ 125 mW 808 nm pump power was launched into the cavity by the 808/930 nm WDM. The spectrum of the laser was measured using an optical spectrum analyzer (OSA). The center wavelength of this laser was ~ 929.77 nm and ~ 40 dB signal to noise ratio (SNR) was achieved. The linewidth of the single frequency fiber laser, with ~ 1.9 mW output power, was measured to be ~44 kHz FWHM (full width at half maximum) by the method of delayed self-heterodyne interferometry. The single longitudinal mode operation of this laser was verified by a scanning Fabry-perot interferometer.

10083-68, Session 14

High power white super-continuum fiber laser and white super-continuum beam combiner

Chang Sun, Tingwu Ge, Na An, Kang Cao, Zhiyong Wang, Beijing Univ. of Technology (China)

A high power white super-continuum (SC) fiber laser and a white SC beam combiner are demonstrated. The white SC laser structure includes a passive mode-locked seed fiber laser, master power amplifiers and the SC generation system which uses photonic crystal fiber (PCF) with small mode area as the high nonlinear medium. In this experiment, we adopt the thermally expanded core fibers technique to fabricate a high power all fiber mode field adapter (MFA) which is used to couple high power pump pulses into the PCF, and it can work successfully under the incident pulse power of 98 W with the transmission efficiency of 82%. Meanwhile, a self-made repetition frequency multiplier (RFM) is utilized to adjust the RF of pulse and control the nonlinear (NL) effects in the amplification process. Finally, a 43 W high power white SC fiber laser source is achieved, with spectrum ranging from 450 nm to 2400 nm, spectral width below 10dB flatness exceeding 1500 nm. In addition, through theoretical simulation and designed specially, a high power (7?1) white SC combiner is obtained, and its average combining efficiency is up to 87.8% with the testing source of the obtained 43 W SC. In the next step, we will use more high power white SC sources to test these seven input fibers of the SC combiner at the same time, and further improve the white SC combining efficiency.

10083-69, Session 15

Investigation of self-phasing dynamics in a Q-switched passively coupled two-gain-element fiber laser array

Hung-Sheng Chiang, James R. Leger, Univ. of Minnesota, Twin Cities (United States)

We have investigated self-phasing in a Q-switched passively coupled two-gain-element fiber laser array. The laser cavity consists of a Ytterbium-doped dual-core double-clad polarization-maintaining fiber and a free-space section (fig. 1). The path length difference between the two cores is sufficiently small to eliminate wavelength tuning as a self-phasing mechanism. The square-polished fiber end serves as a 4%-reflectivity end mirror. A ruled diffraction grating closes the laser cavity at the other end. The two gain elements are passively coupled by a homemade Dammann grating. An acousto-optic (AO) Q-switch in the free-space section provides loss modulation. To achieve high extinction of optical feedback in the OFF state, the laser is operated on the first-order diffraction beam of the AO Q-switch. When the laser modes in the two gain elements are mutually phase-locked, the laser output at the square-polished fiber end forms interference fringes in the Fourier plane of the collimating lens. An afocal imaging system projects this Fourier plane to a suitable location where measurements can be performed. By sampling the signals across the entire fringe pattern, the state of the interference pattern can be reconstructed as a function of time. Fig. 2 shows one of our experimental results. Fig. 2(a) is the optical intensity detected at a fixed location in the fringe pattern. A mode-locked-like pulse train was observed under a Q-switched pulse envelope. Fig. 2(b) shows the phase evolution of the laser mode. The phase changed from its quiescent value to its active value in a time commensurate with the rise time of the Q-switched pulse. The laser was able to operate as a coherent array over practically the entire Q-switched pulse duration, even when significant phase detuning was applied. Fig. 2(c) zooms in onto this phase-locked state. Both the phase fluctuation and the mode-locked-like pulse train have a periodicity that equals the cavity round-trip time (15ns). Also, the phase fluctuation appears to follow the rise and fall of each mode-locked-like pulse. The implication of our observation is that the speed of self-phasing is not bound by the cavity round-trip time.

10083-70, Session 15

A femtosecond Yb-doped fiber laser with generalized vector vortex beams output

Tiancheng Huo, Li Qi, Buyun Zhang, Zhongping Chen, Univ. of California, Irvine (United States)

Light carries both spin and orbital angular momentum (OAM) and the superpositions of these two dynamical properties have found many applications. Many techniques exist to create such light sources but none allow their creation at the femtosecond fiber laser. Here we report on a novel mode-locked Ytterbium-doped fiber laser that generates femtosecond pulses with generalized vector vortex states. The controlled generation of such pulses such as azimuthally and radially polarized light with definite orbital angular momentum modes are demonstrated. A unidirectional ring cavity constructed with the Yb-doped fiber placed at the end of the fiber section to reduces unnecessary nonlinear effects is employed for self-starting operation. Pairs of diffraction gratings are used for compensating the normal group velocity dispersion of the fiber and other elements. Mode-locked operation is achieved based on nonlinear polarization evolution, which is mainly implemented with the single mode fiber, the bulk wave plates and the variable spiral plates (q-plate with topological charge q=0.5). The conversion from spin angular momentum to the OAM and reverse inside the laser cavity are realized by means of a quarter-wave plate and a q-plate so that the polarization control was mapped to OAM mode control. The fiber laser is diode pumped by a wavelength-division multiplexing coupler, which leads to excellent stability and portability.

10083-71, Session 15

All-fiber widely tunable 2 μm fiber laser

Wenyan Tian, Robert A. Stegeman, Eric D. Park, Q-Peak, Inc. (United States)

Tunable fiber laser sources are an attractive technology to provide lasing with narrow spectral bandwidth across a wide spectral region encompassed by a host lasing medium's optical gain bandwidth. An example of an application is the relative simplicity of conducting gas and molecular chemistry assays where a tunable mid infrared laser source readily available. Given this and other similar motivations, various tunable laser technologies have been demonstrated in Tm-doped fiber laser systems in both pulsed and CW format. Recently, a widely tunable Tm-doped fiber laser source pumped by a 1.56 μm Er/Yb co-doped fiber laser with no free-space optics has been demonstrated.

In this paper, we report on an all-fiber, 793-nm, cladding pumped, tunable, Tm-doped, fiber laser based on a custom designed 2-μm intra-cavity fiber-coupled Fabry-Perot tunable filter. Continuous tuning over a 90 nm range has been achieved from 1952 to 2042 nm with a spectral linewidth ≤0.07 nm and a signal-to-noise ratio >55 dB. A wavelength stability of ±0.01 nm over a run time of 2 hours has been demonstrated. The tuning range is entirely defined by the free spectral range of the tunable filter. The large tuning range offers unique flexibility for chemical detection, medical applications, and a tunable seed source suitable for amplification and conversion to an even greater range of spectral regions via nonlinear optical approaches.

10083-72, Session 15

Ring mirror fiber laser gyroscope

Mohamed Y. Shalaby, Kamal Khalil, Abdelrahman E. Afifi, Ain Shams Univ. (Egypt); Diaa A. M. Khalil, Ain Shams Univ. (Egypt) and Si-Ware Systems (Egypt)

Rotation sensing using optical fibers has been developed across the last four decades, and demonstrated an excellent performance in the inertial navigation systems. To increase the scale factor of the FOG structure, the length of the fiber loop should be in the order of kilometers of PM fibers to achieve the high end resolution requirements. This makes the sensitive FOG a very expensive instrument. To overcome this barrier, we propose in this work a new architecture for an optical gyroscope system.

In this work we present a new architecture for a laser gyroscope based on the use of a Sagnac fiber loop mirror. This novel optical gyroscope is based on a Fabry Pérot laser configuration with one or both of its mirrors as a Sagnac loop. The proposed system has the unique property that its scale factor can be increased by increasing the gain of the optical amplifier used in the system as demonstrated experimentally using standard single mode fiber and explained physically by the system operation. The proposed gyroscope system is also capable of identifying the direction of rotation. The system has been constructed using SM fiber coils of 2.1 Km and an SOA as a gain medium. The scale factor has been measured for different SOA current. A scale factor improvement from about 0.5 V/(deg./sec.) to 0.95 V/(deg./sec.) is demonstrated by the simple increase of the SOA current from 150 mA to 250 mA. This new structure opens the door for a new category of low cost optical gyroscopes.

Conference 10084: High Power Lasers for Fusion Research IV

Monday 30–30 January 2017

Part of Proceedings of SPIE Vol. 10084 High Power Lasers for Fusion Research IV

10084-1, Session 1

LMJ status: Second bundle commissioning and assessment of first years of service *(Invited Paper)*

Pierre A. Vivini, Marc G. Nicolaizeau, Commissariat à l'Énergie Atomique (France)

The Laser Megajoule facility, developed by the CEA is designed to provide the experimental capabilities to study high density plasma physics. The 176 Nd:glass laser beams of the facility will deliver a total energy of 1.4MJ of UV light at 0.35 μm and a maximum power of 400 TW. The laser beams are focused on a micro-target inside a 10-meter diameter spherical chamber.

A first bundle of eight laser beams was officially commissioned in October 2014. Since then, several experimental campaigns have been carried out. First to qualify LMJ experimental capability. Secondly to validate radiative hydrodynamics simulations. New plasma diagnostics were installed around the target chamber for that purpose. They include both a second X-ray imager and two broad-band X-ray spectrometers.

The installation of new bundles is continuing, simultaneously to the plasma experiments. A temporary control room has been dedicated to the first steps of every bundle integration. This also simplifies scheduling problems linked with activities that cannot happen at the same time. The next steps of commissioning (power shots, use of target chamber equipment) will be monitored later from the main control room.

Within a same bundle design, some technical improvements have been added: upgraded pulse shaping software, new diffraction grating technology, a perfected alignment process and common reference.

Second bundle commissioning is scheduled for the end of 2016. The full presentation will describe the remaining work in more detail and showcase more recent results of the LMJ.

10084-2, Session 1

Status of NIF laser and high power laser research at LLNL *(Invited Paper)*

Mark W. Bowers, Peter J. K. Wisoff, Mark C. Herrmann, Thomas M. Anklam, Jay W. Dawson, Jean-Michel G. Di Nicola, Constantin L. Haefner, Mark R. Hermann, Douglas W. Larson, Christopher D. Marshall, Bruno M. Van Wonterghem, Paul J. Wegner, Lawrence Livermore National Lab. (United States)

This talk will provide an overview of high power laser research at Lawrence Livermore National Laboratory (LLNL). It will discuss the status of the National Ignition Facility (NIF) laser and recent experimental results. In addition, the talk will describe other laser development activities such as the development of high average power lasers and novel fiber lasers.

The National Ignition Facility (NIF) has been in service since 2007 and operating with > 1 MJ energies since 2009. During this time the facility has transitioned to become an international user facility and increased the shot rate from ~150 target shots per year to greater than 400 shots per year. Today, the NIF plays an essential role in the US Stockpile Stewardship Program, providing data under the extreme conditions needed to validate computer models and train the next generation of stockpile stewards. Recent upgrades include the Advanced Radiographic Capability (ARC), a high energy short pulse laser used to do high resolution radiography.

In addition to the NIF, this talk will include an overview of progress on the high average power laser development, recent results from fiber laser development activities and improvements to laser design and computational capabilities.

10084-3, Session 1

Extreme light infrastructure: Status of the facilities and planned first experiments at ELI-Beamlines *(Invited Paper)*

Georg Korn, ELI Beamlines (Czech Republic)

We will be giving an overview on the development of the "ELI-beamline facility" being built within the Extreme Light Infrastructure (ELI) project based on the European ESFRI (European Strategy Forum on Research Infrastructures) process.

ELI-Beamlines will be a high-energy, repetition-rate laser pillar of the ELI (Extreme Light Infrastructure) project. It will be an international facility for both academic and applied research, slated to provide user capability since the beginning of 2018. The main objective of the ELI-Beamlines Project is delivery of ultra-short high-energy pulses for the generation and applications of high-brightness X-ray sources and accelerated particles. The laser systems will be delivering pulses with length ranging between 10 fs and 150 fs and will provide high-energy Petawatt and 10-PW peak powers. For high-field physics experiments it will be able to provide focused intensities attaining >1022-23 Wcm-2, while this value can be increased in a later phase without the need to upgrade the building infrastructure to go to the ultra-relativistic interaction regime in which protons are accelerated to energies comparable to their rest mass energy on the length of one wavelength of the driving laser.

We will discuss the status of the building and its infrastructure concerning the availability of experimental areas, the development of the lasers including highly stable beam transport solutions and secondary sources of particles and x-rays in the wavelength range between 20 eV-100 keV and their practical implementation in the ELI-Beamline user facility. The sources are either based on direct interaction of the laser beam with a gaseous targets (high order harmonics) or will first accelerate electrons which then will interact with laser produced wigglers (Betatron radiation) or directly injected into undulators (laser driven LUX or later X-FEL). The direct interaction (collision) of laser accelerated electrons with the laser again will lead to short pulse high energy radiation via Compton or Thomson scattering. The planned first commissioning experiments on x-ray generation, particle acceleration (electrons and protons) as well as on plasma physics and their applications together with the available experimental infrastructure will be introduced.

10084-4, Session 1

High power glass laser research progresses in NLHPLP

Jianqiang Zhu, Jian Zhu, Xuechun Li, Baoqiang Zhu, Weixin Ma, Dean Liu, Cheng Liu, Xingqiang Lu, Wei Fan, Zhigang Liu, Dongfeng Zhao, Shenlei Zhou, Yanli Zhang, Li Wang, Mingying Sun, Bingyan Wang, Zhaoyang Jiao, Lei Ren, Guowen Zhang, Jie Miao, Zunqi Lin, Shanghai Institute of Optics and Fine Mechanics (China)

Laser fusion research had been executed on series of Shenguang(SG) high power laser facilities in National Laboratory on High Power Lasers and Physics (NLHPLP) for nearly 50 years in china. Recently, a new high power laser facility with 8 beams laser system and 30kJ/ns/3?output energy has been performed and operated since 2016. Up to now, a multifunction experiment platform including multi-pulse width of ns,ps and fs and active probing beam has been developed. It is becoming a very important experiment platform for Inertial Confinement Fusion (ICF) and High Energy Density (HED).

As an example, the design ideas in a high power laser prototype with four-pass main amplifier and large optical aperture, which has realized the energy output of 15kJ/5ns/1?in 350mm?350mm clear output aperture, and can output 10kJ/5ns/3?, is introduced. From the system design view, the high amplifier efficiency is considered, and a 3? damage threshold between 1? output and final optical aperture is traded off, that is the final aperture is expand by spatial filter, and much more 3?energy can be delivered without optical damage in final optical system.

In order to realize the about aims, many new techniques are proposed and developed. we had improved the disk amplifier efficiency about 15% by special design reflector with antioxidant coating, and reduced the ASE in disk amplifier by Sol-gel coating between Nd:glass and cladding. Optical field with amplitude and phase can be simultaneously tested by WCI(Wave -front Code Image) instrument, so much more information can be obtained than near and far field test, and WCI can test the 1?,2? and 3? optical field in the same time at same position, so we can analyze the 3? beam quality, especial intensity distribution, to improve the damage threshold. The metal sputtering in the final optical structure was eliminated by silica plate on metal support frame also.

In addition, to explore the adaptability of huge high power laser facility with numerous beams for ICF and HED, we give a flexible concept design of geometrical arrangement in the target area to meet the different style experiment requirement.

10084-5, Session 2

Pulse contrast measurement on the NIF Advanced Radiographic Capability (ARC) laser *(Invited Paper)*

Robert L. Acree Jr., John E. Heebner, Tracy S. Budge, Lawrence J. Pelz, John M. Halpin, Lyudmila A. Novikova, Matthew A. Prantil, Ronald J. Sigurdsson, Lawrence Livermore National Lab. (United States)

Accurate characterization of pulse contrast for high-power lasers is critical to the success of experiments exploring the area of inertial confinement fusion. The Advanced Radiographic Capability (ARC) laser at the NIF is a petawatt class laser which produces pulses in the picosecond regime for the creation of diagnostic x-rays. ARC uses four of the NIF's beamlines for amplification while a separate front-end and pre-amplification stage, known as the High-Contrast ARC Front End (H-CAFÉ), is used. To characterize pulse contrast at the output of H-CAFÉ, a means of measurement at long times (>1 ns) has been developed using a photodiode which has achieved a dynamic range of over 90 dB without the need for deconvolution. To our knowledge, this is the highest dynamic range achieved using a photodiode prior to applying deconvolution techniques. Within hundreds of picoseconds of the main pulse, a commercial third-order cross-correlator (Sequoia) is used to characterize the pulse contrast. Together, these diagnostics provide the necessary data for ensuring an adequate amount of pulse contrast prior to injection into the NIF's amplification stages. Efforts were made to mitigate existing pre-pulses and to increase the stability of the system as a long-term operational companion to the NIF.

We describe the development and testing of the photodiode diagnostic and the analysis of the data resulting from contrast measurements. The relationship between these photodiode measurements and those obtained using Sequoia is also discussed. Details are also provided regarding the identification and mitigation of pre-pulses within the H-CAFÉ system.

10084-6, Session 2

Extremely large bimorph deformable mirror for high intense laser beam correction

Alexis V. Kudryashov, Active Optics Night N Ltd. (Russian Federation) and Institute of Dynamics of Geospheres (Russian Federation) and AKA Optics SAS (France); Vadim Samarkin, Alexander B. Alexandrov, Active Optics Night N Ltd. (Russian Federation); Gilles Borsoni, AKA Optics SAS (France); Julia V. Sheldakova, Active Optics Night N Ltd. (Russian Federation); Takahisa Jitsuno, Institute of Laser Engineering, Osaka Univ. (Japan)

In this presentation we are going to talk about the wide-aperture bimorph deformable mirror with the size of the active part equal to 410 by 470 mm. The results of the characterization of such a mirror will be discussed. Also the results of application of such a mirror for high-power laser beam correction of Japanese laser complex (Firex) will be presented. The produced mirror has an almost perfect flatness as well as high surface deformation (several tenth of microns).

10084-7, Session 2

The injection laser system research progresses in NLHPLP

Wei Fan, Hui Wei, Jiangfeng Wang, Xiaochao Wang, Youen Jiang, Dajie Huang, Xinhua Lu, Zhi Qiao, Xuechun Li, Jianqiang Zhu, Zunqi Lin, Shanghai Institute of Optics and Fine Mechanics (China)

The high power laser system was used to drive ignition of ICF, of which the high energy, the uniform focal spot, the accurate and smooth laser waveform and the synchronization between laser beams are key parameters. The injection laser system is to provide the high quality seed pulse. But the FM-to-AM modulation is an important effect in the injection laser system which affects the temporal profile. To avoid the AM-to-FM as much as possible, the single polarization fiber front end, of which the fast axis has a large loss, is constructed and the FM-to-AM modulation without any compensation is less than 4% for 3 hours compared with over 20% of the polarization maintaining fiber front-end with the same structure. Meanwhile,the AM-to-FM on-line monitoring feedback control system was constructed and the group-velocity dispersion can be compensated. To improve the output energy further of the front end, the mili-joule fiber regenerated amplified was investigated and the output energy can be greater than 1mJ with the square wave distortion less than 1.8. In order to improve the service function of the pre-amplifier, the Xenon lamp pumped repetition Nd-glass amplifer was investigated. The output was 1.2J(@1Hz), and the energy stability is about 1.2%(rms) for half an hour and the near field modulation is less than 1.3:1?

10084-8, Session 2

Stored energy, gain, and lasing in an edge-pumped ceramic Yb:YAG disk laser under intense pumping

John Vetrovec, Drew A. Copeland, Amardeep S. Litt, Aqwest, LLC (United States); Eldridge Briscoe, Steven Jensen, General Atomics Aeronautical Systems, Inc. (United States)

We report on testing of an edge-pumped ceramic Yb:YAG disk laser for pulse amplification under intense pumping. The disk has a composite construction with Yb-doped large-aperture central portion cosintered with an undoped perimetral edge. Light from multi-kW pulsed diodes is transported though the disk edge and absorbed in the Yb-doped center. This configuration results in a very simple and compact laser gain module. The disk is operated as a storage amplifier. Amplified spontaneous emission (ASE) and parasitic lasing is mitigated by the geometry of the laser disk edge, which is designed to efficiently outcouple laser fluorescence. This

work presents results of stored energy, gain, ASE mitigation, and lasing tests of the Yb:YAG disk laser under intense pumping. This work was supported in-part by the US Department of Energy grant number DE-SC0011916.

1. J. Vetrovec, D.A. Copeland, and A. Litt, "Yb:YAG ceramic-based laser driver for inertial confinement fusion," SPIE Vol. 9726-45 (2016)

10084-9, Session 3

Amplifier's function transfer measurement to reduced FM-AM conversion

Sebastien Montant, Commissariat à l'Énergie Atomique (France); Jacques Luce, Nicolas Beck, Jérôme Dubertrand, CEA Cesta (France) and Commissariat à l'Énergie Atomique (France); Jean-Paul Goossens, Olivier Hartmann, Arnaud Perrin, Commissariat à l'Énergie Atomique (France)

Spectral broadening is required on high power laser chains like the NIF or the LMJ to avoid Stimulated Brillouin Scattering (SBS) in the laser chains and to smooth the focal spot [1]. Spectral broadening is obtained by sinusoidal temporal phase modulation. However, the spectral broadening is non-homogenous and to reach given performance high broadening is required. But the spectral bandwidth of the laser chain is limited by the third harmonic conversion and by the limited spectral bandwidth of the Nd laser amplifier. Hence, the spectral bandwidth reduction induced in the laser chain leads to temporal shape distortion through the so-called FM to AM conversion [2]. Moreover same effects occur in the Pre Amplifier Module (PAM). To control and enhanced the quality of the PAM a Function Transfer (FT) measurement can be realized in amplitude and phase.

We have developed high resolution spectral diagnostic to perform amplitude and phase transfer function measurement. These diagnostics are based on multi-grating geometry with two single mode PM fibers input. One input fiber is used as reference and the second is used to measure the spectrum at the output of optical components under test. To perform phase measurement we insert a simple cylindrical lens between the spectrometer and the camera.

We have used this diagnostic to characterize a regenerative amplifier. The transfer function is correlated with the temporal profile of laser pulse. We performed precise characterisation of different regenerative amplifier configuration.

[1] S. H. Glenzer et al, Sciences 327, 1228 (2010).

[2] J. E. Rothenberg et al, Proc. SPIE 3492, 51 (1999).

10084-10, Session 3

Establishing optimal power transmission path by the receiver based on the received signal strength with multiple transmitters and receivers

Jeongsook Eom, Gunzung Kim, Yongwan Park, Yeungnam Univ. (Korea, Republic of)

Although wireless power transmission (WPT) technologies have been successfully employed to form many commercial products, there are still many areas of improvement. Investigating the use of multiple transmitters and receivers is one of the important research topic. Laser power beaming (LPB) is one of the long distance WPT technologies. LPB uses a laser beam to send high-intensity light through the air to a remote receiver that converts the light to electricity. LPB has no mutual interference even dense multiple transmitters do not have a mutual influence.

This paper presents the design, simulations, and experiments of LPB system that establishes an optimal power transmission path by the receiver based on the received signal strength. When the laser beam from multiple transmitters aimed at a solar panel at the same time, the received power is the sum of all energy at a solar panel. Our proposed LPB system consists of multiple transmitter and multiple receivers. The transmitter sends its power characteristics as optically coded laser pulses and powers as high-intensity laser beams. Using the attenuated power level, the receiver can estimate the maximum receivable powers from the transmitters and select optimal transmitters. As the receiver requires and consumes electric energy dynamically, it needs to receive laser beams from one or more transmitters. Throughout the simulations and experiments, we verified that different LPB receivers were achieved their required power by the optimal allocation of the transmitter among the different transmitters.

10084-11, Session 3

Laser damage metrology of PETAL optics

Laurent Lamaignère, Martin Sozet, Eric A. G. Lavastre, Jérôme Néauport, Nadja Roquin, Commissariat à l'Énergie Atomique (France); Laurent Gallais, Institut Fresnel (France)

Laser damage resistance is a key factor for the improvement of high power laser system. The PETAL laser, developed by the CEA-CESTA (France), uses meter scale reflective optics to compress, transport and focalize sub-picosecond laser pulse at 1053nm with high-energy. In the case of defect-free material, laser-induced damage in the femtosecond and the sub-picosecond regimes is known to be deterministic since the threshold only depends on the electronic structure of the irradiated materials, the pulse duration and the enhancement of the electric fields in thin film coatings. Based on this consideration, a mono-shot technique has been investigated to assess the intrinsic damage resistance of optical component with only one laser shot. On the other hand, while considering real optical components, manufacturing processes included nanoscale defects in the functional coating. These defects can be ejected when irradiated and strongly reduce the laser damage resistance of optics: rasterscan procedure has then been developed to determine defect-induced damage densities. These densities are found to be high even for fluences well below the intrinsic Laser-Induced Damage Threshold and they increase with the fluence. These experiments bring new information on the operating characteristics of optics in short pulse regime. Once damage is triggered, its evolution under subsequent irradiations has also been studied. Growth experiments have been compared to numerical simulations. The investigations on growth behavior allow a better estimation of the functional lifetime of an optic in its operating conditions. The whole of results, damage initiation and damage growth, is discussed to the light of the laser damage observed on PETAL optics.

10084-12, Session 3

Concept design of the target area of a 5 MJ laser-driver

Lei Ren, Jianqiang Zhu, Shanghai Institute of Optics and Fine Mechanics (China)

Beam-guiding system (BGS) in the target area of a laser-driver maps the rectangular arrangement at the main lasers to a spherical geometry configuration of shooting lasers at the target chamber. It also ensures that all the laser beams share the same light path length when they arrive at the target chamber center. With the output energy raising from ~2MJ to 5MJ, the laser beam quantity will increase to more than 500. In this situation, researches were conducted on the relationship among the beam quantity, beam combination fashion and the radius of the target chamber. Also, beam transmission units (BTU), including transmission models of main lasers and shooting lasers and the switch manner between them, was put forward to simplify the BGS arrangement work. Then we discussed the factors that determine the BTU configuration and general target area shapes. Based on the laser beam combination fashion and BTU, the entire BGS arrangement in the target area of a 5.76MJ laser facility with 576 laser beams was figured out.

10084-14, Session 3

Experimental study on final optics assembly at 351nm laser

Zhaoyang Jiao, Dongfeng Zhao, Mingying Sun, Lei Ren, Jianqiang Zhu, Shanghai Institute of Optics and Fine Mechanics (China)

On high power laser facility, the amplified 1053nm laser from the Nd:glass driver is transported to target chamber where final optics assembly(FOA) frequency convert the beam to the third harmonic and focus it onto the target at TCC. In order to meeting physical experiment requests for beam conditioning and spot size control: a 1? or 2 ? CPP and , in half of the beam-lines, a polarization rotator. And FOA provides local diagnostics for 3? performance of each beam-line. Different facilities being different focusing and color separation are special FOAs that have being developed well during the past decade. The FOA of national Ignition Facility(NIF) with wedge focus lens is being 8J/cm2 at 351nm and the commissioning of Laser Megajoule(LMJ)' with 3? grating lens is designed to 6J/cm2. Now, numerous novel characteristics of FOA have been investigated, including laser energy flux, laser energy conversion efficiency, laser focus performance, and transmission. Recently, we experimentally demonstrated 61 shots laser with 310mm?310mm on commissioning Shengguang-? Upgrade(SG-?UG) to research the FOA performance.

10084-13, Session 4

Update on the Apollon 10 PW laser: Experimental and theoretical investigation of the temporal aspects *(Invited Paper)*

Catherine Le Blanc, Lab. LULI, Ecole Polytechnique (France); Dimitrios N. Papadopoulos, Jiping Zou, Frédéric Druon, Luc Martin, Ilyes Taghzout, Céline Bonnin, Antoine Fréneaux, Audrey Beluze, Nathalie Lebas, Bruno J. Le Garrec, François Mathieu, Patrick Audebert, Lab. LULI, Ecole Polytechnique (France)

The objective of the Apollon 10 PW project is the generation of 10 PW peak power pulses of 15 fs at 1 shot/minute. In this presentation an update on the current status of the Apollon project will be presented, followed by a more detailed presentation of our experimental and theoretical investigations of the temporal characteristics of the laser. More specifically the design considerations as well as the technological and physical limitations to achieve the targeted pulse duration and contrast will be discussed.

10084-15, Session 4

L4 10 PW laser beam line

Gilles Chériaux, Gavin Friedman, Doug Hammond, James T. Heisler, Axel Jochmann, Nirmala Kandalai, Matt Kepler, National Energetics (United States); Daniel Kramer, Bedrich Rus, ELI Beamlines (Czech Republic); Erhard Gaul, Todd Ditmire, National Energetics (United States)

National Energetics is building the 10PW (1.5 kJ, 150 fs, 1 shot/min) for ELI-Beamlines. This is a hybrid laser configuration based on OPCPA for large spectral bandwidth and contrast management and on liquid cooled mixed Nd:glass amplifiers for high energy and thermal management. The presentation will focus on results on the temporal contrast cleaning process and on gain and wavefront measurement of the first amplifier module.

State-of-the-art physics experiments are pushing the development of lasers with ultra-high peak power pulses. 4 PW pulses have been produced with TiSa and 10 PW with the same medium is scheduled at LULI (Apollon) and at ELI-NP.

Another approach is to use Nd-doped glass, whose interest is in its capability of delivering higher energy at the expense of a longer pulse duration. Based on this gain material, the L4 beam line will be delivered by National Energetics to ELI-Beamlines.

Nd:glass high-energy pulses amplified in slab geometry usually exhibit a low repetition rate and therefore do not require specific thermal management other than air convection. In our case thermal effect cannot rely on such traditional cooling scheme. The thermal management in the power Nd:glass amplifiers is managed via liquid cooling of the slabs in a split-disk configuration. Laminar flow is circulated in between amplifier disks allowing for efficient cooling. 1.7 kJ will be obtained. The spectral width is kept large enough for obtaining 120 fs by mixing Silicate and Phosphate glass.

Another point that is crucial in this type of laser is of course the temporal contrast of the main pulse relatively to the pre-pulse. This is managed by a hybrid architecture relying in short pulse ps-OPCPA and a non-linear cleaning process based on idler generation in a degenerated configuration. This solution allows generating a pulse temporal shape that proportional to the cube of the seed.

10084-16, Session 4

High average power, scalable, all diode-pumped solid state petawatt laser system: Enabling future applications with bright secondary sources *(Invited Paper)*

Constantin L. Haefner, Lawrence Livermore National Lab. (United States)

No Abstract Available

10084-17, Session 4

The Laser Megajoule Facility: Laser performances and comparison with computational simulation

Vincent Denis, CEA, CESTA (France)

The Laser MegaJoule (LMJ) is a 176-beam laser facility, located at the CEA CESTA Laboratory near Bordeaux (France). It is designed to deliver about 1.4 MJ of energy to targets, for high energy density physics experiments, including fusion experiments. The assembly of the first line of amplification (8 beams) was achieved in October 2014. A computational system, PARC has been developed and is under deployment to automate the laser setup process, and accurately predict laser energy and temporal shape. PARC is based on the computer simulation code MIRO. For each shot on LMJ, PARC determines the characteristics of the injection laser system required to achieve the desired main laser output and supplies post-shot data analysis and reporting. The presentation compares energy end temporal shapes measured after amplification and after frequency conversion with results computed with PARC. For most of the LASER shots, both measurement and computed results agree within five percent accuracy.

10084-18, Session 4

Broad bandwidth high reflection coatings for petawatt class lasers: Femtosecond pulse laser damage tests, and measurement of group delay dispersion

John C. Bellum, Sandia National Labs. (United States); Trevor B. Winstone, STFC Rutherford Appleton Lab. (United Kingdom); Ella S. Field, Damon E. Kletecka, Sandia National Labs. (United States)

We designed and produced optical coatings for broad bandwidth high reflection (BBHR) of femtosecond (fs) pulses of petawatt (PW) lasers. These BBHR coatings consist of TiO_2/SiO_2 or HfO_2/SiO_2 layer pairs formed by reactive e-beam evaporation with ion-assisted deposition in Sandia's Large Optics Coating Facility. Specifications for HR center wavelength and spectral width of the coatings are for 45-deg angle of incidence (AOI), P polarization (Ppol), with use of the coatings at different AOIs providing corresponding different HR center wavelengths and spectral widths. These coatings must provide high laser-induced damage threshold (LIDT) to handle the PW fluences, and also low group delay dispersion (GDD) to reflect fs pulses without distortion of their temporal profiles. We present results of LIDT and GDD measurements on these coatings. The LIDT tests are at 45-deg or 65-deg AOI, Ppol with 100 fs laser pulses of 800 nm center wavelength for BBHR coatings whose HR center wavelengths are near 800 nm. A GDD measurement for one of the BBHR coatings whose design HR center wavelength is near 900 nm shows reasonably low GDD over the HR band. We report how the LIDT and GDD results compare with previous results of similar measurements.

Conference 10085: Components and Packaging for Laser Systems III

Tuesday - Thursday 31–2 February 2017

Part of Proceedings of SPIE Vol. 10085 Components and Packaging for Laser Systems III

10085-1, Session 1

Assessment of factors regulating the thermal lens profile and lateral brightness in high power diode lasers *(Invited Paper)*

Juliane Rieprich, Martin Winterfeldt, Ferdinand-Braun-Institut (Germany); Jens W. Tomm, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany); Paul A. Crump, Ferdinand-Braun-Institut (Germany)

The lateral beam parameter product, BPP, and resulting lateral brightness of GaAs-based high-power broad-area diode lasers is strongly influenced by the thermal lens profile. We present latest progress in efforts to understand this profile using FEM simulation to interpret how targeted variation in chip construction influences the thermal lens profile, itself determined using thermography (thermal camera). Important factors regulating the lens profile are shown to include the vertical epitaxial structure, the properties of the heatsink and the transition between chip and heatsink, whose behavior is shown to be consistent with the presence of a significant thermal barrier.

10085-3, Session 1

Complete indium-free CW 200W passively cooled high power diode laser array using double-side cooling technology

Jingwei Wang, Pengfei Zhu, Focuslight Technologies, Inc. (China); Hui Liu, Xi'an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences (China); Xuejie Liang, Focuslight Technologies, Inc. (China); Dihai Wu, Xi'an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences (China); Yalong Liu, Dongshan Yu, Focuslight Technologies Inc. (China); Chung-en Zah, Focuslight Technologies Inc. (United States); Xingsheng Liu, Focuslight Technologies Inc. (China)

High power diode lasers have been widely used in many fields. For some applications, passively cooled single bar diode lasers with the output power of more than one hundreds watts are demanded. Besides the output power, a diode laser needs to be robust under on-off power-cycling as well as environmental thermal cycling conditions. To meet the requirements, passively cooled single bar CS-packaged diode laser arrays must have high durability to withstand thermal fatigue and long lifetime. In this work, a novel complete indium-free double-side cooling technology has been presented for packaging passively cooled high power diode laser arrays. Thermal behavior of hard solder CS-packaged diode laser array with different packaging structure was simulated and analyzed. Based on the results, the device structure and packaging process of complete indium-free double-side cooling CS-packaged diode laser array were optimized. A series of CW 200W 940nm high power diode laser arrays were fabricated and characterized. Under the working condition of CW 200W output power, thermal resistance and thermal rollover are 0.3K/W and more than 240W, respectively. The spectrum of FWHM and FW90%E are 3.03nm and 4.33nm, respectively. The lower smile values of less than 0.5?m were obtained. Lifetime and reliability data will be presented in the final paper.

10085-11, Session 1

High temperature semiconductor diode laser pumps for high energy laser applications

Jenna Campbell, Freedom Photonics, LLC (United States); Tadej Semenic, Teledyne Scientific Co. (United States); Paul O. Leisher, Freedom Photonics LLC (United States); Avijit Bhunia, Teledyne Scientific Co. (United States); Milan L. Mashanovitch, Daniel S. Renner, Freedom Photonics, LLC (United States)

High Power Solid State and Fiber Laser systems, which are used in many commercial and military applications, often require semiconductor diode laser pump modules that operate efficiently and reliably. However, the usefulness of such systems in many tactical environments is limited, because thermal management technologies for the diode laser pumps add significant cost, size, weight, and power consumption to the overall system. To mitigate this burden and to expand the applications of High Power Laser systems, it is desirable to design diode pump modules that operate efficiently at high heat sink temperatures. This effort is being addressed by Freedom Photonics and Teledyne Scientific Company through the design of improved laser diode architectures for high-efficiency performance, and a scalable jet-impingement cooling approach that reduces the thermal impedance from the laser junction to the liquid coolant. Rather than relying on DI water, our cooling approach employs 50% water-propylene-glycol as the liquid coolant, which is more compatible with harsh environments. This paper will present experimental results of our 980 nm diode pump modules, operating at a liquid coolant temperature of 50 degrees Celsius. We have demonstrated a 100-Watt laser bar array with 60% electrical-to-optical efficiency. The paper will describe the technical achievements required to reach this performance goal, as well as provide an outlook of future developments on this platform.

10085-4, Session 2

Narrow-line diode laser packaging and integration in the NIR and MIR spectral range *(Invited Paper)*

Alvaro Jimenez, Tobias Milde, Niklas Staacke, Christian Assmann, Sacher Lasertechnik GmbH (Germany); James O'Gorman, Sensor Photonics GmbH (Germany) and Xylophone Optics Ltd (Ireland); Joachim R. Sacher, Sacher Lasertechnik GmbH (Germany)

Narrow linewidth tunable diode lasers is an important tool for spectroscopic instrumentation. Conventional external cavity diode lasers are designed as laboratory instrument and do not allow hand-held operation for portable instruments. A new miniaturized type of tunable external cavity tunable diode laser will be presented. The presentation will focus on requirements on the assembly technology of micro-optic components as well as on the physical properties of such devices. Examples fort he realization of this new technology will be given in the NIR for Alcaline Spectroscopy as well as in the MIR at 1908nm.

10085-5, Session 2

Compact diode laser module at 1116 nm with an integrated optical isolation and a PM-SMF output

Daniel Jedrzejczyk, Julian Hofmann, Nils Werner, Alexander Sahm, Katrin Paschke, Ferdinand-Braun-Institut (Germany)

Efficient laser light sources in continuous-wave (CW) operation emitting single-frequency near-infrared radiation in a spatial fundamental mode are desired for various applications e.g. in the fields of spectroscopy and LIDAR.

In this work, a fiber-coupled diode laser module with a footprint of 47 mm x 34 mm is realized. As a laser light source a distributed Bragg reflector (DBR) ridge waveguide diode laser emitting at 1116 nm is applied [1]. The module comprises temperature stabilizing components and a brightness maintaining micro-lens system as well as an optical micro-isolator with an isolation greater than 30 dB. At the output, a polarization-maintaining single-mode fiber (PM-SMF) with a core diameter of 5.5 µm and a standard FC/APC connector are utilized. The module reaches an output power of 50 mW and the generated diffraction limited beam is characterized by a narrow linewidth (<10 MHz) and a high polarization extinction ratio (PER > 25 dB).

At the conference, the mechanical and optical setup of the module as well as the employed assembly strategy will be discussed. Primarily, the electro-optical characteristics including the optical power ex SMF as well as the spectral and spatial laser beam properties will be presented.

[1] K. Paschke, H. Wenzel, C. Fiebig, G. Blume, F. Bugge, J. Fricke and G. Erbert, "High Brightness, Narrow Bandwidth DBR Diode Lasers at 1120 nm", IEEE Photonics Technology Letters, vol. 25, pp. 1951-1954 (2013).

10085-6, Session 2

Fiber coupled widely tunable intra-cavity beam combined laser source packaging

Apurva Jain, Avo Photonics, Inc. (United States); Yonathan Dattner, Luxmux Technology Corp. (United States)

Packaging solutions developed for Luxmux's BeST SLED family of sources will be discussed along with their applications. In particular, a narrow linewidth (<300 pm) continuously tunable (from 1250 nm to 1750 nm) laser source providing >20mW output power from a compact fiber-coupled butterfly package will be presented.

10085-7, Session 2

Artificial neural network assisted laser chip collimator assembly and impact on multi-emitter module beam parameter product

Hao Yu, Politecnico di Torino (Italy); Giammarco Rossi, Andrea Braglia, OPI Photonics (Italy); Guido Perrone, Politecnico di Torino (Italy)

High power multi-emitter laser diode modules constitute the basic building block of almost all the sources today used for pumping fiber and solid state lasers or in direct diode systems for a broad range of applications, in particular in industrial material processing. In turn these modules are composed of a number of laser chips whose outputs are combined using different techniques depending on the module architectural choices, but always with the requirement of minimal loss and degradation of the beam quality. These constraints, however, are strongly affected by the accurate positioning of the optical components used to shape and steer the beams, and in particular of the lenses that collimate along the "slow" and "fast" axes of each laser chip. To optimize the positioning of such lenses, we have developed a tool based on a back-propagation artificial neural network; with respect to the iterative approaches currently implemented in automatic assembly equipment, our solution reaches the correct position in a much lower number of steps, with great cycle time improvement. The paper describes the tool first, and then introduces an alternative expression for the determination of the Beam Parameter Product (BPP, the key parameter to measure the beam quality) of a multi-emitter laser diode module. Finally, experimental validations with different combinations of collimating and focusing lenses are reported to prove the validity of the proposed approach and to analyze the impact of different choices on the overall module performance in terms of beam quality and coupling efficiency into a collecting fiber.

10085-2, Session 3

Optoelectronic packaging of single photon avalanche diodes

Sven Mahnkopf, Avo Photonics, Inc. (United States); Andrea Giudice, Micro Photon Devices S.r.l. (Italy); David Demmer, Thomas L. Haslett, Avo Photonics, Inc. (United States); Georg Simmerle, Micro Photon Devices S.r.l. (Italy)

Optical, mechanical, and thermal aspects of packaging single photon avalanche diodes for different applications will be discussed. Particular emphasis will be given to fiber coupling at high photon detection efficiencies over a wide wavelength range.

10085-8, Session 3

Reliable QCW diode laser arrays for operation with high duty cycles

Wilhelm Fassbender, Heiko Kissel, Jens Lotz, Tobias Koenning, DILAS Diodenlaser GmbH (Germany); Steven G. Patterson, DILAS Diode Laser, Inc. (United States); Jens Biesenbach, DILAS Diodenlaser GmbH (Germany)

Quasi-continuous wave (QCW) laser bars and arrays have found a wide range of industrial, medical, scientific, military and space applications with a broad variety in wavelength, pulse energy, pulse duration and beam quality. Recent applications require even higher power, duty cycles, increased operating temperatures up to latent heat cooling (conductive cooled) or reliable fluidic cooling close to the bars.

We present the latest performance and reliability data of several novel high-brightness QCW arrays of customized and mass-production modules, in compact and robust industry design for operation with high power and duty cycles. All designs are based on single diode packages consisting of 10mm laser bars, AuSn soldered between two CuW submounts.

The modular components cover a wide span of designs which differ basically in water/conduction (active/passive) cooled, single, linear and circular arranged designs as well as housed and unhoused modules.

We will look into the relation and interaction of achievable duty cycles with variation in repetition rate and pulse width and also variation in peak and average power, doing this at different wavelengths and fill factors. The different assembling technologies of active and passive cooled base plates affect the heat dissipation and therefore the reachable power at different QCW operating conditions as well as the lifetime.

As an example, a package consisting of single diodes, connected to a 10.6*14*2.5mm? DCB submount, passively cooled is considered. This design is of particular interest for mobile applications demanding a compact and lightweight package and no additional cooling. Using 940nm bars we can reach an optical output power of 80W at 80°C base plate temperature with 3Hz, 1% duty cycle and 3.3ms.

As an additional example 12 diodes are connected to a 11.6*33.8*5.3mm? an actively cooled direct-copper-bond macro cooler. This design is suitable for hair removal applications demanding also compactness and light weight in a hand piece paired with high pulse energy. Using 808nm bars and others, we can reach an optical output power of 864W at 20°C base plate temperature with 2Hz, 20% duty cycle and 100ms.

10085-9, Session 3

Thermal characteristics of compact conduction-cooled high power diode laser array packages

Pu Zhang, Xi'an Institute of Optics and Precision Mechanics, CAS (China); Xingsheng Liu, Xi'an Institute of Optics and Precision Mechanics, CAS (China) and Focuslight Technologies, Inc. (China); Qiwen Zhu, Xi'an Institute of Optics and Precision Mechanics, CAS (China); Jingwei Wang, Focuslight Technologies Co., LTD (China)

High power diode lasers (HPLDs) have been widely used in many fields, e.g., pumping solid-state lasers, material processing and medical systems. HPLDs always generate a large amount of waste heat during operation. The waste heat will lead to a significant rise of junction temperature, which reduces internal quantum efficiency and output power, increases the threshold current, shifts the central wavelength, and decreases the reliability and lifetime. Hence thermal management is important for HPLDs. There are mainly two kinds of heat sinks for HPLDs, conduction-cooler and liquid cooler. Conduction-cooled HPLDs are available in harsh environments and can be more widely used than liquid-cooled HPLDs. Therefore, it's a challenge to develop better conductively cooling structure because conduction cooling technique has lower heat dissipation efficiency than liquid cooling.

In this paper, transient thermal behavior of two conduction-cooled package structures of high power diode lasers has been simulated and compared using finite element. The effects of heat sink geometry, pitch size, submount size on the thermal resistance of high power diode laser packages have been analyzed in detail. Based on the simulation, heat dissipation capability of high power diode laser packages was improved. Finally, the performance of optimized high power diode laser array packages at different operation parameters has been characterized at elevated temperature. The effects of temperature on the output power and spectrum are discussed in detail. It showed that the conduction-cooled high power diode laser array packages have good optical performance at elevated environment temperature.

10085-10, Session 3

Collimation optics for high power blue laser diodes

Martin Forrer, FISBA AG (Switzerland)

Depending on the available access to an open diode laser facet or not, a fast axis collimation combined with subsequent slow axis collimation might be a preferred solution. With single emitters packaged in TO Cans however this no viable solution and a single lens collimation is preferred. The choice for the glass material is driven by available high refractive index and low absorption values and optimum moldabiltiy for large quantity scaling.

10085-12, Session 3

The smile effect reduction of diode laser bar by bare bar curve control

Guannan Jia, Shun Yao, Zhiyong Wang, Beijing Univ. of Technology (China); Xiaoying Luo, Jian Cheng, Beijing University of Technology (China)

Recently, more and more attention had been gathered on the beam quality improvement of the high power diode laser. One of the primary and fundamental approaches to improve the beam quality of the high power diode laser is to reduce the smile effect of the diode laser bar. In this paper, a method based on the flip chip placement packaging process was presented and investigated to decrease the smile effect. This method is realized by controlling the curve direction and value of the bare laser bar which is picked up by the pick-up tool (PUT) of the placement machine to compensate the packaging induced strain. When the bare bar is taken by the PUT, the curve direction and value can be measured by scanning the P side surface of the bar with a laser rangefinder, and they can be controlled through adjusting the setting up of the PUT. In this experiment, multiple bars in same batch are chosen, and they are separately adjusted to different curve states (direction and value) before bonding via adjusting the PUT. All the bars are bonded with the same packaging process, and then the smile effect and P-I graph of each sample are measured, separately. The result indicates that the smile effect changes gradually from 3.7?m toward P side to 3.3?m toward N side with the curve of bare bar varying from 8?m toward P side to 6?m toward N side. And when the curve of bare bar is 4?m toward P side, the minimum smile effect is 0.3?m. Meanwhile, the P-I graphs of all samples are almost uniform, and it shows that this method has no effect on photoelectric properties of the diode laser. Finally, in order to demonstrate the reliability of this method, ten random bars are used to bond with the curves of bare bars of 4?m toward P side, and all of the obtaining smile effects are less than 0.5?m.

10085-13, Session 3

Robust adhesive precision bonding of laser optics II

Tobias Müller, Fraunhofer-Institut für Produktionstechnologie IPT (Germany) and Aixemtec GmbH (Germany); Andreas Beleke, Aixemtec GmbH (Germany); Sebastian Haag, Fraunhofer-Institut für Produktionstechnologie IPT (Germany) and Aixemtec GmbH (Germany); Daniel Zontar, Sebastian Sauer, Christoph Baum, Christian Brecher, Fraunhofer-Institut für Produktionstechnologie IPT (Germany); Christian Wenzel, Fraunhofer-Institut für Produktionstechnologie (Germany)

Laser systems face massive economic challenges for cost effective, but yet ultraprecise assembly processes. Assembly costs are mainly driven by the demanding requirements of laser systems leading to challenging final assembly positions. Most challenging is the robust process control of the UV-curing adhesive bonding process. As a highly multifactorial process adhesive bonding processes are subject to a target conflict of rapid curing times within several seconds, robust mechanical properties required for reliable laser systems and before all a high reproducibility in terms of precision. The repeatability of adhesive bonding processes is limited by the shrinkage effects fast-curing adhesives inherit. The work presented aims for a significant reduction of the impact of shrinkage effects during curing and a resulting increase in assembly precision. Three key approaches are the enablers for robust bonding processes: Firstly, sophisticated curing systems tailored to the needs of the bonding task keep the variance of UV-radiation to a minimum. Therefore, the authors equip their self-developed micromanipulator with an UV-curing system. Secondly, the ultraprecise volumetric dispensing in Pico liter range with online-characterization of adhesive volume minimized variation in volume and dispensing position. The authors present a calibration station for contactless jet dispensing systems. Both volume and position are measured and adjusted automatically. Lastly, an automated characterization station for the measurement of adhesive shrinkage is presented. These technologies allow for highly reproducible adhesive bonding processes in automated production environments. They are deployed in Fraunhofer IPT's prototyping projects and feasibility studies and Aixemtec's assembly services and their automated assembly cells.

10085-36, Session PTue

Thermally accelerated ageing test of 60W conduction-cooled-packaged 808nm high power diode laser arrays packaged by Indium solder in CW mode

Zhiqiang Nie, Xi'an Institute of Optics and Precision Mechanics, CAS (China); Zenan Shen, Xiaoning Li, Focuslight Technologies, Inc. (China)

We set up a thermal ageing system with nine workspaces and start three groups of tests together under the different heat sink temperature stress levels of 55°C, 65°C and 80°C with the same constant operating current 60A in CW mode. Although ageing test result under nominal stress conditions is more accurate, it is not effective at cost and time. Nevertheless, on the premise of the same failure mechanism, accelerated ageing test under elevated stress conditions can get the lifetime result on compressed timescales and find the failure causes efficiently. According to the obtained acceleration lifetimes, we use linear regression analysis, the method of least squares and goodness-of-fit test to extrapolate the thermal activation energy and the acceleration parameters, and finally obtain the mean lifetime of lasers at room temperature. We can not only obtain the creditable and exact extrapolated results, but also farthest reduce the aging test time and costs, and accomplish the long lifetime evaluation on high power laser array with short-term ageing data. Moreover, based on the ageing test, we analyze the defects, degradation mechanisms, such as solder migration or facet damage, and discuss several ways of improvement.

10085-37, Session PTue

The implementation of the combined high-speed laser scanning for SRS-Lidar

Aleksandr P. Zhevlakov, Valentin V. Elizarov, Aleksandr S. Grishkanich, Sergey V. Kascheev, Andrey A. Mak, ITMO Univ. (Russian Federation)

We discuss implementation of the combined node scanning SRS UV - lidar system with 261,7 nm wavelength for high-speed and high spatial resolution (about 3 cm) scanning in wide and narrow angle at a distance of 50-100 m. The broadband scanning defined as a technique with one-line scanning provided by rolling aluminum mirror with a frequency of 20 Hz and 20 degrees of oscillation amplitude. The scanning mirror is mounted on the shaft of the stepper motor FL86STH156-6204A with the full step of 1.8 degrees. Narrowband scanning is performed by the deflector moving along a spiral path. Rotating angle wedges of the deflector deviate a beam by an angle of ± 50.

This design constitutes an "optical reduction" wedge between the steering angle and the deflection angle of the optical axis and allows 15 ' positioning accuracy. overview of the entire study area for no more than 1 ms at a frequency of rotation of each of the wedges of 50-200 Hz. Unambiguous definition of the geographical coordinates of the probed object is achieved by using high-precision GPS-module and the Vincenty's algorithms. It allows to build a 3D spatial distribution of concentrations of air pollutants.

10085-38, Session PTue

Simple, compact, and low cost CO2 laser driven by fast high voltage solid state switch for industrial application

Miyu Tanaka, Masaya Tei, Kindai Univ. (Japan); Kazuyuki Uno, Univ. of Yamanashi (Japan); Hitoshi Nakano, Kindai Univ. (Japan)

A longitudinally excited CO2 laser driven with a high voltage fast recovery diode has been developed. Longitudinally excited gas laser has ideal characteristics for industrial applications since the laser that is portable, simple structure, maintenance free, and low cost can be realized. In the longitudinal excitation scheme, the discharge uniformity is not affected by residual charges because a diffused streamer discharge that is formed by spark discharge and optical ionization takes place in the long, small-diameter discharge tube. Strong preionization or a fast gas flow system is not required. However, a discharge switch such as a gap switch is generally used as a switching device in the power supply for longitudinal excitation method. It has several problems such as a short life time and a low allowance for high repetitive operation. In this study, solid state device has been introduced in the power supply to achieve long life time, stable and high repetitive laser operation. A fast recovery diode is used to control the high voltage pulse as an opening switch. Power supply for longitudinally excited CO2 laser is composed of a pulse generator, transformer (ignition coil), capacitor, and a recovery diode, is very simple. When the reverse bias applies to a recovery diode, switch is open, producing high voltage short pulse. Laser oscillation can be achieved, several mJ in laser energy has been obtained. A compact, simple, low cost, and maintenance-free gas laser can be realized.

10085-39, Session PTue

Cladding pump light stripper study for high power fiber laser applications

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Optical fiber lasers and amplifiers have been used for various applications in photonics. They have received a great potential because of its high power and good beam quality. Fiber lasers have tremendous importance towards commercial deployment. In order to achieve the high power in fiber lasers and amplifiers, it is important to extract the unwanted cladding light properly from the fiber. Designing of fiber lasers with very low cladding light output is called cladding light stripper and the structures are capable of extracting a large amount of light from the cladding. This unwanted cladding light is existed from the unabsorbed pump light in the fiber gain medium. The clad pumping technique with double clad optical fibers shows rapid increment of power of fiber lasers and amplifiers. In the present paper we have proposed a cladding light stripper by circularly carving the fiber outer cladding. In which we present and characterize the CO2 laser system processing technique for fiber based cladding light stripper, we have set the optimized parameters for CO2 laser, to achieve the required pitch and depth. We fabricated the stripper of 60 W power handling capacity, and we have maintained the almost constant temperature of cladding light over the length of striping device.

10085-14, Session 4

Narrow linewidth diode laser modules for quantum optical sensor applications in the field and in space *(Invited Paper)*

Andreas Wicht, Ahmad I. Bawamia, Wojciech Lewoczko-Adamczyk, Anja Kohfeldt, Christian Kürbis, Max Schiemangk, Heike C. P. Christopher, Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik (Germany); Achim Peters, Humboldt-Univ. zu Berlin (Germany) and Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik (Germany); Günther Tränkle, Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik (Germany)

No Abstract Available.

10085-15, Session 4

Optical components for tailoring beam properties of multi-kW diode lasers

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One important aspect for the increasing use of diode lasers in industrial applications is the flexibility of diode lasers to tailor the beam properties to the specific needs demanded from the application. For fiber coupled solutions beam shaping with appropriate micro-optical elements is used for efficient fiber coupling of the highly asymmetric diode laser beam, whereas for direct applications optical elements are used to generate specific intensity distributions, like homogenized lines, areas and rings. Applications with diode lasers as solid state laser pump sources often require tailored spectral characteristics with narrow bandwidth, which is realized by using volume Bragg gratings for wavelength stabilization.

In this paper we will summarize several concepts for adapting beam properties of diode lasers by using specific optical components. For building very compact laser modules of up to 2 kW we already presented a concept based on beam shaping of high fill factor bars. In this paper we will focus on further tailoring the beam properties of these very compact laser modules in the wavelength range from 808 nm up to 1020 nm. Fiber coupling of such modules into an 800 µm NA0.22 fiber yielded 1.6 kW without using polarization coupling. Another example is the generation of a 2.5 kW homogenized line with 40 mm length and a width of 4 mm.

10085-16, Session 4

Ultra-narrow band diode lasers with arbitrary pulse shape modulation

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Wideband emission spectra of laser diode bars (several nanometers) can be largely narrowed by the usage of thick volume Bragg gratings (VBGs) recorded in photo-thermo-refractive glass. Such narrowband systems, with GHz-wide emission spectra, found broad applications for Diode Pumped Alkali vapor Lasers, optically pumped rare gas metastable lasers, Spin Exchange Optical Pumping, atom cooling, etc.

Although the majority of current applications of narrow line diode lasers require CW operation, there are a variety of fields where operation in a different pulse mode regime is necessary. Commercial electric pulse generators can provide arbitrary current pulse profiles (sinusoidal, rectangular, triangular and their combinations). The pulse duration and repetition rate however, have an influence on the laser diode temperature, and therefore, the emitting wavelength. Thus, a detailed analysis is needed to understand the correspondence between the optical pulse profiles from a diode laser and the current pulse profiles; how the pulse profile and duty cycle affects the laser performance (e.g. the wavelength stability, signal to noise ratio, power stability etc.). We present the results of detailed studies of the narrowband laser diode performance operating in different temporal regimes with arbitrary pulse profiles. The developed narrowband (16 pm) tunable laser systems at 795 nm are capable of operating in different pulse regimes while keeping the linewidth, wavelength, and signal-to-noise ratio (>20 dB) similar to the corresponding CW modules.

10085-17, Session 4

Optimization of microchannel cooler of high power diode laser array package

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High power diode laser arrays have found increased requirements in the field of pumping solid-state and fiber lasers. Due to thermal crosstalk across diode laser arrays and non-uniformity of soldering interface, junction temperature between each emitters becomes inhomogeneous, consequently leading to spectrum broadening and large beam divergence of pumping diodes. The broadened spectrum results in lower optical-optical efficiency for solid-state and fiber lasers, and then leads to poor performance for the laser systems and additional cost for thermal management. In this work, we employed analytical method and numerical heat transfer as well as computational fluid dynamics based on finite volume method to optimize the structure of microchannel heat sinks so as to obtain uniform junction temperature distribution for the diode laser arrays. The mathematical and three-dimensional numerical models were developed to study the fluid flow and heat transfer of copper microchannel heat sinks with different sizes and arrangements of channels and fins under various mass flow rates. Several kinds of typical diode laser arrays with different stripes and fill factors packaged on current and optimized microchannel heat sinks were compared in regards to thermal resistance and temperature distribution. And the difference between In- and AuSn-soldering packages was also illustrated. These results suggest that uniform junction temperature across the diode laser arrays can be realized with specific sizes and arrangements of the channels and fins for microchannel heat sinks.

10085-18, Session 5

Application specific beam profiles: New surface and thin-film refinement processes using beam shaping technologies *(Invited Paper)*

Dirk Hauschild, LIMO Lissotschenko Mikrooptik GmbH (Germany)

Today, the use of laser photons for materials processing is a key technology in nearly all industries. Most of the applications use circular beam shapes with Gaussian intensity distribution that is given by the resonator of the laser or by the power delivery via optical fibre. These beam shapes can be typically used for material removal with cutting or drilling and for selective removal of material layers with ablation processes. In addition to the removal of materials, it is possible to modify and improve the material properties in case the dose of laser photons and the resulting light-material interaction addresses a defined window of energy and dwell-time. These process windows have typically dwell-times between µs and s because of using sintering, melting, thermal diffusion or photon induced chemical and physical reaction mechanisms. Using beam shaping technologies the laser beam profiles can be adapted to the material properties and time-temperature and the space-temperature envelopes can be modified to enable selective annealing or crystallization of layers or surfaces. Especially the control of the process energy inside the beam and at it's edges opens a large area of laser applications that can be addressed only with an optimized spatial and angular beam profile with down to sub-percent intensity variation used in e.g. immersion lithography tools with ArF laser sources. LIMO will present examples for new beam shapes and related

material refinement processes even on large surfaces and give an overview about new mechanisms in laser material processing for current and coming industrial applications.

10085-19, Session 5

Optics for multimode lasers with elongated depth of field

Alexander V. Laskin, Vadim V. Laskin, AdlOptica Optical Systems GmbH (Germany); Aleksei B. Ostrun, ITMO Univ. (Russian Federation)

Modern multimode high-power lasers are widely used in industrial applications and control of their radiation, especially by focusing, is of great importance. Because of relatively low optical quality, characterized by high values of specifications Beam Parameter Product (BPP) or M?, there is narrow depth of field by focusing of multimode laser radiation. At the same time laser technologies like deep penetration welding, cutting of thick metal sheets get benefits from elongated depth of field in area of focal plane, therefore increasing of zone along optical axis with minimized spot size is important technical task. As a solution it is suggested to apply refractive optical systems splitting an initial laser beam into several beamlets, which are focused in different foci separated along optical axis. Radiation of multimode lasers, for example multimode fiber lasers or fiber-coupled lasers, is practically unpolarized, therefore it is possible to use polarization splitting of laser beam to beamlets and provide reliable control of energy portions in each separate focus, independently of beam size or mode structure. With the multi-focus optics, the length of zone of material processing along optical axis is defined rather by distances between separate foci, which are determined by optical design of the optics and can be chosen according to requirements of a particular laser technology. Due to stability of the distances between foci there is provided stability of a technology process. This paper describes some design features of refractive multi-focus optics, examples of real implementations and experimental results will be presented as well.

10085-21, Session 5

Stress-optic coefficients and temperature dependent refractive indices of potassium terbium fluoride

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Potassium terbium fluoride is a recently developed magneto-optic material which has been proposed for use as an optical isolator. We have performed measurements of the refractive index, thermo-optic coefficient, and stress-optic coefficient of this material. We present a temperature dependent Sellmeier equation along with calculations of temperature and refractive index profiles at various pump power levels in a diode pumped laser. The data are critical to the design of laser systems in which optical isolators are employed.

10085-22, Session 6

SRS modeling in high power CW fiber lasers for component optimization

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Stimulated Raman scattering (SRS) is one of the main limitations to output power of quasi-single-mode CW kilowatt fiber lasers made using standard double-clad fibers (typical cores diameters in the range of 10 to 30 microns). A. Liem, T. Schreiber et al. reported experimental evidence [http://dx.doi.org/10.1364/ASSL.2013.JTh2A.32, http://dx.doi.org/10.1117/12.2039869] that narrower output couplers (OC) FBGs produce more SRS in kW fiber oscillator than wider OCs. We will present a new fiber laser cavity numerical model that can explain this result. Using a commercial fiber laser simulation suite (RP Fiber Power), SRS is computed using the split-step Fourier method with delayed Raman response, which is applied iteratively for several cavity round trips (like by Turitsyn et al. in http://dx.doi.org/10.1364/OE.19.008394), alternating non-linear fiber propagation with ytterbium gain and spectral filtering by the FBGs mirrors. The longitudinally-resolved gain profile is evaluated after each round trip with a separate CW steady-state laser model, using as input the effective FBG reflectivity accounting for the non-linear spectral leakage. Within a few iterations, the model converges towards a complex waveform representative of CW laser output. The narrower the bandwidth of the OC, the longer the instantaneous peak power maxima last in the time domain, leading to more SRS. The model could also be extended to account for SRS generation in the fiber delivery pigtail. This is a powerful tool to design innovative high power fiber components minimizing SRS generation for a given core size. We will present experimental results and compare them to the model predictions.

10085-23, Session 6

Frequency-to-amplitude modulation in angular filtering based on volume Bragg gratings

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Issue of frequency-to-amplitude modulation (FM-to-AM) conversion is one of the key scientific problems in the development of high power lasers, especially in fusion laser drivers. In large aperture and high power lasers, the sinusoidal phase modulated pulses are used to avoid stimulated Brillouin scattering and to obtain spatially-averaged focal spot on the target. Propagation through optical components in the laser chains is not optimal and slightly filters the parts of the optical spectrum. Therefore, the frequency modulation (FM) is partly converted into the amplitude modulation (AM), and this AM will lead to higher-order nonlinear effects or even cause damages to optical elements due to instantaneous ultrahigh intensity in laser propagation process.

Volume Bragg gratings (VBGs) with programmable angular selectivity from 0.1mrad to 10mrad and high efficiency of 99 % is an effective filtering element to clean up the spatial modulations in laser beams. The FM-to-AM conversion is studied with a sinusoidal phase modulation laser pulse with the bandwidth of 0.30nm and 0.15nm, and is demonstrated with an YLF laser with the wavelength of 1053 nm and pulse width of 3ns. The experimental results show that FM to AM conversion level is increasing with the decrease of the spectrum selectivity bandwidth of the VBGs. At the VBG spectrum selectivity bandwidth of 7.9 nm, the FM to AM conversion level is reduced to about 6% for 0.3 nm and 3.5% for 0.15nm, which can be used in high power laser for controlling the beam spot on the target.

10085-24, Session 6

Complex holographic elements recorded in photo-thermo-refractive glass for the visible spectral region

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Volume Bragg gratings (VBGs) recorded in photo-thermo-refractive (PTR) glass are widely used for laser beam control in high power laser systems and fine spectral filtering in UV, visible and near IR spectral regions. Currently VBGs are fabricated in PTR glass by a two-step process where glass is first exposed to UV radiation and then undergoes thermal development. UV radiation is used for recording since the photosensitivity of the conventional PTR glass is limited to the UV region. This is why only planar VBGs that are trivial holograms could be used for UV/vis/IR applications while complex holographic elements could be used only for UV applications within the spectrum of photosensitivity of PTR glass. A new method is proposed where PTR glass is modified in order to record holograms using visible radiation, in particular 532 nm. This approach extends the range of the potential complex optical elements in PTR glass to the visible spectral region. We demonstrate holograms recorded by a superposition of collimated reference and complex object beams at 532 nm. Curved mirrors and lenses were recorded with this method. It was found that such holographic lenses and mirrors provide narrow spectral selectivity combined with high diffraction efficiency. This kind of complex holographic optical elements can replace several optical components providing concurrently imaging and spectral filtering.

10085-25, Session 6

High power laser source for atom cooling based on reliable telecoms technology with all fibre frequency stabilisation

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Cold atom interferometers are emerging as important tools for metrology. Designed into a gravimeter they can be used to measure extremely small changes in the local gravitational field strength and can be used for underground surveying to detect buried utilities, mineshafts and sinkholes prior to civil works. To create a cold atom interferometer narrow linewidth, frequency stabilised lasers are required to cool the atoms and to setup and measure the atom interferometer. These lasers are commonly either GaAs diodes, Ti Sapphire lasers or frequency doubled InGaAsP diodes and fibre lasers. The InGaAsP dfb lasers are attractive because they are very reliable, mass-produced, frequency controlled by injection current and simply amplified to high powers with fibre amplifiers. In this paper a laser system suitable for Rb atom cooling, based on a 1560nm dfb laser and erbium doped fibre amplifier, is described. The laser output is frequency doubled with fibre coupled periodically poled $LiNbO_3$ to a wavelength of 780nm. The output power exceeds 1 W at 780nm. The laser is stabilised at 1560nm against a fibre Bragg resonator that is passively temperature compensated. Frequency tuning over a range of 1 GHz is achieved by locking the laser to sidebands of the resonator that are generated by a phase modulator. This laser design is attractive for field deployable rugged systems because it uses all fibre coupled components with long term proven reliability.

10085-26, Session 6

A SMAT fiber laser for demanding industrial applications

Jianwu Ding, Xi Wei, Jinhui Liu, Yixian Zhou, Xiaocong Lu, Yi Hu, GW Laser Technology Co., Ltd. (China)

In this paper, we present our technical approach toward a more robust industrial fiber laser: instead of solely pushing the single module output power, the SMAT fiber laser integrates extensive sensors, various active failure prevention mechanisms, and the data gathering and the data mining capability to maximize the its reliability and user benefits.

The benefits of a SMAT fiber laser resulted from the unique system design which includes a few key components:

1. An extensive sensor network.

2. A multi-layered real-time protection and intelligent failure-prevention mechanism . Similar to most of the industrial lasers, the SMAT laser will initiate the shutdown protection in any fault event. However, after the fault-triggered shutdown, the SMAT will automatically inspect the integrity of the entire optical chain. If no fiber breakage detected, it could start the individual pump diode power testing to help the operator to identify the root cause of the shutdown and ensure no additional damage occurred during the fault-triggered shutdown. In addition, the SMAT fiber laser has completely integrated the optical chain integrity test: it will perform the integrity check whenever the laser is first powered.

3. A build-in automatic data logging and storage in the SMAT laser and a cloud server to store and analyze data gathered by each SMAT laser.

In conclusion, we present here a intelligent fiber laser system with an extensive sensor network and the automatic data gathering functionality not only for better reliability but also a critical component for Smart Manufacturing.

10085-40, Session 6

1.5kW linear polarized on PM fiber and 2.0kW on non-PM fiber narrow linewidth CW diffraction-limited fiber amplifiers

Nikolai Platonov, Roman Yagodkin, Joel De La Cruz, Alexander Yusim, Valentin P. Gapontsev, IPG Photonics Corp. (United States)

We report on a ruggedized compact modular package narrow linewidth fiber amplifiers with 1.5kW linear polarized output in an all-PM fiber configuration. We also report a 2.0kW non-PM fiber amplifier for various scientific and advanced applications. Both fiber amplifiers have 2m output cable for 15GHz linewidth for the all-PM fiber configuration and 20GHz linewidth on the non-PM fiber configuration. The fiber amplifiers have about 40% wall-plug efficiency and 15nm spectral bandwidth for 1064nm wavelength range. Measured M2 values are ≤ 1.1.

10085-27, Session 7

Environmentally stable seed source for high power ultrafast laser *(Invited Paper)*

Igor Samartsev, Andrey Bordenyuk, Valentin P. Gapontsev, IPG Photonics Corp. (United States)

We present an environmentally stable Yb ultrafast ring oscillator utilizing a new method of mode-locking. The laser is using all-fiber architecture which makes it insensitive to environmental factors, like temperature, humidity, vibrations, and shocks. The new method of mode-locking is utilizing crossed bandpass transmittance filters in ring architecture to discriminate CW lasing. Broadband pulse evolves from cavity noise under amplification after each filter causing strong spectral broadening. The laser is self-starting. It generates Transform limited spectrally flat pulses of 5 – 30 nm width at 6 – 15 MHz repetition rate and pulse energy 0.2 – 15 nJ at 1020 – 1035 nm CWL.

10085-28, Session 7

Novel ultrafast laser design based on intracavity chirped volume Bragg grating

Vadim Smirnov, Alexei L. Glebov, Ruslan Vasilyeu, Leonid

B. Glebov, OptiGrate Corp. (United States); Nikolay Vorobév, A. M. Prokhorov General Physics Institute of the Russian Academy of Sciences (Russian Federation)

Chirped Bragg Gratings (CBGs) in photo-thermo-refractive (PTR) glass allow stretching and compression of ultra-short pulses with high pulse energy and power and minimal beam distortions. PTR glass based CBGs can stretch pulses up to 1 ns while the duration of the recompressed pulses is nearly transform limited. Recent advances in the technology of CBGs in PTR glass enabled fabrication of chirped gratings with diffraction efficiencies exceeding 95% that allows their usage as intracavity elements. In this paper we discuss properties of Nd:Yag laser with CBGs used as output couplers.

10085-29, Session 7

Plug and play connector for high-power, high-energy, femtosecond single mode beam transportation

Claude Aguergaray, Emmanuel Chalumeau, Christophe Pierre, Michael Berisset, Johan Boullet, ALPhANOV (France)

One of key missing components that will enable high-average high-peak power femtosecond lasers to penetrate the industry is a reliable low loss, highly stable, plug and play, connector to couple the light into a large hollow-core single-mode fiber and carry it from lasers placed in a safe and controlled environment, where they can operate at the best performance level, to the target usually located in a much harsher environment. We have developed such a device while keeping in mind the ultimate goal of industrial application, thus maintaining reasonable cost. We have tested our connector with the NKT-DC-200/40-PZ-Si fibers and most importantly with KAGOME hollow core fibers. The connector comprises a simple, yet robust, fiber holding system and a passive light-stripper (no active water-cooling needed) to ensure that cladding light is guided away as quickly as possible. PM fibers can also be precisely aligned. We have demonstrated less than 3% fluctuations over several tens of hours of continuous operation, as well as 2.5% overnight fluctuation switching the laser OFF at night and ON again in the morning. Finally, several series of 50 consecutive plug IN-plug OUT tests have been carried out showing extremely good connection stability. These statistical results show that 94% of the connections have a coupling ratio within 3.5 % of the median. The connector has been designed to operate at 100W level. We have tested it so far with a 10ps, 30MHz, 50W laser and we aim at presenting at the conference results at full power.

10085-30, Session 7

Compact packaging of pulsed 1-micron and 1.55-micron fiber amplifiers

Daniel J. Creeden, Julia R. Limongelli, Jon Blanchard, Adam Marcinuk, Benjamin R. Johnson, Scott D. Setzler, BAE Systems (United States)

We have developed a packaged fiber amplifier configuration that allows for nearly two orders of magnitude of pulse width adjustment from 1ns to >800ns. This has been developed for both the 1-micron and 1.55-micron spectral regions. Our 1.55-micron fiber laser is packaged into a 6.63 x 8.65 x 3.47 in3 box, while our 1-micron fiber laser is packaged into a 13.68 x 8.68 x 3.56 in3 box, with the larger package a result of larger fiber components. These lasers offer a wide range of adjustable operating points, with total output ultimately limited by available pump power. For 1ns pulses, our 1.55-micron system generates up to 6?J of pulse energy (>6kW peak) with transform-limited spectral output. Higher energies and output powers are achievable (up to 33?J at 25kW peak), but the spectral output broadens slightly due to nonlinearities with <5ns pulse durations. For 1ns pulses at 1-micron, the system can generate 10uJ pulse energy (>10kW peak) with high spectral purity. At >10ns pulse durations, the same laser can generate up to 40?J pulse energy (pump limited). A unique aspect of our design is that a single fiber laser package can be electrically adjusted to produce the full range of pulse widths at repetition rates ranging from 100kHz to >1MHz with well-behaved output pulse shapes and no rising-edge pulse distortions typically seen in high gain amplifiers. In this paper, we discuss our laser architecture, performance, packaging layout, packaging limitations, and a path toward more compact designs using standard fiber components.

10085-31, Session 8

Design and evaluation of a diffractive beam splitter for dual-wavelength laser processing

Jun Amako, Toyo Univ. (Japan)

We report on a dual-wavelength diffractive beam splitter for use in parallel laser processing. This element made from a transparent material generates two beam arrays of different wavelengths and allows their overlap at the process points on a workpiece. To achieve dual-wavelength functionality, the splitter is provided with a deep surface-relief profile and its period is unequally divided into zones, each with a given height. The profile is iteratively optimized using a simulated annealing algorithm by perturbing the zone widths and the heights. Weighting parameters are applied to the cost function to control the performance contributions from the two wavelengths. We introduce a heuristic but practical scheme to determine the maximum height and the number of quantization levels, thereby increasing the likelihood of finding a solution by stochastic design. As an example, a 5-fan-out splitter was designed with 40 zones and 22 levels for 1064 and 532 nm, two versatile wavelengths in laser processing, and splitting efficiencies > 80% and splitting uniformities > 0.90 were obtained. Error analysis showed that the splitting performance is rather sensitive to profile errors and tolerances are ~1% of the splitter height. The designed splitter with a depth of 6.2 ?m and a period of 1.0 mm was fabricated from photoresist by maskless grayscale exposure using a high-pixel density digital micro-mirror device. We evaluated the optical properties of the splitter, validating the proposed beam-splitting concept. This achromatic beam splitter can achieve a high throughput with a simple optical configuration, and will ultimately yield the benefits of the dual-wavelength processing.

10085-32, Session 8

Band-stop angular filtering for laser beam with transmitting volume Bragg gratings in photothermorefractive glass

Xiao Yuan, Xiang Zhang, Fan Gao, Soochow Univ. (China)

The uniform near-field distribution and focusing characteristics of laser beam, which is related with the spatial frequencies in laser beams, are very important for high power laser applications, such as laser processing and laser fusion. The traditional pinhole filter can be used to improve the near-field uniformity, but may lead to the pinhole-closure and back-reflection. The angular filter based on transmitting volume Bragg gratings (TBGs) recorded in the photothermorefractive (PTR) glass could be used to improve the near-field beam quality. However, the incident beam must satisfy the Bragg condition and the optical axis of filtered beam is deflected, which makes the laser system very difficult to align. The band-stop angular filter with two TBGs may be a good method to solve the above problems.

In this paper, the band-stop angular filtering is performed and characterized. The band-stop angular filtering is demonstrated with a YLF laser with the wavelength of 1053 nm. The TBGs used in the experiment has the angular selectivity of 1.35mrad, the period of 1.97?m and the diffraction efficiencies of about 92%. Since part of the characteristic spatial frequencies was cleared out with the band-stop angular filter, there was an intensity drop on

the edge of the filtered beam. The optical axis for the incident and output beams keeps basically coaxial after filtering, which can be used as a plug-and-play device in the high-power laser systems. The characteristic spatial frequency of 1.98mm-1 corresponds to the TBG deviation angle of 1.35mrad, and the spatial frequencies around the characteristic frequency of 1.98mm-1 were reduced to 20% compared to that of the original beam. The desired bands in the laser beam can be filtered with different TBGs, which has potential applications in high power lasers.

10085-33, Session 8

Active alignment of DOE based structured light application in consumer electronics

Daniel Zontar, Tobias Müller, Sebastian Sauer, Christian Brecher, Fraunhofer-Institut für Produktionstechnologie IPT (Germany)

New applications with 3D sensing technologies are entering the market every day. Based on diffractive optical elements, structured light is a key factor to realize computer vision based sensing solutions. Tight quality requirements and fast ramp up times lead to new approaches during packaging. Active alignment can compensate uncertain tolerances during early stages of the product development, which eases prototyping and ramp up of production. Additionally, challenges of high volume markets, like consumer electronics, have to be addressed too. Low variance in cycle time with high throughput and reliability are necessary factors for production. In this paper we will present an active alignment solution for random dot pattern applications. Based on an industrial gantry and control system, a specialized part handling system has been designed. Built upon a customizable micromanipulator design, measurement and UV curing capabilities have been integrated additionally. The measurement system is consists of four cameras installed in a dome construction to collect projected light from the package during alignment. These images are processed by our alignment algorithm which derives suitable quality metrics which further can be transformed into movements of the micromanipulator. We will discuss general quality metrics and our approach to fuse the image data streams before examination. We will further present our algorithm design which directly connects to the industrial control environment. Finally the curing process is initiated by integrated UV illumination on the gripper. A shrinkage compensation strategy is necessary to preserve the obtained optimum beyond the bonding process.

10085-34, Session 8

Simultaneous position and angle control for outgoing laser beam design using two galvanometer mirrors

Tomohiko Hayakawa, Masatoshi Ishikawa, The Univ. of Tokyo (Japan)

The outgoing beam in the laser system is designed by considering two parameters: position and angle. Each of them is actively controlled by the positioning stage system and galvo system. Moreover, combining the two systems allows control of the two parameters that cause complexity of the system, deterioration of accuracy, and cost increase. Thus, in this study, we propose techniques that enable position and angle control simultaneously using two commercially available galvos. Two mirrors are set next to each other, and each standard angle is set at +45° and ?45° from the horizontal, and rotate in cooperation with each other. Mathematical calculations revealed that the outgoing beam angle from the system is defined by the angles of the two mirrors, and the one-dimensional position of the outgoing beam is defined by the angles of the two mirrors along with the distance between the rotational center of the two mirrors when the reflected light from the first mirror encounters with the second mirror. In addition, our proposed system has the following features. It is simple, inexpensive, and its accuracy is equivalent to that of the galvos. Finally, using a visible laser, two galvos, and a camera, we confirmed that the one-dimensional position and angle can be configured arbitrarily by our method. In future studies, this system can be applied in dynamic laser forming and three-dimensional printing systems to increase the degree of freedom of both the systems.

10085-35, Session 8

Beam shaping with numerically optimized photonic crystals

Darius Gailevicius, Vytautas Purlys, Martynas Peckus, Vilnius Univ. (Lithuania); Kestutis Staliunas, Univ. Politècnica de Catalunya (Spain); Roaldas Gadonas, Vilnius Univ. (Lithuania)

Photonic crystals (PhCs) fabricated in the bulk of dielectric media have already been demonstrated to show a low-pass spatial (angular) filter functionality. [1] These PhC filters are fabricated in inorganic glasses through a femtosecond laser writing process. The most promising aspect of such filters is their direct integration into the cavities of laser micro-resonators. In particular, the integration of such filters in microchip lasers as demonstrated recently [2], where the brightness of emitted radiation as well as its spatial quality was strongly increased. The maximum available level of improvement depends on the PhC angular range of filtering. Therefore it is very important to optimize the structure of the filtering PhC to obtain optimum filtering.

The linearly chirped PhC has been shown to increase the filtering efficiency [3], however the structure can be even more optimized. Here we show that the interior-point optimization algorithm [4] (combined with a heuristic model) can offer even better geometries while avoiding time-costly global optimization techniques. By taking the chirped solution as a seed, we arrive at optimized solutions for different PhC lengths. We demonstrate the feasibility of the solutions by fabricating optimized PhCs in Foturan photosensitive glass, further demonstrating and expanding the range of available applications for hybrid devices. The filters are formed with 2D alternating lattice configuration with transverse and longitudinal periods: 1.2 and minimum 4.8 um, for 633 nm operation wavelength. We show that for a low-pass (up to 34 mrad) configuration the filtering range can be improved multiple times.

[1] L. Maigyte and K. Staliunas, Spatial filtering with photonic crystals, Appl. Phys. Rev. 2, 011102 (2015)

[2] D. Gailevicius et al., Photonic Crystal Microchip Laser, submitted 2016,

https://dl.dropboxusercontent.com/u/80903325/MicrochipPhCLaser%20SciRep%20final.pdf

[3] V. Purlys et al., Spatial filtering by chirped photonic crystals, Phys. Rev. A 87, 033805 (2013)

[4] R.H. Byrd et al., An Interior Point Algorithm for Large-Scale Nonlinear Programming, SIAM Journal on Optimization 9(4), 877–900, 1999.

Conference 10086: High-Power Diode Laser Technology XV

Monday - Tuesday 30–31 January 2017

Part of Proceedings of SPIE Vol. 10086 High-Power Diode Laser Technology XV

10086-1, Session 1

600 W high brightness diode laser pumping source

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600 W high brightness diode laser pumping source

With continuous increase in output power of fiber lasers, small volume, low weight, high electro-optic efficiency and high brightness diode laser pump source has become the inevitable trend of development. Using spatial beam combination and polarization beam combination, BWT Beijing has achieved 650W output from a fiber with NA 0.22 and core diameter of 200?m. In order to improve the overall stability and compact size, 68 emitters with wavelength of 976nm are packaged in a module of size 180?150?70mm3. At 650W, coupling efficiency reaches 94%, and electro-optical efficiency is higher than 49%. Its brightness is slightly higher than that of 158W module from BWT commercially available.

To optimize the design, steady state propagation of electromagnetic wave in free space is simulated. With assumption of slowly varying field, ABCD matrix is used to describe the propagation and transformation of beams output from diode lasers. Combined with basic acceptance condition of fiber coupling and initial beam parameters of diode laser emitters, the acceptable set of key optical components that meets certain conditions can be numerically calculated.

10086-2, Session 1

Highly-efficient high-power pumps for fiber lasers

Valentin P. Gapontsev, Nikolay Moshegov, Ivan Berezin, Alexey Komissarov, Pavel A. Trubenko, Dmitri Miftakhutdinov, Igor Berishev, Vadim V. Chuyanov, Oleg Raisky, Alexander Ovtchinnikov, IPG Photonics Corp. (United States)

In addition to other inherent advantages Fiber Lasers have highest power efficiency compared to other types of industrial-grade kilo-Watt-class lasers. IPG Photonics has recently released ECO-series fiber lasers with wall plug efficiency higher than 50%.

We report on high efficiency multimode pumps that enable ECO-Fiber Lasers. We discuss on chip and packaged pump design and performance. Peak out-of-fiber power efficiency as high as 68% was achieved with passive cooling.

Some applications do not require ultimate power efficiency. For such application we have developed passively cooled pumps with out-of-fiber power efficiency greater than 50% maintained up to operating current of 22A. We report on approaches to design diode chip and packaged pump that possess such performance.

10086-3, Session 1

Advances in high brightness fiber-coupled laser modules for pumping multi-kilowatt CW fiber lasers

David M. Hemenway, Wolfram Urbanek, David C. Dawson, Zhigang Chen, Ling Bao, Manoj Kanskar, Mark DeVito, Dahv A. Kliner, Robert Martinsen, nLIGHT Corp. (United States)

We report on the continued progress by nLIGHT to deliver the highest brightness fiber laser pumps based upon single emitter technology at 915 nm. Our internal advances to the elementTM line have allowing us to scale the power into 105 µm – 0.15 NA fiber to 180W, which is a 25 W increase from our current industry leading 155 W, 105 µm e14. Our improvements are achieved by thoroughly re-optimizing the opto-mechanics to enable two rows of nine emitters which are polarization multiplexed, to be efficiently coupled into 105 µm fiber, with an excitation NA of 0.15 at the 95% power enclosure level. Most importantly, these are repeatable results obtained from 10 prototype packages. Lastly, we will show that we have not sacrificed package level reliability by accumulating over 8000 hours of lifetest without a failure due to the increased in irradiance on the proximal face of the fiber.

10086-4, Session 1

High-brightness and high-efficiency fiber-coupled module for fiber laser pump with advanced laser diode

Yohei Kasai, Fujikura Ltd. (Japan); Yuji Yamagata, OPTOENERGY Inc. (Japan); Yoshikazu Kaifuchi, Akira Sakamoto, Daiichiro Tanaka, Fujikura Ltd. (Japan)

We have developed a new module with 200 W output power and 58% power conversion efficiency by employing newly designed laser diodes and optical system. The developed module consists of the same wavelength laser diodes with only spatial multiplexing. Therefore the module has several advantages like no additional loss from polarization optics, low material cost and high efficiency at a fiber laser system by single-wavelength excitation.

The newly developed laser diodes are optimized in terms of efficiency by adjusting cavity-length and emitter-width. It is possible to increase power without degrading the efficiency by widening emitter width because thermal and electrical resistance decrease. But beam parameter products of horizontal direction become larger at higher operation current due to the thermal lens effect, and power coupling to the fiber core becomes difficult. We have simulated and optimized the design of beam parameter of horizontal direction of the laser diode and the fiber parameters that include core diameter and NA. We have also designed optics in the module to reduce the aberration. As a result, 200 W output power is achieved at 18 A current and 25 degrees heatsink, remaining the fiber cladding diameter to be conventional 125 um. Power conversion efficiency reaches 63% and keeps high even at higher current, 58% is achieved at 200 W output power at the 18 A operation current.

10086-5, Session 1

Advances in the power, brightness, weight and efficiency of fiber-coupled diode lasers for pumping and direct diode and direct diode applications

Steven G. Patterson, Tina Guiney, Joseph Braker, Dean Stapleton, Kim Alegria, David A. Irwin, Christopher Ebert, DILAS Diode Laser, Inc. (United States)

DILAS Diode Laser, Inc. continues to improve and optimize high-brightness fiber-laser pump modules for pumping and direct diode applications. Highlights include a 330W module in full production weighing in at 300 grams, achieving greater than 55% electrical-to-optical efficiency at the

operating power from a 225micron/0.22NA fiber and a power-scaled version capable of >600 W, >50% efficiency and weighing in at less than 400 grams. These modules, intended for military applications, will be used to highlight the underlying technology, which is applicable a broad range of commercial capability. In particular, the macro-channel coolers enabling these modules eliminate the need for micro-channels and de-ionized water and reduce pressure drop across the system. Pulsed life test data will presented. Optional VBG stabilization is available on all versions for applications requiring wavelength stability over a wide temperature range. A road map to modules with >900W of output power will also be presented, based on a double-sided version of the macro-channel cooler. Other modules such as DILAS' single-emitter architecture will be presented as well as a new, lightweight version of the commercially available 200 micron fiber unit that permits powers of 200W to from a 200micron/0.22NA fiber at 793nm.

10086-32, Session 1

Recent brightness improvements of 976 nm high power laser bars

Alexander Bachmann, Christian Lauer, Michael Furitsch, Harald König, Martin Müller, Uwe Strauss, OSRAM Opto Semiconductors GmbH (Germany)

Pump modules for fiber lasers and fiber-coupled direct diode laser systems require laser diodes with a high beam quality. While in fast axis direction diode lasers exhibit a nearly diffraction limited output beam, the maximum usable output power is usually limited by the slow axis divergence blooming at high power levels. Measures to improve the lateral beam quality are subject of extensive research. Among the many influencing factors are the chip temperature, thermal crosstalk between emitters, thermal lensing, lateral waveguiding and lateral mode structure.

We present results on the improvements of the lateral beam divergence and brightness of gain-guided mini-bars for emission at 976nm. For efficient fiber coupling into a 200 μm fiber with NA 0.22, the upper limit of the lateral beam parameter product is approximately 15 mm*mrad. Within the last years, the power level at this beam quality has been improved from 44 W to 52 W for the chips in production, enabling more cost efficient pump modules and laser systems.

Our work towards further improvements of the beam quality focuses on advanced chip designs featuring reduced thermal lensing and mode shaping. Recent R&D results will be presented, showing a further improvement of the beam quality by 15%. Also, results of a chip design with an improved lateral emitter design for highest brightness levels will be shown, yielding in a record high brightness saturation of 4.8 W/mm*mrad.

10086-6, Session 2

kW-class direct diode laser for sheet metal cutting based on commercial pump modules

Ulrich Witte, Frank Schneider, Fraunhofer-Institut für Lasertechnik (Germany); Carlo Holly, Chair for Laser Technology, RWTH Aachen University (Germany); Angelo Di Meo, David Rubel, Frederick Boergmann, Fraunhofer ILT (Germany); Martin Traub, Fraunhofer-Institut für Lasertechnik (Germany); Hans-Dieter Hoffmann, Fraunhofer ILT (Germany); Simon Drovs, Thomas Brand, Andreas Unger, DILAS Diodenlaser GmbH (Germany)

We present a direct diode laser with an optical output power of more than 800 W ex 100 μm with an NA of 0.17. Compared to other approaches, the laser system is completely based on cost efficient components. We use 6 commercial pump modules that are wavelength stabilized by use of VBGs with the individual center wavelengths of 936 nm, 940 nm, 944 nm, 972 nm, 976 nm and 980 nm. Based on commercial dielectric filters, an efficiency of 95% is demonstrated for dense wavelength multiplexing of the submodules around 940 nm. None the less, the optical to optical efficiency of this first laboratory set-up is limited to 65% and the electro-optical efficiency to 30% for maximum output power. In order to prove system performance and reliability, metal sheet cutting tests were performed. Stainless steel with thicknesses ranging from 0.8 mm to 4.2 mm was cut with a quality that corresponds to cutting with standard 1 μm fiber lasers. Based on a detailed analysis of loss mechanisms, we show that the design can be easily scaled to output powers in the range of 2 kW and to an optical efficiency of 45%.

10086-7, Session 2

Continued Improvement in reduced-mode (REM) diodes enable > 180 W from 105 μm 0.15 NA fiber-coupled modules

Manoj Kanskar, nLIGHT Corp. (United States)

There is an increasing demand for high-power, high-brightness diode lasers from 8xx nm to 9xx nm for applications such as fiber laser pumping, materials processing, solid-state laser pumping, and consumer electronics manufacturing. The kilowatt CW fiber laser pumping (915 nm - 976 nm), in particular, requires the diode lasers to have both high power and high brightness in order to achieve high-performance and reduced manufacturing costs. This paper presents continued progress in the development of high brightness fiber-coupled product platform, elementTM. The kilowatt CW fiber laser pumping (915 nm for industrial fiber lasers & 976 nm for directed energy fiber amplifiers) particularly requires the diode lasers to have both high power and high brightness in order to achieve high-performance. Recent improvements in fiber-coupled power has been enabled by significant advances in the slow-axis brightness of broad area lasers. We have demonstrated slow-axis brightness as high as 4.3 W/mm-mrd resulting from reducing the number of allowed modes in the slow-axis direction. This new generation of reduced-mode diodes (REM-diodes) have half the slow-axis divergence compared to regular BALs at the same operating powers. As a result, we have achieved >180 watts from a 2?9 elementTM in the 9xx nm spectral range out of a 105 μm/0.15 NA beam at 12A. We will present performance and reliability data on these devices. Further slow-axis brilliance improvement is underway and we will report the latest findings.

10086-8, Session 2

Development of a 300W 105/0.15 fiber pigtailed diode module for additive manufacturing applications

Hao Yu, Politecnico di Torino (Italy); Giammarco Rossi, Andrea Braglia, OPI Photonics (Italy); Guido Perrone, Politecnico di Torino (Italy)

Additive manufacturing (AM) from metal powders is emerging as the most important industrial fabrication revolution of the last decades because with this approach shape complexity does not imply additional costs and, moreover, the use of material is globally reduced compared to traditional technologies. Two trends are becoming evident for next generation of metal powder laser based AM machines: big machines equipped with kilowatt-range high-beam-quality lasers for large parts on the one side, and smaller but faster and cheaper machines for small part production, such as in personalized prosthetics, on the other side. Laser sources for these small/mid size AM machines must combine a power in the order of 200-400W and medium/high brightness with small size and low cost. Today, most of these machines use fiber lasers but the availability of small and compact direct diode laser modules would open new market possibility. Targeting this application, we have developed a direct diode multi-emitter module that is able to deliver 300W in a 105 um core - 0.15 NA fiber, with an occupation of just 94 cm2 and thus a best-in-class figure of 3.2 W/cm2 of footprint. The module is based on proprietary layout architecture and exploits polarization and wavelength multiplexing applied to the beam stacking of a plurality of single emitters to scale the power without degrading the beam quality. The paper describes the development steps of this module, discussing also some trade-off design alternatives, and then reports on its currently ongoing characterization.

10086-9, Session 2

Tailored bars at 976 nm for high-brightness fiber-coupled modules

Heiko Kissel, Paul Wolf, DILAS Diodenlaser GmbH (Germany); Alexander Bachmann, OSRAM Opto Semiconductors GmbH (Germany); Christian Lauer, OSRAM Opto SemiconductorsGmbH (Germany); Harald König, OSRAM Opto Semiconductors GmbH (Germany); Bernd Köhler, DILAS Diodenlaser GmbH (Germany); Uwe Strauss, OSRAM Opto Semiconductors GmbH (Germany); Jens Biesenbach, DILAS Diodenlaser GmbH (Germany)

Fiber lasers and fiber-coupled direct diode laser systems more and more replaces traditional tools in mechanical engineering, cutting, welding and brazing. The demand for high-power and high-brightness laser sources is further increased by new applications such as 3D printing. Many metals, plastics and other relevant materials in industrial production show absorption of light in the wavelength range around 1 µm.

In 2007, DILAS proposed the approach to tailor the output beam characteristics of laser diodes to an acceptable angle and diameter of a desired target fiber, thus drastically simplifying the coupling optics to basically only fast and slow axis collimation lenses. Over the last years, we developed and improved this tailored bar (T-Bar) concept together with the tooling for fully automated mass production of fiber-coupled T-Bar modules for pumping as well as for direct applications.

We present results on the improvement of T-Bars tailored for optimized coupling into fibers with a diameter of 200 µm with NA 0.22 corresponding to a beam parameter product of 22 mm·mrad. Cost efficient coupling to this fiber requires a tailored beam parameter product smaller than 15 mm·mrad in slow axis direction corresponding to a slow axis beam divergence of 7° (full angle, 95% power content). The improved T-Bars fulfil this requirement up to an output power of 52 W with an increased brightness of 3.5 W/mm·mrad (+73%) and a power conversion efficiency achieving 70% (+6%). This progress in the T-Bar performance together with modifications in the module design led to the increase of the reliable output power from 135 W in 2009 to 360 W in 2016 also giving a review of the main development steps and further R&D improvements.

10086-10, Session 3

kW-class diode laser bars

Stephan G. Strohmaier, Götz Erbert, Arne-Heike Meissner-Schenk, Matthias Lommel, TRUMPF Laser GmbH (Germany); Berthold Schmidt, TRUMPF Photonics (United States); Thorben Kaul, Matthias M. Karow, Leibniz Institut für Höchstfrequenztechnik (Germany); Paul A. Crump, Ferdinand-Braun-Institut, Leibniz Institut für Höchstfrequenztechnik (Germany)

Over the past years laser systems for industrial applications have moved their center of gravity from CO2 technology to diode-pumped solid state lasers. The access to continually improved brilliant, highly efficient, highly reliable semiconductor laser diodes is therefore of paramount importance to the whole laser industry.

Following this strategic motivation, TRUMPF has established its first advance development laboratory in Berlin, Adlershof with a focus on High Power Diode Lasers. The TRUMPF Berlin facility cooperates closely with the Ferdinand Braun Institute (FBH) and other local institutes to yield new diode technology platforms for our future laser systems.

A key research topic for the TRUMPF-FBH collaboration is the development of diode laser bars with significantly higher output power, conversion efficiency and brightness levels than currently commercially available. These developments will enable enhanced performance in TRUMPF disk laser, fiber laser and direct diode laser systems.

Progress in high performance diode laser bars will be presented, that exploit advanced InAlGaAs/GaAs-based epitaxial structures, novel waveguide and lateral designs, new materials and superior cooling architectures. In recent studies, a single 10 mm wide diode laser bar was shown to deliver 880 W of continuous wave output power at 850 A of electrical current, as presented in Figure 1. The bar has a resonator length of 4 mm and was operated at a cooling water temperature of 15°C. The mounted device is achieving an electro-optical efficiency in excess of 60% even at 880 W CW output power. Further test and performance progress will be presented in more detail.

10086-11, Session 3

Ultimate high power operation of 9xx-nm single emitter broad stripe laser diodes

Yoshikazu Kaifuchi, Fujikura Ltd. (Japan); Yuji Yamagata, OPTOENERGY Inc. (Japan); Ryozaburo Nogawa, Rintaro Morohashi, Fujikura Ltd. (Japan); Yumi Yamada, OPTOENERGY Inc. (Japan); Masayuki Yamaguchi, Fujikura Ltd. (Japan)

High power and high efficiency 9xx-nm wavelength single emitter laser diodes (LDs) are strongly required for fiber laser pumping and other industrial uses. In this work, design optimization of broad stripe laser diodes was experimentally studied to achieve ultimate high power operation. Laser structure is based on Self-Aligned-Stripe (SAS) grown by metal organic vapor phase epitaxy. Asymmetric Decoupled Confinement Heterostructure (ADCH) is adopted as for basic vertical layer structure.

Vertical layer design was tuned in terms of optical confinement and carrier transportation through the multi layers, resulting in lower threshold current and reduced operation voltage. Newly designed LD with 4mm cavity and 150um stripe width shows power conversion efficiency (PCE) improvement of more than 4% compared to conventional one. The peak value of PCE is 68% and high efficiency of more than 65% is maintained up to 17W output power. We compared high power operation characteristics for newly designed LDs with different stripe width (Ws) of 100?m to 220?m, where cavity length is fixed at 4mm. As widening stripe width, the maximum output power increases monotonically because of lowered electrical resistance. For the widest Ws of 220?m, the maximum output power reaches 33W, which is 50% improvement in comparison with Ws=100?m. PCE values are also remarkably improved in high power range, resulting in high efficiency operation of more than 60% PCE even at 27W output power.

10086-12, Session 3

Progress in joule-class diode laser bars and high brightness modules for application in long-pulse pumping of solid state amplifiers

Paul A. Crump, Matthias M. Karow, Steffen Knigge, André Maassdorf, Günther Tränkle, Ferdinand-Braun-Institut (Germany); Jens Lotz, Wilhelm Fassbender, Jörg Neukum, DILAS Diodenlaser GmbH (Germany); Jörg Körner, Ragnar Bödefeld, Joachim Hein, Lastronics GmbH (Germany)

Diode laser bars with the highest powers are required for advanced high-energy-class diode pumped solid state lasers. Increased diode laser performance enables new operation modes that require higher pump power densities, longer pulses and higher repetition rates. In addition, as power scales and price in €/W falls, the purchase price of diode-laser-based systems approaches that of flash-lamp-based systems, enabling their wider deployment. We present performance progress in diode laser bars, passively cooled diode laser stacks and resulting high brilliance pump modules, targeting long-pulse operation, as needed for pumping Yb:CaF2 crystals (2ms 10Hz). Bars with long resonators and high fill factors are used for low resistance and efficient cooling, with emitter width and period tailored for peak performance. Advanced epitaxial structures are used for high efficiency at high power close to wavelength of 940 nm and for efficient external wavelength stabilization for pumping of the zero phonon line close to 978 nm. Facet passivation is used for long life at high powers. Overall, operation at 1.2J per bar (600W 2ms 10Hz) is confirmed, with narrow lateral far field, high efficiency and narrow spectra shown to be maintained. Results are presented for passively-cooled single bar assemblies and monolithic stacked QCW arrays, both adapted for long resonators and high current operation. Stacks are integrated into highly brilliant pump modules, as needed for deployment in real systems.

Performance of bars, passively cooled stacks and high brilliance pump modules is summarized and prospects for further performance enhancements are reviewed.

10086-13, Session 3

High-power laser diodes with high polarization purity

Etai Rosenkrantz, Dan Yanson, Ophir Peleg, Moshe Blonder, Ilya Baskin, Noam Rappaport, Genady Klumel, SCD SemiConductor Devices (Israel)

Fiber-coupled multi-emitter laser diode modules rely on power scaling for fiber laser pumping. Beam multiplexing techniques such as geometrical, spectral, and polarization beam combining (PBC) are commonly used. For PBC, linear polarization with a high degree of purity is important, as any imperfectly polarized light leads to optical losses and heating inside the module. Furthermore, PBC is typically performed in a collimated portion of the beams, which cancels the angular dependence of the PBC element, e.g., beam-splitter.

We have developed TE-polarized high-power single emitters at 9xx nm that exhibit both reduced far-field divergence and high polarization purity. The laser diodes are shown to have a variable degree of polarization, which depends both on the operating current and far-field divergence. We present angle-resolved polarization measurements demonstrating correlation between the polarization purity and the ignition of high-order modes in the slow-axis emission of the emitter. It is demonstrated that the ultimate laser diode brightness includes not only the standard parameters such as power, emitting area and beam divergence, but also the degree of polarization (DoP), which is a strong function of the slow-axis beam quality.

Reduced slow-axis divergence, therefore, contributes not only to high spatial brightness, but also to high polarization beam combining efficiency.

10086-14, Session 3

Design and characterization of a novel power over fiber system integrating a high power diode laser

Mico Perales, Mei-huan Yang, ChengLiang Wu, MH GoPower Company Limited (Taiwan); Wei-sheng Chao, Kun-hsein Chen, Terry Zahuranec, MH GoPower Company Limited (Taiwan)

High power 9xx nm diode lasers along with MH GoPower's (MHGP's) flexible line of Photovoltaic Power Converters (PPCs) are spurring high power applications for power over fiber (PoF), including applications for powering high voltage IGBT gate drivers, remote sensors, converters used in RF over Fiber (RFoF) systems, and system power applications, including powering UAVs. In PoF, laser power is transmitted over fiber, and is converted to electricity by photovoltaic cells (packaged into Photovoltaic Power Converters, or PPCs) which efficiently convert the laser light. In this research, we design a high power PoF system, incorporating a high power 976 nm diode laser, a cabling system with fiber break detection, and a multi-channel PPC module. We then characterizes system features such as its ability to dynamically adjust laser power to maintain PPC electrical output stability, the PPC module's thermal response, fiber break detection system effectiveness, and the diode laser optical output stability. These results are utilized to identify system enhancements. We describe these design enhancements, and report the resulting performance improvements. The optimized PoF system will serve as a scalable model for those interested in researching, developing, or deploying a high power, voltage isolated, and optically driven power source for high reliability utility, communications, defense, and scientific applications.

10086-15, Session 4

Miniaturized laser amplifier modules for wavelength of 1180 nm with pm-fiber input and optical output power > 1W

Julian Hofmann, Daniel Jedrzejczyk, Alexander Sahm, David Feise, Frank Bugge, Katrin Paschke, Ferdinand-Braun-Institut (Germany)

High power laser emission > 1 W at a wavelength of 1180 nm is demanded for various applications in the biomedical field as well as for spectroscopy and LIDAR applications. Compact and efficient ridge-waveguide laser diodes are promising candidates for these applications featuring also a stable narrow band emission and a good beam quality [1]. But they lack of power. Therefore, we developed miniaturized laser amplifier modules with polarization maintaining (pm)-fiber inputs to boost the power of existing laser sources to over 1 W in a simple master oscillator power amplifier configuration (MOPA). The amplifiers are based on a vertical layer structure which shows a lifetime of more than 2000 h tested with broad area diode lasers.

The compact modules have a footprint of only 47 mm x 34 mm and a height of 13 mm. Within, the light injected by the pm-fiber is coupled into an amplifier chip. These chips have a 1 mm long ridge waveguide section at the entrance for spatial mode filtering followed by a tapered amplifier section which works as main amplifier. The tapered amplifiers need only a small seeding power in the range of 20 mW. The output of the module is free-space allowing easy access to the emitted beam. The inlet, on which laser and optics are mounted, is thermalized by a Peltier element.

At the conference we will present simulations of the optical system, mounting algorithms and results for a module emitting more than 1 W at a wavelength of 1180 nm.

[1] K. Paschke, F. Bugge, G. Blume, D. Feise, W. John, S. Knigge, M. Matalla, H. Wenzel, and G. Erbert, "Watt-level continuous-wave diode lasers at 1180 nm with InGaAs quantum wells" Proc. SPIE, vol. 8965, 896509 (2014).

10086-16, Session 4

Advances in 79x-nm fiber-coupled modules with application to Tm fiber laser pumping and DPAL

Steven G. Patterson, Tina Guiney, Dean Stapleton, Joseph Braker, Kim Alegria, David A. Irwin, Christopher Ebert, DILAS Diode Laser, Inc. (United States)

DILAS has leveraged its industry-leading work in manufacturing low SWaP fiber-coupled modules extending the wavelength range to 793nm for Tm fiber laser pumping. Ideal for medical, industrial and military applications, modules spanning from single emitter-based 9W to TBar-based 200W of 793nm pump power will be discussed. The highlight is a lightweight module capable of >200W of 793nm pump power out of a package weighing < 400 grams. In addition, other modules spanning from single emitter-based 9W to TBar-based 200W of 793nm pump power will be presented. In addition, advances in DPAL modules, emitting at the technologically important wavelengths near 766nm and 780nm, will be detailed. Highlights include a fully microprocessor controlled fiber-coupled module that produces greater than 400W from a 600 micron core fiber and a line width of only 56.3pm. The micro-processor permits the automated center wavelength and line width tuning of the output over a range of output powers while retaining excellent line center and line width stability over time.

10086-17, Session 4

Development of highly-efficient laser diodes emitting around 1060nm

Agnieszka Pietrzak, Ralf Huelsewede, Martin Zorn, JENOPTIK Diode Lab GmbH (Germany); Jens Meusel, JENOPTIK Laser GmbH (Germany); Juergen Sebastian, JENOPTIK Diode Lab GmbH (Germany)

An overview is presented on the recent progress in the development of high power laser bars and single emitters emitting at wavelengths around 1060 nm. The development is focused on high reliability, thermal stability and high efficiency of the laser devices. The benefits and limits of different laser designs for achieving the target performance are discussed.

10086-18, Session 4

1180 nm GaInNAs quantum well based high power DBR laser diodes

Jukka Viheriälä, Antti T. Aho, Heikki A. Virtanen, Mervi Koskinen, Mihail M. Dumitrescu, Mircea Guina, Tampere Univ. of Technology (Finland)

Many applications in spectroscopy and medicine require compact yellow-orange semiconductor lasers. This wavelength range is not accessible with compact directly emitting GaAs-based or GaN-based semiconductor lasers. Moreover, the frequency-doubling approaches suffer from the lack of high-power frequency-stable narrow-linewidth laser diodes emitting at 1170-1250nm because the highly strained GaInAs/GaAs quantum wells (QWs) for this wavelength range induce high defect densities, affecting the laser efficiency, linewidth and life-time.

Emission at 1180nm is achievable with dilute-nitride GaInNAs/GaAs QWs. A small amount of N, of about 1%, reduces the strain and improves carrier confinement, enabling high-power emission under high pumping. Better carrier confinement improves the temperature stability. The improved temperature stability benefits the miniaturization of frequency-doubled lasers and the development of photonic integration approaches, which are limited by thermal management issues. The ability of lasers to operate at elevated temperatures reduces the constraints of mounting them far from the frequency doubling crystals operating at elevated temperatures.

The fabricated 1180 nm ridge-waveguide distributed Bragg reflector (DBR) lasers achieved continuous-wave output powers ranging between 660 and 210 mW at ambient temperatures between 5 and 80 °C and 560 mW continuous-wave output power in uncooled operation at room temperature. Increased output power in room-temperature uncooled operation up to 2.75 W was achieved by tapering the ridge of the gain section. The lasers exhibit narrow-linewidth emission, good temperature stability and showed no degradation in 2000h lifetime tests performed in continuous-wave operation with 900 mA bias at room-temperature.

10086-19, Session 4

Low temperature green (In,Ga,Al)P-GaP diode lasers grown on high-index GaAs substrates

Nikolay Ledentsov, Vitaly A. Shchukin, VI Systems GmbH (Germany); Yuri M. Shernyakov, Marina Kulagina, Alexey S. Payusov, Nikita Y. Gordeev, Mikhail V. Maximov, Ioffe Institute (Russian Federation)

We report on low threshold current density (<400A/cm^2) green (<570?nm) injection lasing at reduced temperatures in (Al(x)Ga(1–x))0.5In0.5P–GaAs–based diodes. The epitaxial structures are grown on high–index (811)A GaAs substrates and contain monolayer–scale tensile–strained GaP insertions aimed at reflection of the injected nonequilibrium electrons preventing their escape from the active region. 50μm–wide stripe lasers with uncoated facets were fabricated. Thick waveguide concept results in a vertical beam divergence with a full width at half maximum of 15 degrees. The wavelength of 569nm is realized at 85K. In a different laser diode structure low threshold current density (100 A/cm^2) in the orange spectral range (598 nm) is realized at (–85) degrees C. At room temperature lasing at 628nm at threshold current density ~2kA/cm^2 and a total power above 3W is demonstrated. By changing the temperature and applying several laser diodes with particular compositions and the thicknesses of the active layers, wavelength tunable lasing in the green–yellow–orange–red spectral range can be realized within the same material system.

10086-20, Session 4

Broadened waveguide laser structures at 780 nm

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Two AlGaAs/GaAs broadened waveguide laser structures, one asymmetric, one nearly symmetric, were designed for high power at ~ 780 nm. The design concept is based on low losses and higher gain for the fundamental mode with higher losses and lower gain for higher-order modes. To achieve these results, the positions of the quantum wells, thicknesses of the cladding layers, doping profiles, and the compositions of all the layers are carefully chosen. The structures are designed to have a loss of about 0.5/cm for the TE0 mode and more than 5/cm for higher order modes for both structures. The asymmetric structure has a lower threshold current and a slope (~ 0.9 W/A) of the light-current curve, about double that of the symmetric structure. The reduced threshold current of the asymmetric structure is due in part to the higher quantum well confinement factor (1.47% compared to 0.935%). Increased L-I slope for the asymmetric structure results mainly from increased hole injection efficiency because the quantum wells are close to the p-side. Ridge-guide lasers with the asymmetric structure produced >

350 mW at 25°C. The beam divergence of the asymmetric structure was 14° x 6°. Further optimization of such structures using these design concepts should result in improved performance at power levels in excess of 500 mW.

10086-21, Session 4

High power fiber coupled diode lasers for display and lighting applications

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The performance of diode lasers in the visible spectral range has been continuously improved within the last few years, which was mainly driven by the goal to replace arc lamps in cinema or home projectors. Diode lasers as light sources enable higher brightness and higher efficiency applications than conventional xenon or LED based lighting concepts. They are therefore thought to be the next generation light sources in a variety of applications, including cinema projectors or car lights. In addition, the availability of high power diode lasers in the visible spectral region also enables new applications in the medical area, but also the usage as pump sources for other solid state lasers.

In this paper we report on latest results at different wavelengths, like 405 nm and 520 nm. Based on the same concept as described before, we realized a 10 W module at a wavelength of 405 nm coupled into a 200 µm NA 0.22 fiber. For applications, which require only moderate power below 5 W, we developed a very compact module with up to 3 emitters, which has a size of only 62x37x27 mm. With such a module we realized 2.4 W @ 405 nm and 3.5 W @ 450 nm, each coupled into a 200 µm NA 0.22 fiber. Based on the same platform we build a green module with 2.5 W @ 520 nm coupled into a 100 µm NA 0.22 fiber.

New developments also include the use of fiber coupled multi single emitter arrays at 450 nm with an output power of 60 W from a 200 µm NA 0.22 fiber.

10086-22, Session 5

Coherent beam combining architectures for high power tapered laser arrays

Guillaume Schimmel, Sylvie Janicot, Marc Hanna, Lab. Charles Fabry (France); Jonathan Decker, Paul A. Crump, Götz Erbert, Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik (Germany); Ulrich Witte, Martin Traub, Fraunhofer-Institut für Lasertechnik (Germany); Patrick Georges, Gaëlle Lucas-Leclin, Lab. Charles Fabry (France)

Coherent beam combining (CBC) aims at increasing the spatial brightness of lasers. It consists in maintaining a constant phase relationship between different emitters, in order to combine them constructively in one single beam. We have investigated the CBC of an array of five individually-addressable high-power tapered laser diodes at ? = 976 nm, in two architectures: the first one utilizes the self-organization of the lasers in an interferometric extended-cavity, which ensures their mutual coherence; the second one relies on the seeding of the emitters by a single-frequency laser diode (MOPA). In both cases, the coherent combining of the phase-locked beams is ensured on the front side of the array by a transmission diffractive grating with 98% efficiency.

The passive phase-locking of the laser bar is obtained up to 5 A (per emitter). An optimization algorithm is implemented to find the proper currents in the five ridge sections that ensured the maximum combined power on the front side. Under these conditions we achieve a maximum combined power of 7.5 W.

In the active MOPA configuration, we can increase the current in the tapered sections to 6 A for a combined power of 11.2 W, corresponding to a combining efficiency of 76%. Peak power is limited by the beam quality of the tapered emitters and by fast phase fluctuations between emitters. These results confirm the potential of CBC of tapered lasers for power scaling within a high-brightness beam. These results are comparable to the current state-of-the-art in CBC of laser diodes.

10086-23, Session 5

About the impact of the materials properties in the catastrophic degradation of high power GaAs based laser diodes

Jorge Souto, José Luis Pura, Alfredo Torres Perez, Juan Jimenéz, Univ. de Valladolid (Spain)

The catastrophic degradation of high power lasers depends on both external factors, associated with the technological processes followed to fabricate the laser, and also on intrinsic aspects related to the materials forming the laser structure, more specifically the active zone. The materials properties, optical, thermal and mechanical, play a paramount role in the degradation of the laser. The degradation is the consequence of the formation of dislocations and the subsequent propagation as a consequence of the thermal stresses induced by local hot spots in the active zone of the laser. The temperature distribution and the associated thermal stresses are determined by the thermal and mechanical properties of the laser structure. The propagation of the defects forming the dark line defects (DLDs) is driven by the optical absorption at the hot regions of the QW, which locally increases the temperature; the high thermal anisotropy of the structure results in temperature gradients responsible for the thermal stresses leading to dislocations generation once the yield strength of the laser structure is attained. We analyse here the impact of the optical (optical absorption), thermal (thermal conductivity) and mechanical (mechanical strength) properties of the laser structure on the catastrophic degradation, looking at the influence of the laser structure, the presence of defects, and the dimensionality of the different layers forming the active zone of the laser. A combination of cathodoluminescence observation of the defects and thermomechanical modelling taking account of the specific materials properties of the laser structure are used to analyse the laser degradation.

10086-24, Session 5

Unraveling the phase-amplitude coupling modulation in a delay-coupled diode lasers functionality

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Nonlinear dynamic coupling between phase and amplitude of the optical electric field is caused by carrier-induced variations in real and imaginary parts of refractive index in the laser cavity. Manipulation of phase-amplitude coupling factor (as represented by ?) is a major determinant of fundamental aspects of semiconductor lasers, including line-width, chirp under current modulation, mode stability, and dynamics in presence of optical feedback and injection. In the steady state, ? is constant, but varies in highly dynamical regimes or pulse operation where the variation in carrier density is quite large, ? has been recently shown to vary with optical feedback and optical injection. Nevertheless, so far understanding of the impact of optical injection induced modulation in ? remains poor. Here, we describe for the first time manipulating ? of a semiconductor laser with optical injection in the short cavity leading to frequency discretization and tuning by changing the injection, is demonstrated numerically for the first time. We numerically investigate the effect of phase-amplitude coupling modulation on power spectra in semiconductor lasers subject to optical injection. We observed the signature of frequency discretization and uncovered the physical mechanism for the existence of multistability.

10086-25, Session 5

Non-uniform DFB-surface-etched gratings for enhanced performance high power, high brightness broad area lasers

Jonathan Decker, Jörg Fricke, André Maassdorf, Götz Erbert, Ferdinand-Braun-Institut (Germany); Günther Tränkle, Leibniz Institut für Höchstfrequenztechnik (Germany); Paul A. Crump, Ferdinand-Braun-Institut (Germany)

Spectrally-stabilized high power, high brightness broad area diode laser are required for many applications, such as pumping narrow absorption bands in solid state and fiber lasers, or direct diode material processing systems (power-scaled via spectral beam combining). As external wavelength stabilization adds costs and complexity a monolithic approach is preferred. When surface-etched distributed feedback (DFB) gratings are used for monolithic stabilization of narrow-stripe broad area (NBA) lasers, with W=30 µm wide aperture, well-optimized devices are shown to deliver an output power of 5W with 50% conversion efficiency and a spectral linewidth < 1nm. Stabilization is achieved using a surface etched DFB-grating of 40th order, whose grooves are uniform, i.e. all etched with the same shape and depth. Surface-etched gratings introduce a high index contrast into the semiconductor, leading to scattering losses which increase rapidly as the grooves enter the vertical waveguide, limiting the slope efficiency, and thus the output power and efficiency. The resulting etch-depth process window for highly efficient, spectrally well-stabilized devices is small (<100nm) for uniform gratings. Therefore, novel non-uniform surface etched DFB-gratings have been developed, where the etching depth varies along the cavity length. Such a variation has the potential to reduce scattering losses at comparable etching depths and increase the process window. In this contribution we review progress in exploiting non-uniform grating designs for enhanced performance in DFB-NBA lasers and show that exemplary apodized grating configurations, with decreasing etching depth toward the front facet, enable enhanced spectrally stabilized output power (6W) at high conversion efficiency (50%).

10086-26, Session 5

Catastrophic optical bulk degradation (COBD) in high-power single- and multi-mode InGaAs-AlGaAs strained quantum well lasers

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High-power single-mode (SM) and multi-mode (MM) InGaAs-AlGaAs strained-quantum-well (QW) lasers with lasing wavelengths of 915 - 980 nm are critical components for terrestrial and space satellite communications systems. Since these applications require high reliability of these lasers, it is crucial to investigate reliability, failure modes, and underlying degradation mechanisms of these lasers aged under long-term life-tests. However, there have been limited reports on degradation mechanisms in high-power InGaAs-AlGaAs strained QW lasers. Our present study addresses this issue by performing long-term life-tests followed by failure mode analysis and physics of failure investigation using various nondestructive and destructive micro-analytical techniques.

We performed long-term accelerated life-tests on SM and MM InGaAs-AlGaAs strained QW lasers under ACC mode. Our life-tests have accumulated over 25,000 test hours for SM lasers and over 35,000 test hours for MM lasers. EBIC was employed to identify failure modes of SM lasers, whereas angle polishing and EL were employed to identify failure modes of MM lasers. All the SM and MM failures that we studied showed catastrophic and sudden degradation and all of these failures were bulk failures due to catastrophic optical bulk degradation (COBD). Since degradation mechanisms responsible for COBD are not well understood, we employed deep level transient spectroscopy and time-resolved photoluminescence techniques to study traps and non-radiative recombination centers in both pre- and post-aged lasers. Lastly, focused ion beam and high-resolution TEM were employed to prepare TEM specimen to study defects in post-aged SM and MM lasers. Our physics of failure investigation results will be presented.

10086-27, Session 5

Coherent beam combining within tilted wave laser diode emitters and arrays

Robert H. Dueck, Consultant (United States)

Tilted Wave Laser diode dmitters represent a novel, interesting, and promising approach to the design and construction of high power laser diodes. These devices, manufactured by VI Systems, are in general broad area devices. More importantly, they make use of an effective large vertical cavity that reduces the overall power density within the device delaying the onset of thermal rollover and COD effects. A challenge of the TWL approach is a dual-beam emission wherein each of the two beams is a single-mode beam in the vertical dimension. This paper addresses resent efforts to efficiently coherently beam combine these two beams into one single-mode beam having what is quite likely a world class combination of brightness, power, and conversion efficiency for a broad area diode array. The method of coherent beam combining explored herein utilizes a custom diffractive element and phasing is accomplished through a novel yet simple optical element positioning procedure. Encouragingly, results showed that the phase relationship between the two beams is maintained throughout a very wide range of power levels alleviating requirements to re-adjust the phasing as a function of output power. Combining efficiency was on the order of 80%, near the theoretical efficiency maximum for the diffractive element.

10086-28, Session 6

Individualized FAC on bottom tab subassemblies to minimize adhesive gap between emitter and optics

Sebastian Sauer, Tobias Müller, Andreas Beleke, Daniel Zontar, Sebastian Haag, Christoph Baum, Christian Brecher, Fraunhofer-Institut für Produktionstechnologie IPT (Germany)

High Power Diode Laser (HPDL) systems with short focal length fast-axis collimators (FAC) require submicron assembly precision. Conventional FAC-Lens assembly processes require adhesive gaps of 50 microns or more in order to compensate for component tolerances (e.g. deviation of back focal length) and previous assembly steps (bonding of chip on submount). In order to control volumetric shrinkage of fast-curing UV-adhesives shrinkage compensation is mandatory.

The novel approach described in this paper aims to minimize the impact of volumetric shrinkage due to the adhesive gap between HPDL edge emitters and FAC-Lens. Firstly, the FAC is actively aligned to the edge emitter without adhesives or bottom tab. The relative position and orientation of FAC to emitter are measured and stored. Consecutively, an individual subassembly of FAC and bottom tab is assembled on Fraunhofer IPT's mounting station with a precision of ±1 micron. Translational and lateral offsets can be compensated, so that a narrow and uniform glue gap for the consecutive bonding process of bottom tab to heatsink applies. Accordingly, FAC and bottom tab are mounted to the heatsink without major shrinkage compensation.

Fraunhofer IPT's department assembly of optical systems and automation has made several publications regarding active alignment of FAC lenses, volumetric shrinkage compensation and FAC on bottom tab assembly in

automated production environments. The approach described in this paper combines these and is the logical continuation of that work towards higher quality of HPDLs.

10086-29, Session PTue

Disruptive laser diode source for embedded LIDAR sensors

Andreas Kohl, Celine Canal, Arnaud Laugustin, Quantel Laser (France); Olivier Rabot, Quantel Laser (France)

Imaging based on laser illumination is present in various fields such as medicine, security, defense, civil engineering and automotive sector. In this last domain, laser scanners also known as LIDAR can assist driving by detecting objects in front of a vehicle. Based on time-of-flight measurements after emission of a near-infrared laser pulse, the profile of objects can be measured together with their location in various conditions, creating then a 3D mapping of the environment. To be embedded on a vehicle, these systems require compactness, low-cost and reliability. An attractive candidate for the laser source is certainly laser diodes as long as they can provide sufficiently short pulses at a high repetition rate and their electrical-to-optical efficiency is high enough to be compatible with portable systems.

A recent breakthrough in laser diode and diode driver technology made by Quantel (France) now allows laser emission higher than 2 mJ with pulses as short as 15 ns in a footprint of 4x5 cm2 (including the diode driver !!) and an electrical-to-optical conversion efficiency of the whole laser diode source higher than 30%. Emission in the range of 800-1000 nm is considered to be eye safe when taking into account the high divergence of the output beam so that these laser sources can be used for end consumer applications. An overview of the development and architecture of these laser sources will be given in which highly efficient diode bars and a dedicated pulse generator were integrated. Further work is on-going for miniaturization of the laser diode while shortening the pulse length and maintaining the output energy at a high level.

10086-30, Session PTue

Auto-locked laser systems for precision metrology

Hermina C. Beica, Adam Carew, Andrejs Vorozcovs, Patrick J. Dowling, Alexander Pouliot, Gurpreet Singh, A. Kumarakrishnan, York Univ. (Canada)

We describe a unique, low-cost, vacuum-sealed, auto-locked external cavity diode laser system that relies on components from original equipment manufacturers, specially machined parts, and powerful central processors. The laser cavity relies on an interchangeable optical base-plate consisting of a laser diode and optical elements which allow operation at desired wavelength ranges. The laser cavity design is based on optical feedback from a narrow-band interference filter to achieve a narrow laser linewidth. To suppress ambient pressure fluctuations and reduce sensitivity to temperature drifts, the laser cavity is rapidly thermally stabilized using Peltier coolers, and it can be evacuated within minutes and vacuum-sealed for months. The laser frequency can be scanned or locked to atomic and molecular spectral lines using a digital controller. The digital signal processor of the controller is capable of frequency stabilization using techniques such as pattern matching and first or third derivative feedback on the basis of a variety of algorithms stored in memory. We have operated our laser systems at 780 nm and 633 nm for spectroscopy in rubidium and iodine, respectively. The performance of the laser systems, which have a linewidth of ~1 MHz and lock stability of ~500 kHz, will be characterized using Allan deviation measurements. We also present precise measurements of gravitational acceleration g using a state-of-the-art industrial gravimeter (Scintrex FG5X) with an absolute accuracy of 1 ppb. The value of g measured with our laser systems was in agreement with a baseline established using an iodine-stabilized He-Ne laser, and revealed lower scatter.

10086-31, Session PTue

Effect of Al composition in confining layer on output characteristic of 808 nm laser diodes

Abhishek Sharma, Alok Jain, Pramod Kumar, Kamal Lohani, Solid State Physics Lab. (India)

GaAs/AlGaAs/InAlGaAs based edge emitting laser diodes, for high power applications, are studied in present paper for achieving low threshold current. Effect of change of Al composition in the confining layer on threshold current density and slope efficiency was studied using simulation software PICS3D. Al composition is varried from 17% to 45% in the confining layer of LOC waveguide structure emitting at 808 nm wavelength. Threshold current density increases rapidly if Al composition is decreased below 30%. For 30% Al composition threshold current density is 142.6A/cm2 and for 17% Al composition it increases to 323.2 A/cm2. On the other hand if we increase the Al composition above 30%, threshold current density increases after 35%, but relatively at a slow rate. For 45% Al composition threshold current density increases to 158.3 A/cm2.We have also studied the change in the slope efficiency for change in Al composition. Variation in slope efficiency is not that sharp as was in the case of threshold current density. Best slope efficiency of 1.11 W/A occurs at 25-30% Al composition. After 30% Al composition slope efficiency decreases slowly to 1.06 W/A for 45% Al composition. Slope efficiency also decreases slowly below 25%. It falls to 1.05W/A for 17% Al composition.

We have concluded that 30% of Al composition is best suited for achieving low threshold current and high slope efficiency. 30% Al composition in the confining layer provides enough barrier height for carrier confinement and it also reduces the electron leakage current to improve the laser diode performance of high power laser diodes.

10086-33, Session PTue

High power single lateral mode 1050 nm laser diode bar

Guoli Liu, Jingwei Li, Li Fan, Zuntu Xu, John M. Morales, David A. Schleuning, Bruno Acklin, Coherent, Inc. (United States)

We present recent progress of a 1050 nm laser bar operating with a single lateral mode. The device is based on an InGaAs/AlGaAs single quantum well and an asymmetric large optical cavity waveguide structure. By optimizing the AlGaAs composition, doping profiles, and QW thickness, low internal loss 0.5 cm-1 and high internal quantum efficiency 98% are obtained. A standard ridge waveguide (10% fill factor; 4mm cavity length) bar is made for performance testing giving 72% peak electro-optical efficiency and 1.0 W/A slope efficiency at 25°C. To obtain high single lateral mode power, the current confinement and optical loss profile in lateral direction are carefully designed and optimized to suppress higher order lateral modes. We demonstrate 1.5W single lateral mode power per emitter from a 19-emitter 10mm bar at 25°C. High electro-optical efficiency are also demonstrated at 25°C from two separate full-bar geometries on conduction cooled packaging: 20 W with >50% electro-optical efficiency from a 19-emitter bar and 50 W with >45% electro-optical efficiency from a 50-emitter bar.

Conference 10087: Vertical External Cavity Surface Emitting Lasers (VECSELs) VII

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Part of Proceedings of SPIE Vol. 10087 Vertical External Cavity Surface Emitting Lasers (VECSELs) VII

10087-1, Session 1

Development of next generation OPS laser products *(Invited Paper)*

Juan L. Chilla, Coherent, Inc. (United States)

Starting with the first commercially available solid state laser at 488 nm in 2001, we have translated the advantages of the OPS technology into products. These advantages include wavelength flexibility, broad pump tolerance, efficient spectral and spatial brightness conversion and high power scaling. Examples of the first generation of commercial lasers based on OPS technology are being used in a wide range of applications, including scientific, bio-instrumentation, medical, military and entertainment.

An active development program is required in order to compete favorably and displace alternative laser technologies in this broad array of markets. Our group is embarked in several programs to develop OPS technology in different directions, including: high power scaling; expansion of the spectral coverage; novel cavity designs and packaging techniques, etc.

Performance and capabilities of the technology are important but not the only requirements for a successful product. Over the last few years our efforts have been focused in making our lasers more suited to our customer's applications.

In this talk we will describe our recent progress in the direction of smaller and more efficient lasers to facilitate integration and adoption in different applications.

10087-2, Session 1

Schemes for efficient quantum-well pumping of AlGaInP disk lasers *(Invited Paper)*

Uwe Brauch, Cherry M. N. Mateo, Hermann Kahle, Roman Bek, Michael Jetter, Marwan Abdou Ahmed, Thomas Graf, Peter Michler, Univ. Stuttgart (Germany)

The keys to high-power operation of disk lasers are a thin active layer (low threshold), a small Stokes shift (low heat load) and an efficient cooling. This is best realized with a limited number of QWs, which are pumped close to their laser wavelength, and which are in close contact with one (intra-cavity) diamond heat sink or – even better – sandwiched in-between two diamonds. To get sufficient pump absorption many passes of the pump radiation are needed. Depending on the pump beam one can either take advantage of the resonance for the laser mode or implement a special resonance fitting for the pump conditions. Unfortunately, the semiconductor-cavity resonance is reduced by the intra-cavity heat-sink(s) and an external multi-pass optics (known from Yb disk lasers for the standard disk design and redesigned for the sandwiched disk) has to be used in addition. Designs of disk and pump optics – both for operation in reflection and transmission – and results for AlGaInP disk lasers will be discussed. Preliminary results include 1.5 W of output at 4 W of absorbed pump power and an absorption efficiency of 90 % with a standard 24-pass pump optics and a high-brightness 640-nm pump beam, 2.5 W of cw and 3.5 W of quasi-cw output when pumped with a low-brightness fiber-coupled diode-laser array through a standard 16-pass pump optics, and proof of principle of the laser operation of QW-pumped sandwiched membrane disk laser in a 24-pass transmissive pump optics.

10087-3, Session 1

Industrial integration of high coherence tunable single frequency semiconductor lasers based on VECSEL technology for scientific instrumentation in NIR and MIR *(Invited Paper)*

Vincent Lecocq, Innoptics SAS (France); Baptiste Chomet, Univ. Montpellier (France); Laurence Ferrières, Stéphane Denet, Innoptics SAS (France); Mikhaël Myara, Univ. Montpellier (France); Isabelle Sagnes, Grégoire Beaudoin, Lab. de Photonique et de Nanostructures (France); Arnaud Garnache, Laurent Cerutti, Univ. Montpellier (France)

Laser technology is finding applications in areas such as high resolution spectroscopy, radar-lidar, velocimetry, or atomic clock where highly coherent tunable high power light sources are required. Offering such performances in the Near- and Middle-IR range, GaAs- and Sb-based VECSEL technologies seem to be a well suited path to meet the required specifications of demanding applications. Here we report the realization of industry ready packaged single frequency VeCSEL devices emitting in the 0.8-1.1 µm and 2-2.5 µm spectral range with performances that do not exist on the market today; they combine high power (>200mW) with a low divergence diffraction limited TEM00 beam (<2°FWHM, M?<1.2), low intensity fluctuations (< 0.2% rms), low phase fluctuations (< 1MHz rms 1ms IT) and continuous wavelength tunability over 400GHz with a total covered spectral range over 3THz. In addition, the compact design without any movable intracavity elements offers a robust single frequency regime with a long term wavelength stability better than few GHz/h. Thanks to this combination of power-coherence-wavelength tunability performances and compactness, those devices surpass the state of the art commercial technologies. Moreover, a dedicated control electronics was implemented to improve overall stability, and the integration of a flat photonics technology (meta material, sub-? metallic mask...) will allow, in a near future, the realization of compact VeCSEL devices emitting new coherent light states such as VORTEX or two frequency lasers for applications to optical tweezers or THz emission, for instance.

10087-4, Session 1

GaSb-based VECSEL for high-power applications and Ho-pumping *(Invited Paper)*

Joachim Wagner, Peter Holl, Marcel Rattunde, Steffen Adler, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany); Karsten Scholle, Peter Fuhrberg, LISA Laser Products OHG (Germany); Elke Diwo-Emmer, Rolf Aidam, Wolfgang Bronner, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany)

The (AlGaIn)(AsSb) materials system has been shown to be ideally suited to realize VECSEL for the 2-3 µm wavelength range [1,2]. Using barrier pumping with standard commercial 1470 nm diode lasers, cw output powers of 17 W @ 20°C heatsink temperature have been achieved for 2.0 µm emitting GaSb-based VECSEL with ternary GaInSb quantum well active region. The corresponding slope efficiency is 32% @ 20°C. Here recent advances in this laser technology will be reviewed with special emphasis on chip design and mounting technology.

In order to convert the high cw-power of the VECSEL into pulses with a high peak power, we have investigated concepts for a VECSEL-pumped q-switched Ho:YAG laser. We will discuss different variants of this hybrid semiconductor / solid state laser combination, including the lasing characteristics of the VECSEL in the case of intra-cavity pumping. Up to 3.3 mJ of pulse energy were achieved with a compact setup (corresponding to a peak power of 30 kW at 110 ns pulse length) combined with stable pulsing behaviour. This high-peak power hybrid laser system is ideally suited for medical surgery as well as free-space LIDAR for e.g. wind mapping.

References

[1] O. Ochotnikov, Ed., “Semiconductor Disk Laser”, Wiley-VCH, 2010

[2] P. Holl et al, IEEE J Sel Top Quantum Electron. 21 (6), (2015).

10087-5, Session 2

Non-equilibrium effects in VECSELs *(Invited Paper)*

Jörg Hader, Isak Klien, Jerome V. Moloney, The Univ. of Arizona (United States); Stephan W. Koch, Philipps-Univ. Marburg (Germany)

Recent experimental progress in mode locking Vertical External Cavity Surface Emitting Laser’s (VECSEL’s) has pushed the intracavity pulse width close to 100fs, which is on the order of the intraband scattering time in the Quantum Well’s (QWs). In these situations the interband polarizations cannot be adiabatically eliminated and a quantitative microscopic model for the non-equilibrium carrier and polarization dynamics is required. In our model Maxwell’s equations propagate the light field while the Semiconductor Bloch equations are solved to determine the interaction of the light field with the optically active QWs.

The higher order correlation effects such as polarization dephasing and carrier dynamics due to electron-electron and electron-phonon scattering are treated using the second Born-Markov approximation.

We present recent results on modeling non-equilibrium effects in semiconductor and graphene saturable absorbers. Here, the dependence of the saturation fluence on pulse lengths and spectral frequency are analyzed. The fully self-consistent model is usede to study mode locking and multiple wavelength continuous wave operation in VECSELs. To achieve mode locking, thousands of cavity round trips are required. In order to make these calculations numerically feasible, effective rates are systematically extracted from the full second Born-Markov calculations. Shortcomings of simplified models are discussed.

10087-6, Session 2

Characterisation of nonlinear lensing and ultrafast carrier dynamics in SDL gain structures *(Invited Paper)*

Keith G. Wilcox, Adrian H. Quarterman, Conor J. C. P. Smyth, Shamil Mirkhanov, Univ. of Dundee (United Kingdom)

We report on recent developments in the characterisation of non-linear lensing in semiconductor disk laser gain samples. We find that there is a significant nonlinear lens present and the magnitude and sign of this depend on the conditions under which it is being observed. Under experimental conditions which are, to date, the closest to intra-cavity conditions, with 350 fs pulses at the same wavelength a mode-locked SDL using that gain chip would operate at we find that the lens is always negative and its magnitude is almost independent of pump intensity. We also report on the experimental observation of different mode-locking regimes in SDLs including dual wavelength mode-locking and pulse molecule formation and compare these experimentally observed modes of operation with predictions from microscopic modelling previously reported in by Kilen et. al. [1]

[1] I. Kilen et. al. Optica, 1 (4) 192-197 (2014)

10087-7, Session 2

Optical efficiency and gain dynamics of semiconductor disk lasers *(Invited Paper)*

Cesare G. E. Alfieri, Dominik Waldburger, Sandro M. Link, Matthias Golling, Ursula Keller, ETH Zürich (Switzerland)

Ultrafast optically pumped semiconductor disk lasers (SDLs) provide an enabling combination of gigahertz pulse repetition rates, short pulse durations, high peak power and good beam quality. However, the successful demonstration of shorter pulse durations with pulses as short as 100 fs has come at the expense of lower optical-to-optical pump efficiency for ultrafast SDLs based on active InGaAs quantum wells (QWs). The optical pump efficiency, which also depends on the pulse repetition rate, decreases with the pulse duration to values typically below 1% in the sub-300-fs regime. For a better understanding of this trade-off between shorter pulse durations and optical efficiency we present an empirical model based on three time constants: the carrier lifetime in the conduction band, the time required for a pulse to empty the carrier reservoir of a QW and the time needed to refill the QW through the continuously pumped GaAs barriers. With the time constants used as fitting parameters we obtain a reasonably good agreement for the measured efficiency of all previously published MIXSEL results. Furthermore we have investigated the SDLs gain dynamics and our measurements have confirmed that shorter pulses significantly reduce the gain saturation fluence. A simplified description of the QWs as a 3-level system could accurately reproduce the gain saturation curves and let us identify spectral hole burning as the main cause of the reduced gain and efficiency. This will be a challenge for further improvements of the ultrafast performance of ultrafast SDLs based on InGaAs QWs.

10087-8, Session 2

Characterization of optically pumped semiconductor lasers in pulsed mode as a function of temperature

Yanbo Bai, Jeffrey Wisdom, Patrick Hyland, Christian Scholz, Juan L. Chilla, Coherent, Inc. (United States)

The OPS chip is pumped by a fiber coupled diode laser bar with direct modulation of the current driver. The duty cycle is 1% and the pulse width is a few hundreds of nanoseconds. Time dependent thermal simulation indicates that the temperature rise of the active region is less than 5 degrees at the maximum pump power of 50W. Average output power of the pump laser and the OPS are measured with a high sensitivity thermal pile. Assisted by the knowledge of the pulse shape measured with a fast Si detector, the peak power is obtained from the average power. The same measurement is repeated when the heatsink temperature is changed from 25 up to 200 degrees. The result of this work is temperature dependent threshold power and slope efficiency in the limit of negligible self-heating, which reveals intrinsic chip characteristics independent of thermal packaging. The threshold power decreases then increases as a function of temperature showing a minimum, which is related to the detuning between the material gain the cavity resonance for optimal performance at elevated internal temperatures in cw mode. The slope efficiency monotonically decreases as a function of temperature, which reveals the existence of thermally activated loss channels in OPS operation.

10087-9, Session 3

Highly coherent modeless broadband VECSEL *(Invited Paper)*

Mikhaël Myara, Univ. Montpellier (France); Mohamed Sellahi, Institut National de Recherche en Sciences et Technologies Pour l’Environnment et l’Agriculture (France);

Grégoire Beaudoin, Isabelle Sagnes, Lab. de Photonique et de Nanostructures (France); Arnaud Garnache, Institut d'Electronique du Sud, Univ. Montpellier (France)

We report on the highly coherent modeless broadband continuous wave operation of a semiconductor vertical-externalcavity-surface-emitting laser. The laser design is based on a frequency-shifted-feedback scheme provided by an acoustooptic frequency shifter inserted in a linear or a ring travelingwave cavity. The aim of such a design is to eliminate the traditionnal spectral resnonances occuring in usual laser cavities by chirping the optical wave inside the cavity, in order to reach a wideband (> 100 GHz) continuous spectrum. The light emitted benefits obviously of the high coherence properties of VeCSELs concerning the transverse mode and the polarisation state, but it is also coherent in the time domain in spite of its wideband emission. This specific coherence property can be studied like with any laser, by investigating the homodyne signal obtained by injecting this light through an unbalanced two-arms interferometer : the result is a beating which spectral width is the image of the coherence.

The modeless laser designed is based on a GaAs multiple quantum well structure providing large gain at 1.07?m. This laser exhibits a coherent optical spectrum over 330GHz, with 70mW output power and a high beam quality. The light polarization is linear (> 30dB extinction ratio). The laser dynamics exhibits a low intensity noise close to class A regime, with a ?1.5MHz cutoff frequency. The homodyne interferometric beating leads to a ?54kHz wide spectrum, corresponding to a coherence time of ?19?s, as long as the one of a DFB single-frequency laser with 1MHz linewidth.

10087-10, Session 3

Multi-angle VECSEL cavities for dispersion control and multi-color operation *(Invited Paper)*

Caleb Baker, Maik Scheller, Alexandre Laurain, Hwang-Jye Yang, R. Jason Jones, Jerome V. Moloney, The Univ. of Arizona (United States); Antje Ruiz Perez, Wolfgang Stolz, Philipps-Univ. Marburg (Germany); Sadhvikas J. Addamane, Ganesh Balakrishnan, The Univ. of New Mexico (United States)

We present a novel Vertical External Cavity Surface Emission Laser (VECSEL) cavity design which makes use of multiple interactions with the gain region under different angles in a single round trip. Typical Resonant, Periodic Gain (RPG) structures possess high gain and can generate up to 100W of CW power, however, due to their design, they possess unfavorable Group Delay Dispersion (GDD) profiles for femtosecond pulse generation with pronounced dispersion resonances within their gain bandwidths. These resonances shift with increasing angle of incidence onto the gain structure.

We utilize this GDD shift by constructing a cavity possessing multiple gain interactions under two significantly different fold angles, which we ensure have similar mode sizes and overlap the pump spot. This design allows for optimization of the net, round-trip GDD while still maintaining the high gain of resonant structures. The effectiveness of this scheme is demonstrated with sub-500 femtosecond pulses at near 400MHz repetition and Watt-level of average power, yielding record peak intensities for the VECSEL class of gain media.

In further investigations, we find that in CW operation, the intracavity standing wave resulting from the overlap of the multiple cavity arms on the gain produces an interference pattern that yields spatial hole burning ideal for multi-color operation. A highly stable two-color VECSEL is shown and a comparison is made to the stability of multi-wavelength emission in more traditional cavity designs.

10087-11, Session 3

Low-noise III-V metasurface based semiconductor vortex laser and rotational Doppler velocimetry *(Invited Paper)*

Mohamed Seghilani, Baptiste Chomet, Mikhaël Myara, Mohamed Sellahi, Institut d'Electronique du Sud, Univ. Montpellier (France); Luc Legratiet, Isabelle Sagnes, Grégoire Beaudoin, Lab. de Photonique et de Nanostructures (France); Philippe Lalanne, Lab. Photonique, Numérique et Nanosciences (France) and Univ. Bordeaux 1 (France); Arnaud Garnache, Institut d'Electronique du Sud, Univ. Montpellier (France)

The generation of a coherent state, supporting a large photon number, with controlled orbital-angular-momentum L=l h/2? (of charge l per photon) presents both fundamental and technological challenges: we demonstrate a surface-emitting laser, based on III-V semiconductor technology with an integrated metasurface, generating vortex-like coherent state in the Laguerre-Gauss basis. We use a first order phase perturbation to introduce a weak orbital anisotropy, based on a dielectric metasurface and non-linear laser dynamics, allowing selecting vortex handedness. This coherent photonic device was characterized and studied, experimentally and theoretically. It exhibits a low divergence diffraction limited beam, emitting 50mW output power in the near-IR, a charge l=± 1,... ± 4, and single frequency operation in a stable low noise regime. Moreover, similarly to linear Doppler Shift, light carrying orbital angular momentum L, scattered by a rotating object at angular velocity ?, experiences a rotational Doppler shift ?·L. We show that this fundamental light–matter interaction can be detected exploiting self-mixing in a vortex laser under Doppler-shifted optical feedback, with quantum noise-limited light detection. This will allow us to combine a velocity sensor with optical tweezers for micro-manipulation applications, with high performances, simplicity and compactness. Such high performance laser opens the path to widespread new photonic applications.

10087-12, Session 4

Commercial mode-locked vertical external cavity surface emitting lasers

Walter Lubeigt, Bartlomiej Bialkowski, Jipeng Lin, Christopher R. Head, Nils Hempler, Gareth T. Maker, Graeme P. A. Malcolm, M Squared Lasers Ltd. (United Kingdom)

In recent years, M Squared Lasers have successfully commercialized a range of mode-locked vertical external cavity surface emitting lasers (VECSELs) operating between 920-1050nm and producing ps-range pulses with average powers >1W and pulse repetition frequencies (PRF) of ~200MHz. These laser products offer a low-cost, easy-to-use and maintenance-free tool for the growing market of nonlinear microscopy. In particular, the relatively low PRF operation of Dragonfly lasers represents a challenging requirement for modelocked VECSELs due to the very short (few ns) lifetime of electron in GaAs at low injection level. As a result, the energy storage in a VECSEL is seriously limited leading to double pulsing behavior in longer cavities as the time between consecutive pulses is increased.

In the last year, efforts have been directed to reduce the pulse duration to <200fs while keeping the average power (>1W) and PRF (200MHz) in order to present a credible alternative to ultrafast Ti:Sapphire lasers. This paper will describe and discuss the latest efforts undertaken to avoid double pulsing and approach these targets in a laser system operating at 990nm. Most notably, the design of Dragonfly laser cavity was considerably modified and a nonlinear pulse compression stage using a single-mode, polarisation-maintaining optical fibre was added to the system. This resulted in pulses as short as 190fs with average powers approaching 600mW at

990nm. Additional investigations with a VECSEL operating at 1045nm will also be discussed.

10087-13, Session 4

High power sub-200fs pulse generation from a colliding pulse modelocked VECSEL *(Invited Paper)*

Alexandre Laurain, The Univ. of Arizona (United States); Declan Marah, Univ. College Cork (Ireland); Robert Rockmore, The Univ. of Arizona (United States); John G. McInerney, Univ. College Cork (Ireland); Jörg Hader, The Univ. of Arizona (United States); Antje Ruiz Perez, Stephan W. Koch, Wolfgang Stolz, Philipps-Univ. Marburg (Germany); Jerome V. Moloney, The Univ. of Arizona (United States)

High power semiconductor laser producing short pulses at high repetition rates are interesting for numerous applications, such as such as multi-photon imaging, high-resolution time domain terahertz spectroscopy, self-referenced gigahertz frequency combs, or ultrafast communication systems. The peak power achievable by a modelocked VECSEL is often limited by the stability of the modelocked regime. At high pumping level, non-stationary or harmonic modelocking emerges, reducing the peak power of the pulses. In this letter we present a passive and robust mode-locking scheme for a Vertical External Cavity Surface Emitting Laser. We placed the semiconductor gain medium and the semiconductor saturable absorber mirror strategically in a ring cavity to provide a stable colliding pulse operation. With this cavity geometry, the two counter propagating pulses synchronize on the SESAM, saturating the absorber together, which minimizes the energy lost and creates a transient carrier grating due to the interference of the two beams. The interaction of the two counter-propagating pulses is shown to extend the range of the modelocking regime and to enable higher output power when compared to the conventional VECSEL cavity geometry. In this configuration, we demonstrate a pulse duration of 195fs with an average power of 225mW per output beam at a repetition rate of 2.2GHz, giving a peak power of 460W per beam, establishing a new state-of-the-art in term of pulse duration and peak power combination. The remarkable robustness of the modelocking regime will be discussed and a rigorous pulse characterization will be presented.

10087-14, Session 4

High-power 100-fs SESAM-modelocked VESCEL *(Invited Paper)*

Dominik Waldburger, Sandro M. Link, Cesare G. E. Alfieri, Matthias Golling, Ursula Keller, ETH Zürich (Switzerland)

Ultrafast vertical external-cavity surface-emitting lasers (VECSELs) are versatile laser sources and feature high-power operation. To date the best modelocking results have been achieved with a semiconductor saturable absorber mirror (SESAM). Ultrafast optically pumped semiconductor disk lasers (SDLs) are compact, cost-efficient and provide excellent beam quality at gigahertz pulse repetition rates for applications such as for example multi-photon imaging, ultrafast communication and in particular self-referenced gigahertz frequency combs. The highest peak power obtained with an ultrafast VECSEL is 4.35 kW in 400-fs pulses and the shortest pulses until now are 107 fs at 3 mW average output power.

Here we present a SESAM-modelocked VECSEL with pulses as short as 96 fs and 100 mW average output power. These are to the best of our knowledge the shortest pulses achieved by a fundamentally modelocked SDL and result in a very high peak power of 0.56 kW at a pulse repetition rate of 1.63 GHz. The short pulse duration was achieved by introducing a small amount of positive group delay dispersion with a single path through an external 2-mm thick ZnSe window plate that compensated the initially negatively chirped 107-fs output pulses.

Currently the power is limited by the transition from fundamental modelocking to multi-pulse operation, which reduces the pulse peak power and introduces additional noise. Therefore, we present a study of the multi-pulse behavior of the high-power 100-fs SDL resulting from the complex modelocking mechanism. This study also provides an insight into special issues of pulse characterization that may suggest stable fundamental modelocking even if this is not the case.

10087-15, Session 5

Growth, processing, and characterisation of ZnCdMgSe multi-quantum well vertical gain structures *(Invited Paper)*

Brynmor E. Jones, Peter J. Schlosser, Univ. of Strathclyde (United Kingdom) and Fraunhofer Ctr. for Applied Photonics (United Kingdom); Joel De Jesus, Thor A. Garcia, Maria C. Tamargo, The City College of New York (United States); Jennifer E. Hastie, Univ. of Strathclyde (United Kingdom)

II-VI selenide quantum wells, lattice-matched to InP substrates, offer optical gain from the blue to the red; however, the development of electrically-pumped II-VI visible semiconductor lasers has been hindered by the significant defects associated with p-type doping this material. Optically-pumped vertically-emitting lasers on the other hand offer a much more flexible format and need not have a monolithic distributed Bragg reflector (DBR). With the advent of high power GaN laser diodes, such as those we have previously used to pump AlGaInP-based semiconductor disk lasers (SDLs), there is an opportunity to develop optically-pumped ZnCdMgSe-based SDLs for fundamental operation throughout the visible. Here we present the design, growth, processing and characterisation of ZnCdMgSe multi-quantum well gain structures, transferred to single crystal diamond windows following substrate removal.

10087-16, Session 5

High-power 625 nm VECSEL prototype

Jussi-Pekka Penttinen, Tomi Leinonen, Antti Rantamäki, Ville-Markus Korpijärvi, Emmi L. Kantola, Iiro Leino, Mircea Guina, Tampere Univ. of Technology (Finland)

We report a frequency doubled OP-VECSEL prototype emitting several watts of continuous-wave light at 625 nm. Such lasers could be used, for example, in infinite focus laser projection or in laser shows. The key features for these applications are the high luminosity of the 625 nm short red wavelength combined with the low divergence VECSEL beam. After additional frequency doubling step from red to 313 nm and wavelength control, single-frequency operation could be used in beryllium ion trapping experiments, potentially replacing many of the complicated laser systems currently in use.

Fundamental emission at 1250 nm was obtained using a dilute nitride (GaInNAs) gain mirror grown by plasma-assisted molecular beam epitaxy. The gain mirror was pumped with an 808 nm diode. The cavity containing a nonlinear crystal for frequency-doubling was sealed in a compact air-cooled prototype casing that had connectors for an external pump source and a user interface. At the time of writing, we have validated stable 4 W continuous-wave output power in free-space, with a low diverging circular beam.

10087-17, Session 5

Advances in 750 nm VECSELs *(Invited Paper)*

Esa J. Saarinen, Sanna Ranta, Jari Lyytikäinen, Antti Saarela, Tampere Univ. of Technology (Finland); Alexei Sirbu, Vladimir Iakovlev, RTI-Research SA (Switzerland); Eli Kapon, Ecole Polytechnique Fédérale de Lausanne (Switzerland); Mircea Guina, Tampere Univ. of Technology (Finland)

Lasers operating in the transmission window of tissue at wavelengths between 700 and 800 nm are needed in numerous medical and biomedical applications, including photodynamic therapy and fluorescence microscopy. However, the performance of diode lasers in this spectral range is limited by the lack of appropriate compound semiconductors. Here, we review our recent research on 750 nm VECSELs. Two approaches to reaching the 750 nm wavelength will be discussed. The first approach relies on intra-cavity frequency doubling a wafer-fused 1500 nm VECSEL. The VECSEL gain chip comprises a GaAs-based DBR and an InP-based gain section, which allows for optical pumping with low-cost commercial diodes at 980 nm. With this scheme we have achieved watt-level output powers and tuning of the laser wavelength over a 40 nm band at around 750 nm. The second approach is direct emission at 750 nm using the AlGaAs/GaAs material system. In this approach visible wavelengths are required for optical pumping. However, the consequent higher costs compared to pumping at 980 nm are mitigated by the more compact laser setup and prospects of doubling the frequency to the ultraviolet range.

10087-18, Session 6

The optically pumped semiconductor membrane external-cavity surface-emitting laser (MECSEL): A concept based on a diamond-sandwiched active region *(Invited Paper)*

Hermann Kahle, Institut für Halbleiteroptik und Funktionelle Grenzflächen, Univ. Stuttgart (Germany); Cherry M. N. Mateo, Uwe Brauch, Institut für Strahlwerkzeuge, Univ. Stuttgart (Germany); Philipp Tatar-Mathes, Roman Bek, Michael Jetter, Institut für Halbleiteroptik und Funktionelle, Univ. Stuttgart (Germany); Thomas Graf, Institut für Strahlwerkzeuge, Univ. Stuttgart (Germany); Peter Michler, Institut für Halbleiteroptik und Funktionelle, Univ. Stuttgart (Germany)

Semiconductor disk lasers (SDLs) became an important stand-alone class of solid-state lasers due to their wide range of applications in biophotonics, television or projectors, spectroscopy and lithography. SDLs, also called vertical-external-cavity surface-emitting lasers (VECSELs), deliver near diffraction limited beam quality, continuous-wave operation, a flexible external resonator, are also power scalable in a certain range and have been realized with various material systems. However, these systems suffer from heat incorporation into the active region caused by the excess energy of the pump photons together with the low thermal conductivity of the substrate and the included distributed Bragg reflector. To overcome these limitations we realized a novel concept, the semiconductor membrane external cavity surface-emitting laser (MECSEL) where the active region is sandwiched between two diamond-heatspreaders. The barrier pumped AlGaInP-based laser showed an unreached performance of more than 0.5 W output power at a wavelength of around 660 nm at an elevated heatsink temperature of 10°C. Furthermore, a wide tuning range of ~24 nm was measured at a heatsink temperature of 3°C. These results indicate the enormous potential to revolutionize the semiconductor based disk lasers regarding available output powers at room temperature and material combinations. A detailed characterization as well as latest results of this new laser concept will be presented.

10087-19, Session 6

Development of optically pumped DBR-free semiconductor disk lasers *(Invited Paper)*

Zhou Yang, Alexander R. Albrecht, The Univ. of New Mexico (United States); Jeffrey G. Cederberg, MIT Lincoln Lab. (United States); Mansoor Sheik-Bahae, The Univ. of New Mexico (United States)

Semiconductor disk lasers (SDLs) are attractive for applications requiring good beam quality, wavelength versatility, and high output powers. Typical SDLs utilize the active mirror geometry, where a semiconductor DBR is integrated with the active region by growth or post-growth bonding. This imposes restrictions for the SDL design, like material system choice, thermal management, and effective gain bandwidth. In DBR-free geometry, these restrictions can be alleviated. An integrated gain model predicts DBR-free geometry with twice the gain bandwidth of typical SDLs, which has been experimentally verified with active regions near 1 μm and 1.15 μm. The lift-off and bonding technique enables the integration of semiconductor active regions with arbitrary high quality substrates, allowing novel monolithic geometries. Bonding an active region onto a straight side of a commercial fused silica right angle prism, and attaching a high reflectivity mirror onto the hypotenuse side, with quasi CW pumping at 780 nm, lasing operation was achieved at 1037 nm with 0.2 mW average power at 1.6 mW average pump power. Laser dynamics show that thermal lens generation in the active region bottlenecks the laser efficiency. Investigations on total internal reflection based monolithic ring cavities are ongoing. These geometries would allow the intracavity integration of 2D materials or other passive absorbers, which could be relevant for stable mode locking. Unlike typical monolithic microchip SDLs, with the evanescent wave coupling technique, these monolithic geometries allow variable coupling efficiency.

10087-20, Session 6

The development and fundamental analysis of type-II VECSELs at 1.2 μm *(Invited Paper)*

Christoph Möller, Christian Fuchs, Christian Berger, Fan Zhang, Arash Rahimi-Iman, Martin Koch, Philipps-Univ. Marburg (Germany); Antje Ruiz Perez, NAsP III/V GmbH (Germany); Stephan W. Koch, Philipps-Univ. Marburg (Germany); Jörg Hader, Jerome V. Moloney, Nonlinear Control Strategies, Inc. (United States); Wolfgang Stolz, Philipps-Univ. Marburg (Germany) and NAsP III/V GmbH (Germany)

Since the invention of VECSELs, vast spectral coverage has been demonstrated with emission wavelengths in the range from the UV to almost the MIR. Accordingly, a great variety of different quantum well and quantum dot gain designs have been applied so far to achieve such versatility. A novel gain design for GaAs based VECSELs emitting at wavelengths >1.2 μm employs type-II quantum wells, which exhibit spatially indirect charge-carrier recombination. The first VECSEL based on such a design has been demonstrated very recently.

Our device consists of ten (GaIn)As/Ga(AsSb)/(GaIn)As heterostructures arranged as a resonant periodic gain. We summarize the development of this pioneering structure and discuss the fundamental laser characteristics,

such as carrier densities, gain temperatures and slope efficiency. Remarkable output powers up to 4 W are demonstrated in multi-transverse mode operation at 1.2 µm. Also, the performance in TEM00 operation is investigated, with an M? < 1.13.

One major difference to conventional type-I gain structures is a characteristic blue shift of the material gain. Due to the importance of the detuning in quantum well based surface-emitters, the blue shift has to be considered as a critical designing parameter. Hence, we carry out a detuning study in order to determine an optimal detuning. As an important part of the optimization, the experimental results are compared with fully microscopic simulations.

10087-21, Session 7

Various phenomena of self-mode-locked operation in optically pumped semiconductor lasers *(Invited Paper)*

Chia-Han Tsou, National Chiao Tung Univ. (Taiwan); Hsing-Chih Liang, National Taiwan Ocean Univ. (Taiwan); Kai-Feng Huang, Yung-Fu Chen, National Chiao Tung Univ. (Taiwan)

This work presents several optical experiments to investigate the phenomenon of self mode locking (SML) in optically pumped semiconductor lasers (OPSLs) with a linear cavity. The SML operation means that no additional active or passive mode-locking elements are used in the laser cavity except for the gain medium. First of all, we experimentally find that the occurrence of SML can be assisted by the existence of the first high-order transverse mode. On the other hand, the continuous SML cannot be observed in the absence of high-order transverse modes. Numerical analysis is performed to confirm that the critical pump power for obtaining the SML operation agree very well with the pump threshold for exciting the fundamental transverse mode. Moreover, we quantitatively investigate the influence of multiple high-order transverse modes on the temporal state. A physical aperture is inserted into the cavity to manipulate the excitation of high-order transverse modes. While more high-order transverse modes are excited, it is experimentally found that the pulse train is modulated by more beating frequencies of transverse modes. In addition to typical mode-locked pulses, we originally observe that under the influence of the reflection feedback, the phase locking between lasing longitudinal modes can be assisted to form bright-dark pulse pairs in the scale of round-trip time. A theoretical model based on the multiple reflections in a phase-locked multi-longitudinal-mode laser is developed to confirm the formation of bright-dark pulse pairs.

10087-22, Session 7

Towards self-mode locking of AlGaInP-VECSELs

Roman Bek, Quynh Duong-Ederer, Univ. Stuttgart (Germany); Max Vaupel, Philipps-Univ. Marburg (Germany); Hermann Kahle, Thomas Schwarzbäck, Univ. Stuttgart (Germany); Arash Rahimi-Iman, Philipps-Univ. Marburg (Germany); Michael Jetter, Univ. Stuttgart (Germany); Martin Koch, Philipps-Univ. Marburg (Germany); Peter Michler, Univ. Stuttgart (Germany)

Since 2000, semiconductor saturable absorber mirrors (SESAMs) have been used to realize mode locking of vertical external-cavity surface-emitting lasers (VECSELs), achieving femtosecond pulse durations, GHZ repetition rates and several Watts of average output power. Despite these excellent results, SESAMs which have to be carefully adjusted to the gain structure can be a limiting factor for the development of a cost-effective pulsed laser system. In recent years, a new concept of VECSEL mode locking, the self-mode locking technique, has been demonstrated. While the mechanism behind this kind of mode locking is not yet fully explained, most publications focus on the effect of Kerr lensing.

We present first experiments on SESAM-free mode locking of red-emitting AlGaInP-VECSELs with different cavity geometries based on the assumption of Kerr lensing in the active region. Our semiconductor samples are grown by metal-organic vapor-phase epitaxy with an active region containing GaInP quantum wells embedded in AlGaInP barriers and cladding layers. In order to exploit the effect of Kerr lensing, a slit is placed inside the cavity acting as a hard aperture. When the beam width is confined, pulsed operation is observed by oscilloscope and autocorrelation measurements. Ongoing research is focusing on a detailed characterization of the pulsed laser to improve one's understanding of the obtained SESAM-free mode-locked operation.

10087-23, Session 7

Mode-locked VECSEL SESAM with intracavity antenna for terahertz emission

Theo Chen Sverre, Andrew P. Turnbull, Paul C. Gow, Elena Mavrona, Christopher R. Head, Anne C. Tropper, Vasilis Apostolopoulos, Univ. of Southampton (United Kingdom)

THz time domain spectroscopy (TDS) allows the rapid detection and identification of large organic molecules, such as pharmaceutical or explosive compounds; however THz-TDS systems use bulky femtosecond lasers and long mechanical delay lines, and thus lack of portability restricts their application. Here we describe an approach that may allow the footprint of such a system to be drastically reduced. We report the characterisation of a VECSEL Semiconductor Saturable Absorber Mirror (SESAM) structure with a gold strip-line antenna fabricated on its surface. The SESAM/antenna was used to mode-lock a 1035-nm optically-pumped VECSEL, with the cavity mode focussed to a 90-micron spot within the 1 mm antenna gap. Pulses of 250-fs duration were generated, and a bias of up to 150 V could be applied to the strip-line with little effect on the mode-locking. When the SESAM/antenna was used as the emitter in a standard TDS system, irradiated at 1035 nm with spot size and pulse energy comparable to those found in the mode-locked VECSEL cavity, it was observed to generate a THz signal through the SESAM DBR and substrate. Generation of high-power narrow-band THz radiation intracavity-pumped by a dual-frequency cw VECSEL was previously reported by Scheller M. [Opt Exp (2010)]. In this paper we shall describe progress towards an ultra-compact TDS system with broad-band THz pulses intracavity-pumped by a mode-locked VECSEL. The VECSEL provides both the THz pulse train and the synchronised infrared pulse train used for heterodyne detection.

10087-24, Session 7

Stabilized dual-comb MIXSEL *(Invited Paper)*

Sandro M. Link, Dominik Waldburger, Cesare G. E. Alfieri, Matthias Golling, Ursula Keller, ETH Zürich (Switzerland)

Stabilized dual-comb semiconductor disk laser (SDLs) are very promising compact and cost-efficient sources for applications relying on two optical frequency combs such as dual-comb spectroscopy or asynchronous optical sampling. By placing a birefringent crystal inside the laser cavity two gigahertz modelocked beams with a difference in pulse repetition frequency of 4.25 MHz are simultaneously emitted at a center-wavelength of 968 nm. The optically pumped SDL is a modelocked integrated external-cavity surface emitting laser (MIXSEL), which combines the saturable absorber of a semiconductor saturable absorber mirror (SESAM) and the gain structure of a vertical external-cavity surface emitting laser (VECSEL) in a single semiconductor structure and therefore allows for modelocking in a simple straight linear cavity. We present the full stabilization of the microwave frequency comb that results from the optical interference of the two

modelocked beams, and hence represents a direct link between the optical terahertz spectrum and the electronically accessible microwave regime. The microwave spectrum is directly stabilized by two feedback loops without the need for any f-to-2f interferometry. We measure the absolute stability of the optical modes with a mode-spacing of 1.82 GHz (5.7 pm) by beating the optical spectrum of the dual-comb MIXSEL with a single frequency laser, resulting in a standard deviation of less than 800 kHz (2.5 fm) over 1 s and less than 5 MHz (15 fm) over 40 s in stabilized operation. Furthermore, we use a high-finesse etalon as a sample under test for a first proof-of-principle spectroscopy demonstration with our stabilized dual-comb MIXSEL.

10087-25, Session PTue

Numerical study of VECSELs for generation of mid-infrared radiation

Adam K. Sokol, Lodz Univ. of Technology (Poland); Lukasz Piskorski, Lodz University of Technology (Poland); Robert P. Sarzala, Lodz Univ. of Technology (Poland)

In spite of intense efforts of many research centers, efficient and compact devices emitting high-power radiation with high-quality output beams and operating in the mid-infrared range (3-5 ?m) have not yet been demonstrated. This spectral range is important for many applications, such as: free-space optical communication, biomedical diagnostic, laser spectroscopy, thermovision, environment monitoring or gas sensing. Currently available mid-infrared sources suffer from various disadvantages, for example: large size, low output power, low quality of output beams or need of cryogenic cooling, and their performance may not be satisfactory from the point of view of the potential customer. Vertical-external-cavity surface-emitting lasers (VECSELs) seem to be an interesting alternative for these sources since they enable generation of high-power radiation with high-quality output beams at room temperature and are relatively compact. Two different approaches for developing VECSELs for generation of mid-infrared (3-5 ?m) radiation are studied in the paper with the aid of numerical modeling. The first of them consists in enhancing a wavelength of currently available GaSb-based structures beyond 3 ?m. The second approach consists in using a dual-wavelength VECSEL, emitting two coaxial beams of different wavelengths, to generate 3-5 ?m radiation with the aid of a difference frequency generation technique.

10087-26, Session PTue

Improved gain chip holder design for high efficient, high power AlGaInP-VECSEL

Philipp Tatar-Mathes, Institut für Halbleiteroptik und Funktionelle Grenzflächen, Univ. Stuttgart (Germany); Hermann Kahle, Institut für Halbleiteroptik und Funktionelle, Univ. Stuttgart (Germany); Cherry M. N. Mateo, Uwe Brauch, Institut für Strahlwerkzeuge, Univ. Stuttgart (Germany); Roman Bek, Michael Jetter, Institut für Halbleiteroptik und Funktionelle, Univ. Stuttgart (Germany); Thomas Graf, Institut für Strahlwerkzeuge, Univ. Stuttgart (Germany); Peter Michler, Institut für Halbleiteroptik und Funktionelle, Univ. Stuttgart (Germany)

Semiconductor disk lasers with their flexible resonator geometry and the superior beam properties are realized in various material systems as an important stand-alone class of laser devices.

However, in the red spectral range with AlGaInP-materials as active region of a VECSEL, the quantum defect resulting from the energy difference between pump photons and emitted laser photons causes heat incorporation. The low thermal conductivity of the substrate with the included distributed Bragg reflector leads to a strong temperature-dependent performance due to the limited charge-carrier confinement. Therefore, a good bonding between VECSEL-Chip and intra-cavity heat spreader is indispensable. Here, a newly designed sample-holding device for VECSEL-Chips is presented which improves the laser performance tremendously.

With this device, the VECSEL has a slope efficiency of approx. 23% with a maximum output power of about 1.1 W emitting at 665 nm. All the measurements were taken at a heatsink temperature of 10°C. We present a full characterization of the laser system including a comparison between standard and the new device.

Conference 10088: Nonlinear Frequency Generation and Conversion: Materials and Devices XVI

Monday - Wednesday 30–1 February 2017

Part of Proceedings of SPIE Vol. 10088 Nonlinear Frequency Generation and Conversion: Materials and Devices XVI

10088-1, Session 1

1.9 W yellow, CW, high-brightness light from a high efficiency semiconductor laser-based system

Anders K. Hansen, Mathias Christensen, Technical Univ. of Denmark (Denmark); Danny Noordegraaf, Norlase ApS (Denmark); Peter Heist, Evangelos Papastathopoulos, Valentin Loyo-Maldonado, JENOPTIK Laser GmbH (Germany); Ole B. Jensen, Technical Univ. of Denmark (Denmark); Michelle L. Stock, Norlase (Denmark); Peter M. W. Skovgaard, Norlase ApS (Denmark)

Semiconductor lasers are ideal sources for efficient electrical-to-optical power conversion and for many applications where their small size and potential for low cost are required to meet market demands. Yellow lasers find use in a variety of bio-related applications, such as photocoagulation, imaging, flow cytometry, and cancer treatment. However, direct generation of yellow light from semiconductors with sufficient beam quality and power has so far eluded researchers. Meanwhile, tapered semiconductor lasers at near-infrared wavelengths have recently become able to provide near-diffraction-limited, single frequency operation with output powers up to 8 W near 1120 nm.

We present a 1.9 W single frequency laser system at 562 nm, based on single pass cascaded frequency doubling of such a tapered laser diode. The laser diode is a monolithic device consisting of two sections: a ridge waveguide with a distributed Bragg reflector, and a tapered amplifier. Using single-pass cascaded frequency doubling in two periodically poled lithium niobate crystals, 1.93 W of diffraction-limited light at 562 nm is generated from 5.8 W continuous-wave infrared light. When turned on from cold, the laser system reaches full power in just 60 seconds. An advantage of using a single pass configuration, rather than an external cavity configuration, is increased stability towards external perturbations. For example, stability to fluctuating case temperature over a 30 K temperature span has been demonstrated. The combination of high stability, compactness and watt-level power range means this technology is of great interest for a wide range of biological and biomedical applications.

10088-2, Session 1

3.5 W of diffraction-limited green light at 515 nm from SHG of a single-frequency tapered diode laser

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Multi-Watt efficient compact green laser sources are required for a number of applications e.g. within biophotonics, laser pumping and laser displays. The low power of single-mode diode lasers directly emitting in the green spectral region (about 100 mW) points to nonlinear frequency conversion of infrared diode lasers as the most promising approach.

We present the generation of 3.5 W green light at 515 nm from SHG of a newly developed tapered diode laser, itself yielding more than 9 W at 1030 nm. SHG is performed in single pass through two cascaded nonlinear crystals with re-focusing and dispersion compensating optics between the two nonlinear crystals. Such a SHG cascade can generate more power than the sum of the second harmonic power generated in the individual crystals. The 515 nm light is diffraction limited and single-frequency. Using feedback from a photodiode the output power is stabilized to better than ±0.4%. All optical components are mounted on a baseplate and enclosed in a box measuring 183 x 114 x 50 mm3.

Such a laser source could be an ideal replacement of inefficient Argon-ion lasers at 515 nm in many applications relying on this exact wavelength. Furthermore, the laser has great potential for applications within biophotonics and as a pump source for Ti:sapphire lasers. Examples of such applications will be presented.

10088-3, Session 1

149.8 nm, the shortest wavelength generated by phase matching in nonlinear crystals

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Narrow band light sources in the vacuum ultraviolet (VUV) region are attractive for photo lithography and high resolution photoelectron spectroscopy. Phase matching is essential to generate high power VUV lights by using a narrow band, low peak intensity, nanosecond (ns) pump source. In this research, sum frequency mixing has been demonstrated below 150 nm in KBeBO3F2 by using the fundamental (?) with its fourth harmonic (4?) of a 6 kHz Ti:sapphire laser system. The laser system we have developed in this research, consists of a Ti:sapphire laser system and a frequency conversion stage. We generated 149.8-nm radiation, which is the shortest wavelength ever obtained to our knowledge by phase matching in nonlinear crystals. The 5? output powers were 3.6 ?W at 149.8 nm and 110 ?W at 154.0 nm, respectively. The phase matching angles measured from 149.8 to 158.1 nm are larger by 3-4 degrees than those expected from the existing Sellmeier equation. The optical transmission spectra of some KBBF crystals were measured by the spectrophotometer. The transmittance near the absorption edge support the generation of coherent radiation below 150 nm. The improvement of a prism-coupled device contributed to the generation of coherent radiation below 150 nm. Another reason for the present break through to the shorter wavelength is the use of the short pulse driving source compared with our previous research.

10088-4, Session 1

Compact, integrable, and long life time Raman multiline UV-Vis source based on hypocycloid core Kagome HC-PCF

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Raman-gas filled HC-PCF has proved to be an outstanding Raman-convertor, as illustrated by the generation of more than 5 octaves wide Raman comb using a hydrogen-filled Kagome HC-PCF pumped with high power picosecond-laser, or the generation of multiline Raman-source in

the UV-Vis using a very compact system pumped with micro-chip laser. Whilst these demonstrations are promising, a principal challenge for the industrialization of such Raman source is its lifetime as the H2 diffusion through silica is high enough to leak out from the fiber within only a few months. Here, we report on a HC-PCF based Raman multiline source with a very long life-span. The system consists of hydrogen filled ultra-low loss HC-PCF contained in highly sealed box, coined CombBox, and pumped with a 532 nm micro-chip laser. This combination is a turnkey multiline Raman-source with a "shoe box" size. The CombBox is a robust and compact component that can be integrated and pumped with any common pulsed laser. This Raman-source total average power is 32 mW (i.e. estimated peak power of 4 kW), and its spectrum is composed of 24 lines spanning from 355 to 745 nm. The power density of the strongest line is in the range of 18.4 W/nm. Both the output power and the spectrum remained constant over its monitoring duration more than six months. The spectrum of this multiline laser superimposes with no less than 17 absorption peaks of fluorescent dyes from the Alexa Fluor family used as biological markers.

10088-5, Session 1

100μJ-level single frequency linearly-polarized nanosecond pulsed laser at 775 nm

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We report a single frequency, linearly polarized, near diffraction-limited, pulsed laser source at 775 nm by frequency doubling a single frequency nanosecond pulsed all fiber based master oscillator-power amplifier, seeded by a fiber coupled semiconductor DFB laser diode at 1550 nm. The laser diode was driven by a pulsed laser driver to generate ~ 5 ns laser pulses at 260 Hz repetition rate with ~ 50 pJ pulse energy. The pulse energy was boosted to ~ 200 ?J using two stages of core-pumped fiber amplifiers and two stages of cladding-pumped fiber amplifiers. The multi-stage synchronous pulse pumping technique was adopted in the four stages of fiber amplifiers to mitigate the ASE. The frequency doubling is implemented in a single pass configuration using a periodically poled lithium niobate (PPLN) crystal. The crystal is 3 mm long, 1.4 mm wide, 1 mm thick, with a 19.36 ?m domain period chosen for quasi-phase matching at 33 ?. It was AR coated at both 1550 nm and 775 nm. The maximum pulse energy of ~ 97 ?J was achieved when ~ 189 ?J fundamental laser was launched. The corresponding conversion efficiency is about 51.3%. The pulse duration was measured to be 4.8 ns. So the peak power of the generated 775 nm laser pulses reached ~20 kW. To the best of our knowledge, this is the first demonstration of a 100 ?J-level, tens of kilowatts-peak-power-level single frequency linearly polarized 775 nm laser based on the frequency doubling of the fiber lasers.

10088-6, Session 1

Intracavity frequency-doubled degenerate laser

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Visible lasers have a wide range of applications in imaging, spectroscopy and displays. Unfortunately, they suffer from coherent artifacts such as speckle. Various compounding techniques have been developed to remove speckle, but these methods usually involve mechanically moving parts and require long acquisition times. A different approach to prevent speckle formation is developing lasers with low spatial coherence. A careful design of the laser cavity can facilitate lasing in many spatial modes with distinct emission pattern. The total emission from those mutually incoherent lasing modes has low spatial coherence. To date, several types of such lasers have been developed, but most of them have emission beyond the visible spectrum, making them unsuitable for imaging or display applications that require visible light.

An alternative way of making visible sources, especially of green color, is frequency doubling of infrared (IR) lasers. We develop a green light source with low spatial coherence via intracavity frequency doubling of a solid-state degenerate laser. The second harmonic emission is distributed over a few thousands independent transverse modes, and exhibits low spatial coherence. A strong suppression of speckle formation is demonstrated for both fundamental and second harmonic beams. Using the green emission for fluorescence excitation, we show the coherent artifacts are removed from the full-field fluorescence images. The achievable high power, low spatial coherence, and good directionality make the green degenerate laser an attractive illumination source for parallel imaging and projection display.

10088-7, Session 1

Picosecond pulsed micro-module emitting near 560 nm using a frequency doubled gain-switched DBR ridge waveguide semiconductor laser

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Semiconductor laser sources in the green-yellow spectral range around 560 nm are highly demanded in applications like fluorescence spectroscopy and stimulated emission depletion (STED) microscopy. Here, pulsed laser sources in the picosecond regime, which show high temporal and spectral stability at arbitrary repetition frequencies, are of particular interest.

However, there are no efficient semiconductor laser sources for direct emission in the yellow spectral range. Thus, single-pass second harmonic generation (SHG) is preferred. Recently, we demonstrated efficient pulsed frequency doubling to 558 nm in a bench-top experiment using a gain-switched distributed Bragg reflector ridge waveguide laser with freely triggerable pulse emission and a periodically poled lithium niobate ridge waveguide crystal [1].

We now successfully realized the integration into a micro-module, using the same laser and crystal as in Ref. [1] but a simplified concept for crystal coupling. It is done by a single GRIN-lens which collects the laser radiation and focusses it into the crystal´s waveguide.

The pulsed pump radiation shows a narrow spectral width of about 0.12 nm at wavelengths between 1115 nm and 1116 nm and a pulse width below 200 ps FWHM at repetition frequencies up to 40 MHz. SHG results in pulses of ~60 ps FWHM without significant trailing pulses and a pulse peak power of 310 mW. The spectral properties are quite stable at different temperatures and repetition frequencies.

At the conference we will present a detailed study of this pulsed micro-module and discuss challenges of micro-integration.

[1] A. Kaltenbach, R. Bege, K. Paschke, and G. Tränkle, "Generation of 0.7 W second harmonic picosecond pulses near 560 nm using a DBR diode laser and a ridge-waveguide PPLN crystal," in 2015 European Conference on Lasers and Electro-Optics - European Quantum Electronics Conference, (Optical Society of America, 2015), paper CD_P_35.

10088-8, Session 3

Instantaneous spectral span of 2.85 - 8.40 μm achieved in a Cr:ZnS laser pumped subharmonic OPO *(Invited Paper)*

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Degenerate (subharmonic) optical parametric oscillators (OPO) show great promise for the generation of broadband mid-infrared (MIR) frequency combs. Their main features are low pump threshold, dramatic extension of the spectrum of the pump laser, and phase locking to the pump frequency comb. Here we report on obtaining instantaneous spectrum ranging from 2.85 to 8.40 ?m at -30 dB level from a subharmonic OPO pumped by an ultrafast Cr:ZnS laser. Our experimental setup includes a free running Kerr lens mode locked 2.35 ?m Cr2+:ZnS laser, with 62-fs time-bandwidth limited pulse duration, 800-mW average power, and 79 MHz repetition rate that synchronously pumps a ring-cavity OP-GaAs based OPO. A 0.5-mm-long OP-GaAs crystal has a quasi-phase-matching (QPM) period of 88 ?m and is designed to provide a broadband parametric gain at OPO degeneracy. A 0.3-mm-thick ZnSe wedge inside the cavity was used to minimize group velocity dispersion. Spectral span of 1.56 octaves in the MIR that we achieved can be further improved by fabricating an in-coupling dielectric mirror with (i) broader reflectivity range and (ii) with compensation of the residual group velocity dispersion. The broad spectrum achieved, 2.85 - 8.40 ?m (2320 cm-1 wide instantaneous span), overlaps with a plethora of fundamental molecular IR resonances and can be used for frequency comb spectroscopic detection applied to such fields as remote sensing, study of fast combustion dynamics and medical diagnostics, to name a few.

10088-9, Session 3

Frequency comb generation in quadratic nonlinear cavities

Maria Parisi, Simona Mosca, Iolanda Ricciardi, Istituto Nazionale di Ottica (Italy); Tobias Hansson, Institut National de la Recherche Scientifique (Canada); Francois Leo, The Univ. of Auckland (New Zealand) and Univ. libre de Bruxelles (Belgium); Stephane Coen, Miro Erkintalo, The Univ. of Auckland (New Zealand); Stefan Wabnitz, Univ. degli Studi di Brescia (Italy) and Istituto Nazionale di Ottica (Italy); Pasquale Maddaloni, Luigi Santamaria, Paolo De Natale, Maurizio De Rosa, Istituto Nazionale di Ottica (Italy)

Nonlinear interactions in quadratic materials have for long been used to replicate and extend optical frequency combs (OFCs), originally generated in the visible and NIR, to other spectral regions where direct comb generation cannot be accomplished. In the last years, however, the occurrence of multiple cascaded second-order processes in a continuously pumped nonlinear cavity have proved to lead to the direct generation of entirely new OFCs, capable of multi-octave emission potentially across the whole transparency range of the nonlinear material. We experimentally observed the emergence of quadratic combs in a continuously-pumped cavity-enhanced second-harmonic generation (SHG) system, containing a second-order nonlinear crystal, showing that the onset of an internally pumped OPO immediately starts a series of multiple, cascaded quadratic processes, possibly leading to the formation of frequency combs [1]. Similar OFCs have more recently been observed in a nearly degenerate OPO.
We therefore developed a unified description of temporal and spectral dynamics, introducing single mean-field equations to model quadratic combs in both SHG and OPO cavities, revealing a new kind of walk-off-induced cavity modulation instability that triggers the formation of optical frequency combs and corresponding dissipative temporal patterns in both singly [2] and doubly resonant cavity configurations.

[1] S. Mosca, I. Ricciardi, M. Parisi, P. Maddaloni, L. Santamaria, P. De Natale, and M. De Rosa, Nanophot. 5, 316 (2016).

[2] F. Leo, T. Hansson, I. Ricciardi, M. De Rosa, S. Coen, S. Wabnitz, and M. Erkintalo, Phys. Rev. Lett. 116, 033901 (2016).

10088-10, Session 4

Experimental Investigation of Mid-infrared Supercontinuum Generation in Chalcogenide Step-index Optical Fibers *(Invited Paper)*

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We experimentally demonstrate mid-infrared (MIR) supercontinuum (SC) generation spanning ~2.0 to 15.1 ?m in a 3 cm-long chalcogenide step-index optical fiber. The pump source is generated by the difference frequency generation with a pulse width of ~170 fs, a repetition rate of ~1000 Hz, and a wavelength range tunable from 2.4 to 11 ?m. To the best of our knowledge, this is the broadest MIR SC generation observed so far in optical fibers. It facilitates the fiber-based applications in sensing, medical and biological imaging areas.

10088-11, Session 4

Supercontinuum comb sources for broadband communications based on AlGaAs-on-insulator *(Invited Paper)*

Hao Hu, Minhao Pu, Technical Univ. of Denmark (Denmark); Francesco Da Ros, DTU Fotonik (Denmark); Michael Galili, Kresten Yvind, Toshio Morioka, Technical Univ. of Denmark (Denmark); Leif Katsuo Oxenløwe, DTU Fotonik (Denmark)

As cost and energy consumption are becoming limiting factors in high-capacity systems, using fewer lasers with less energy consumption grows desirable and demonstrations of ultra-high-capacity optical transmission based on nonlinear fiber based spectral broadening of a seed laser frequency comb have been reported. The prospect of moving the fiber-based frequency comb sources onto a photonic chip platform holds many attractive features, including ultra-high bandwidth, stable polarization and phase, absence of stimulated Brillouin scattering (SBS), and the possibility of photonic integration with a seed laser.

AlGaAs-on-insulator (AlGaAsOI) has shown to be a very promising nonlinear material platform. It combines high intrinsic material nonlinearity (on the order of 10-17 W/m2), large index contrast between AlGaAs (3.3) and silica cladding (1.5), and low linear and nonlinear losses. The bandgap of AlGaAs can also be engineered by changing the Al concentration to avoid two-photon absorption (TPA) in the telecom wavelengths.

In this talk, we will present the first photonic chip based frequency comb, relying on spectral broadening of a mode-locked laser comb in an AlGaAsOI nano-waveguide, with a sufficient comb output power to support several hundred Tbit/s optical data. We use a 33.6 nm wide part of the generated comb spectrum to carry 80?40 Gbaud WDM channels with PDM-16-QAM modulation format. The high comb OSNR allows us to send the signal over 30 spatial channels, and we demonstrate successful 9.6 km transmission in a heterogeneous 30-core fiber reaching a total of 661 Tbit/s after FEC overhead subtraction.

10088-12, Session 4

A fiber based supercontinuum source using CMOS laser diode drivers

Yuting He, Orly Yadid-Pecht, Univ. of Calgary (Canada)

There have been intense research efforts on developing compact and low-cost supercontinuum sources, which have various application areas including telecommunications, spectroscopy, and optical coherence tomography. This research employs complementary metal–oxide–semiconductor (CMOS) technology to design and implement two integrated laser diode drivers for reducing the size and cost of supercontinuum sources. The designed supercontinuum source consists of a gain-switched 1550 nm laser diode, an erbium-doped fiber amplifier (EDFA) and 10-meter-long highly nonlinear fiber (HNLF). A continuous-wave (CW) CMOS driver with a maximum output current of 600 mA is developed for driving a 980 nm laser diode in an EDFA. The CW pumped laser diode can provide a stable optical output power up to 350 mW to an erbium-doped fiber. A picosecond pulsed CMOS driver is designed and applied for gain-switching the 1550 nm distributed feedback laser diode to produce optical pulses with a pulse width of 200 ps, a repetition rate of 5.6 MHz and a peak power of 5.9 mW. The optical output of the gain-switched laser diode is amplified by the EDFA to high-peak-power picosecond laser pulses and then launched into the HNLF for supercontinuum generation. The generated supercontinuum has an average power of 62 mW and a pulse energy of 11.1 nJ. The spectral bandwidth of the supercontinuum is 806 nm, spanning from 1298 nm to 2104 nm at the -40 dB level.

10088-13, Session 4

All-fiber supercontinuum source with flat, high power spectral density in the range between 1.1 μm to 1.4 μm based on an Yb3+ doped nonlinear photonic crystal fiber

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Supercontinuum light sources provide a high power spectral density with a high spatial coherence. Coherent octave-spanning supercontinuum can be generated in photonic crystal fibers (PCFs) by launching short pulses into the fiber. In the field of optical metrology respective light sources are very interesting. For most applications, only a small part of the entire spectrum can be utilized. In biological tissue scattering, absorption and fluorescence limits the usable spectral range. Therefore, an increase of the spectral power density in limited spectral regions would provide a clear advantage over spectral filtering. This study describes a method to increase the spectral power density of supercontinuum sources by amplifying the excitation wavelength inside a nonlinear photonic crystal fiber (PCF). An all-fiber-based setup enables higher output power and power stability. An ytterbium doped photonic crystal fiber was manufactured by a nanopowder process (drawn by the fiberware GmbH, Germany) and used in a fiber amplifier setup as the nonlinear fiber medium. In order to characterize the fiber's optimum operational characteristics, group-velocity dispersion (GVD) measurements were performed. The performance of the fiber-based setup was compared with a free space setup. Finally, the system as a whole was characterized in reference to common solid state-laser-based supercontinuum light sources. An improvement of the power density was observed in the spectral range between 1100 nm to 1400 nm.

10088-14, Session 4

High-power mid-infrared fiber-based supercontinuum sources *(Invited Paper)*

Stefan Kedenburg, Tobias R. J. Steinle, Andy Steinmann, Harald Giessen, Univ. Stuttgart (Germany)

We present mid-infrared supercontinuum sources based on chalcogenide, tellurite, and liquid-filled capillary fibers and sub-picosecond oscillator pumping. Depending on the fiber geometry and material, the experimentally achieved spectral bandwidths and output powers vary significantly. In As2S3 chalcogenide step-index fibers we achieve a maximum output power of 550 mW at a spectral width of 2 μm, covering the important transparent atmospheric window between 3 and 5 μm. In tellurite step-index fibers we attain an ultra-broadband spectrum ranging from 1.3 to 5.3 μm with an average power of 150 mW. The spectral behavior of the supercontinua is investigated by changing the pump wavelength, core diameter, fiber length, and pump power. As pump source we use high repetition rate (42 MHz) optical parametric oscillators/amplifiers which deliver Watt-level pulses tunable between 1.4 – 4.1 μm. These supercontinuum sources promise to be excellent laboratory tools for high resolution spectroscopy owing to their high brilliance and near TEM00 spatial beam profiles.

10088-15, Session 4

Exploring nonlinear pulse propagation, Raman frequency conversion and near octave spanning supercontinuum generation in atmospheric air-filled hollow-core Kagomé fiber

Seyedmohammad Abokhamis Mousavi, Hans Christian H. Mulvad, Shaif-ul U. Alam, Natalie V. Wheeler, Thomas D. Bradley, Peter Horak, John R. Hayes, Seyed Reza Sandoghchi, David J. Richardson, Francesco Poletti, Univ. of Southampton (United Kingdom)

We have generated Raman frequency conversion and supercontinuum light in a hollow core Kagomé fiber filled with air at atmospheric pressure, and developed a numerical model able to explain the results with good accuracy. A solid-state laser was used to launch short pulses (~6ps) at 1030nm into an in-house fabricated hollow core Kagomé fiber with negative core curvature [1] and both ends open to the atmosphere. The fiber had a 150THz wide transmission window and a record low loss of ~12dB/km at the pump wavelength. By gradually increasing the pulse energy up to 250μJ, we observed the onset of different Kerr and Raman based optical nonlinear processes, resulting in a supercontinuum spanning 850-1600nm range at maximum input power.

In order to study the pulse propagation dynamics of the experiment, we used a generalized nonlinear Schrodinger equation (GNLSE). Our simulations showed that the use of a conventional damping oscillator model for the time-dependent response of the rotational Raman component of air was not accurate enough at such high intensities and large pulse widths. Therefore, we adopted a semi-quantum Raman model for air, which included the full rotational and vibrational response, and their temperature-induced broadening. With this, our GNLSE results matched well the experimental data, which allowed us to clearly identify the nonlinear phenomena involved in the process.

Aside from the technological interest in the high spectral density of the supercontinuum demonstrated, the validated numerical model can provide a valuable optimization tool for gas based nonlinear processes in air-filled fibers.

References

[1] N. V. Wheeler, T. D. Bradley, J. R. Hayes, M. A. Gouveia, Y. Chen, S. R. Sandohgchi, F. Poletti, M. N. Petrovich, and D. J. Richardson, "Low Loss Kagome Fiber in the 1 μm Wavelength Region," in Advanced Photonics 2016 (IPR, NOMA, Sensors, Networks, SPPCom, SOF), OSA Technical Digest (online) (Optical Society of America, 2016), paper SoM3F.2

10088-16, Session 4

High power Raman-converter based on H2-filled inhibited coupling HC-PCF

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The advent of gas-filled hollow-core photonic crystal fibers (HC-PCF) has opened new path for the strong interaction between the light and the matter, and to generate non-linear optical phenomena with extremely high efficiency [1]. Following the development of the guidance principle of the Kagome fibers, called inhibited-coupling (IC) [2], the advent of hypocycloid-core contour in hollow-core fibers allowed to drastically reduce the fiber transmission loss [3], especially in the visible and near infrared with a record loss of 17 dB/km at 1 ?m [4]. Due to these fiber transmission performances, the non-linear processes have been enhanced with the small effective area and the fiber length. Consequently the gas-filled IC Kagome HC-PCF has become an efficient high power conversion frequency stage via stimulated Raman scattering (SRS).

Here, we report on high power Raman-converter based on hydrogen-filled IC HC-PCFs pumped by an Yb-fiber high power picosecond laser. The flexibility of this fiber Raman-convertor enables to operate in two SRS emission regimes by simply controlling the fiber length or the gas pressure. It can set to either generate favorably a high power single laser line at a frequency outside the conventional laser wavelengths, or to generate an extremely wide Raman comb. Based on this we demonstrate a picosecond pulse Raman source of 9.3 W average power at 1.8 μm, and an ultra-wide Raman comb spanning over more than five octaves from UV to mid-infrared, containing around 70 laser lines [5].

10088-17, Session 5

Upconversion based spectral imaging in 6 to 8 μm wavelength regime

Saher Junaid, Peter T. Lichtenberg, Christian Pedersen, DTU Fotonik (Denmark)

Due to lack of sensitive detectors and imaging systems, non-linear frequency upconversion has been exploited to convert mid-Infrared signals into the visible spectral region, thus exploiting efficient and cheap Si-based CCD camera technology. AGS (AgGaS_2) crystals have been used here for non-linear upconversion in the 5 to 12 μm wavelength regime. The single-pass upconversion system consists of a non-linear crystal, a broad-band light source (glow bar) and a CW mixing laser at 1064 nm. Angle tuning of the non-linear crystal is incorporated to control the phase match condition which is used to up-convert mid-infrared wavelengths across the field of view of the imaging system. A polystyrene film with spectral features in the 6 to 8 μm wavelength region and a USAF resolution target are initially used to check the applicability of the system for spectral imaging. Thermal light is passed through a polystyrene film and resolution target and the transmitted light is converted to near infrared light via sum frequency generation with a 1064 nm mixing laser. Acquired images contain both spectral and spatial information. A series of images are obtained by varying the phase match condition through angle tuning of the crystal. After post processing, a sequence of monochromatic images can be obtained. A theoretical model has been developed for the scanning of the phase match condition via crystal rotation and results are compared with the experimental data.

The system is meant for spectral imaging in 6 to 8 μm regime targeting molecular spectral histopathological diagnosis of esophageal cancer.

10088-18, Session 5

Broadband upconversion imaging around 4 μm using an all-fiber supercontinuum source

Laurent Huot, NKT Photonics A/S (Denmark) and Technical Univ. of Denmark (Denmark); Christian Pedersen, DTU Fotonik (Denmark); Peter Tidemand-Lichtenberg, Technical Univ. of Denmark (Denmark); Peter M. Moselund, Lasse Leick, NKT Photonics A/S (Denmark)

The combination of high brightness mid-IR supercontinuum lasers and upconversion detection systems opens a unique possibility for combining two leading edge technologies pointing towards extremely fast and extremely sensitive imaging and spectroscopy in the mid-IR range.

We present a novel mid-IR imaging system born from the combination of an all fiber mid-IR supercontinuum source developed at NKT with ultra sensitive upconversion detection technology from DTU Fotonik. The source delivers 100 mW of average power and its spectrum extends up to 4.2 μm. In this setup, the supercontinuum light is first collimated and passed through a sample. The transmitted infrared signal is then focused into a bulk AgGaS2 nonlinear crystal and subsequently mixed with a synchronous mixing signal at 1550 nm extracted from the supercontinuum's pump laser. Through the process of sum frequency generation, an upconverted signal ranging from 1070 nm to 1140 nm is generated and acquired using an InGaAs camera. The high brightness of the pump source allows for efficient upconversion in a single pass configuration and enables the use of a large mixing mode inside the nonlinear crystal which enhances spatial and spectral resolution of the system. Additionally, the broadness of the supercontinuum spectrum increases the field of view of the imaging.

We discuss the performance of the system in terms of spatial resolution, point spread function, and spectral resolution and investigate its use as a hyperspectral imaging setup.

10088-19, Session 5

Polarization spectroscopy with upconversion detector for detection of methane and the methyl radical in flame

Rasmus Lyngbye Pedersen, Dina Hot, Zhongshan S. Li, Lund Univ. (Sweden)

Mid-infrared (MIR) polarization spectroscopy (PS) has shown promise for detection of combustion related molecular species that lack accessible transitions in the UV/visible spectral regions. However, due to the small photon energy in the MIR, direct detection with InSb detectors intrinsically suffer from high thermal noise. It is therefore of interest to improve the detector, where in this work an upconversion detection system replaced the InSb detector. This system consists of combining the signal with a strong 1064nm pump laser using sum frequency generation (SFG) in a periodically poled lithium niobate (PPLN) crystal, placed inside a Nd:YVO laser cavity. The upconverted signal has a wavelength of around 800nm, which can be detected using a silicon-based camera, with better noise properties than the InSb detector.

A comparison between the two detectors was performed when PS was used for detection of methane diluted in a Nitrogen gas flow at ambient condition. This was done using a tunable MIR laser which scanned the R(13) absorption line of methane around 3148.9 cm-1 . The laser operated at 10 Hz with 3mJ per pulse. A four times lower detection limit of methane was achieved, from 400 ppm with the InSb detector to 90 ppm with the upconversion.

By compensating for temperature broadening effects, it is possible to achieve quantitative methane measurements in flame using PS. The introduction of upconversion detection allow us to measure species with weaker signals, and we will present concentration measurements of the methyl radical in a methane flame and a DME flame.

10088-20, Session 5

Investigation of mid-IR picosecond image upconversion

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Mid-infrared (MIR) upconversion represents an innovative alternative to standard MIR cameras such as the InGaAs or MCT camera. The upconversion process can provide ultrafast and sensitive upconversion of MIR wave-vectors to the visible (VIS) or near-infrared (NIR), thus transferring MIR images to a wavelength band covered by Si-based detectors and CCD cameras. Here we want to use the fast response time of the ?(2) nonlinearity to demonstrate and investigate one picosecond upconversion imaging at 1900 nm. The upconversion imaging is realized inside a lithium niobate (LiNbO3) bulk crystal. In order to increase the quantum efficiency, the actual setup is synchronously pumped so that pump pulses and the signal pulses are synchronized in time and space. In our setup, a mode-locked laser generates a MIR signal at 1900 nm with a peak power of 46 kW in synchronism with a pump beam at 1550 nm having a peak power of 910 W. Both signals have a pulse width of approximately 1 ps.

In order to facilitate accurate MIR imaging, we have investigated the upconversion imaging properties, such as the effective field-of-view (FOV) of the upconversion process and the influence of the pump beam diameter used, impacting the resolution of the upconverted MIR images significantly. Due to the broadband nature of the 1 ps pulses used, the phase matching properties become more complex and expanded models are presented.

10088-21, Session 5

Cross-propagating beam-deflection measurements of third-order nonlinear optical susceptibility

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Here we present a modified beam-deflection (BD) technique which involves an orthogonal interaction geometry for excitation and probe beams by using femtosecond laser pulses. In this geometry the optical interaction length is determined by a combination of the beam sizes and shapes along with the pulsewidths. The great sensitivity of the BD method (demonstrated sensitivity to nonlinearly induced phase distortion of wavelength/20,000) allows such measurements. Our recently developed BD method is used to determine the sign, magnitude, and ultrafast dynamics of bound electronic and nuclear responses [1], [2] . Various time-resolved and polarization dependent techniques have been reported for measurement of the nonlinear refraction (NLR) of materials by having excitation and probe beams interacting nearly collinearly; however, the polarization combinations are limited because of the interaction geometry. This new cross-propagating technique is sensitive to third-order nonlinear susceptibility tensor components for which the standard geometry is insensitive. In particular, this geometry allows measurements of nonlinear susceptibility tensor elements with longitudinal field components in addition to those available with the standard geometries. It may also allow detection of recently proposed magneto-electric susceptibility tensor components [3]. This greatly extends the number of measurable nonlinear optical susceptibility elements by probing an index change (and absorption change) with electric field polarized parallel to the wavevector of the excitation beam.

References:

[1] Matthew Reichert, Peng Zhao, Jennifer M. Reed, Trenton R. Ensley, David J. Hagan, and Eric W. Van Stryland, "Beam deflection measurement of bound-electronic and rotational nonlinear refraction in molecular gases," Opt. Express 23, 22224-22237 (2015)

[2] Matthew Reichert, Honghua Hu, Manuel R. Ferdinandus, Marcus Seidel, Peng Zhao, Trenton R. Ensley, Davorin Peceli, Jennifer M. Reed, Dmitry A. Fishman, Scott Webster, David J. Hagan, and Eric W. Van Stryland, "Temporal, spectral, and polarization dependence of the nonlinear optical response of carbon disulfide," Optica 1, 436-445 (2014)

[3] S. C. Rand, W. M. Fisher, and S. L. Oliveira, "Optically induced magnetization in homogeneous, undoped dielectric media," J. Opt. Soc. Am. B 25, 1106-1117 (2008)

10088-22, Session 6

Producing sub-mJ level carrier-to-envelope-phase stable pulses in the long-wave mid-IR *(Invited Paper)*

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Here we report a mid infrared OPCPA delivering 7 microns pulses at a repetition rate of 100 Hz. The parametric amplification is achieved within ZGP crystals pumped by laser pulses from a compact Ho:YLF picosecond CPA operating at 2.05 ?m. Both OPCPA and pump laser are seeded by outputs from a single fibered oscillator what ensures the optical synchronization. The seed of the OPCPA results from DFG of 2 outputs from the oscillator within a CSP crystal what leads to CEP stabilization without needs of active feedback loop. The Ho:YLF CPA consists of bulk stretcher and compressor based on Volume Bragg Gratings (VBG) and of 2 amplification stages, a regenerative amplifier and a cryogenically-cooled multipass amplifier both pumped by a cw Thulium-doped fiber laser operating at 1.9 ?m. The regenerative amplifier delivers an output energy of 4 mJ whereas the cryogenically-cooled multipass amplifier delivers an energy per pulse up to 100 mJ after 2 passes. The maximum energy achievable after compression by the VBG is limited by laser damage threshold and size of VBG and amounts to 73 mJ with a pulse duration of 17 ps. While pumping 3 ZGP amplification stages with an overall pump energy of 12 mJ, we have obtained before compression 0.5 mJ at 7 microns with a spectral width corresponding to 4 optical cycles for a compression at the Fourier limit. Upcoming work will consist to increase the output energy with the available pump by using larger aperture crystals and to optimize the compression

10088-23, Session 6

Ductile mode dicing for PPLN waveguide devices

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Generation of 780 nm at the watt level is an active area of research for Rubidium atom cooling systems. Making them efficient, compact and robust is important if this technology to be utilized within space/sea borne systems. Periodically poled lithium niobate (PPLN) waveguides has had a resurgence of interest as a component for generating 780 nm light for quantum systems with applications ranging from: global position, clocks, gravitation wave detection, and ordnance detection in the form of precision gravitometers [1]. PPLN waveguides have been demonstrated at the half-watt level using second harmonic generation from readily available and space qualified telecommunication pump sources [1]. Total system efficiencies of 56% have been reached [1] and are an order of a magnitude more efficient than the equivalent bulk system.

To further improve on total system efficiency a potential route is to improve waveguide efficiency by improving fabrication; it is well known that a reduction in RMS sidewall surface roughness (Sq) reduces the amount of scatter from a waveguide [2]. We have demonstrated by a ductile dicing approach a sidewall surface roughness of 0.46 nm (Sq) can be achieved with optimized machining conditions. These results represent an eight fold reduction in Sq over the 3.72 nm demonstrated in prior work on diced lithium niobate waveguides [3]. We will present our latest results in ultra-precision ductile dicing and how this can be applied to the development of PPLN waveguide devices for high efficiency second harmonic generation.

References

[1] T. Lévèque, L. Antoni-Micollier, B. Faure, J. Berthon, "A laser setup for rubidium cooling dedicated to space applications," Appl. Phys. B, 116, 997–1004 (2014).

[2] T.G. Bifano, T.Dow and R.O. Scattergood, "Ductile-regime grinding: a new technology for machining brittle materials," Journal of Engineering for Industry (Transactions of the ASME), 113, 184–189 (1991).

[3] J. Sun and C. Xu, "466 mW green light generation using annealed proton-exchanged periodically poled MgO: LiNbO3 ridge waveguides," Optics Letters, 37, 2028-2030 (2012).

10088-24, Session 6

Directional coherent light via fast Rabi-induced sideband emission

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We introduce a unique technique for generating directional coherent emission that could be utilized to create coherent sources in a wide range of frequencies from the extreme ultraviolet (XUV) to the deep infrared. This is accomplished without population inversion by pumping a two level system with a far detuned strong optical field that induces splitting of the two-level system. The nonlinear process of four-wave mixing then occurs across the split system driving coherent emission at sidebands both red and blue detuned from the pump frequency and propagates both forward and backwards along the pump beam path. We observed this phenomenon in dense Rb vapor. The sideband emission exhibits a short pulse duration with threshold-like behavior dependent both on pump intensity and Rb vapor density. This technique offers a new capability for manipulating the emission frequency simply through intensity induced atomic modulation that can be scaled to most frequency regimes using various atomic/molecular ensembles and pump energies.

10088-25, Session 6

Measurement of the second order nonlinear optical coefficient of GaAs, GaP and InGaAs

Shekhar Guha, Jean Wei, Joel M. Murray, Jacob O. Barnes, Air Force Research Lab. (United States); Peter G. Schunemann, BAE Systems (United States)

Orientation patterned GaAs and GaP crystals are increasingly being used for frequency conversion of laser beams into desired wavelengths. The ternary alloy InGaAs has smaller band gap energy compared to GaAs and is expected to have a nonlinear optical coefficient that is higher than that of GaAs. We will present the results of measurements of the second order nonlinear optical coefficient of InGaAs, along with recent measurements of GaAs and GaP obtained through second harmonic generation of a tunable carbon dioxide laser in the 9.2 to 10.6 ?m range. The results will be compared to available values obtained at other wavelengths [1,2]

REFERENCES

[1] T. Skauli, K. L. Vodopyanov, T. J. Pinguet, A. Schober, O. Levi, L. A. Eyres, M. M. Fejer, J. S. Harris, B. Gerard, L. Becouarn, and E. Lallier, G. Arisholm, "Measurement of the nonlinear coefficient of orientation-patterned GaAs and demonstration of highly efficient second-harmonic generation", Optics Letters , Vol. 27, No. 8, 628, (2002)

[2] I. Shoji, T. Kondo, A. Kitamoto, M. Shirane, and R. Ito, "Absolute scale of second-order nonlinear-optical coefficients", J. Opt. Soc. Am. B, Vol. 14, No. 9, 2268, 1997

10088-26, Session 6

Improved mid wave infrared generation in parasitic-light-suppressed periodically poled lithium niobate crystal

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Several watts of power have been obtained near the wavelength range of 3400nm by difference frequency mixing of 1064 nm and 1550 nm lasers for both continuous wave and pulsed pumping cases [1], [2] with incident pump powers in the tens of watts regime. High power fiber lasers in the hundreds of watts regime are increasingly available, especially in the 1000 to 1100 nm range. One potential limitation for scaling the mid-wave infrared (MWIR) power to higher values is the parasitic generation of second harmonic light in the 500 to 550 nm range when increasing the pump power, leading to green induced infrared absorption (GRIIRA) [3]. A potential way to suppress the parasitic second-harmonic generation (SHG) is to use engineered quasi-phase matched (QPM) structure with a relative ϖ-phase shift in only the SHG [4].

We use two PPLN crystals of identical dimensions (3 mm x 5 mm x 40 mm) with grating spacing's of 30 μm for difference frequency mixing; one of which is engineered with the additional green suppression structure. Laser beams at 1064 nm (pump) and 1550 nm (signal) were co-incident on the crystals with beam radii (HWe-1M) of 30 μm and 50 μm respectively, focused by a 15 cm focal length lens. The generated idler power near 3400 nm was recorded at various pump and signal power levels. With an incident pump power of 47 W and signal power of 23 W, the idler power (of about 2 W) obtained from the crystal with green suppressed structure was found to be approximately 33% higher than the crystal without green suppression. Transmission through each crystal was verified as well as a visual confirmation after high power exposure and no permanent damage was observed in either crystal.

REFERENCES

[1]. R. T. Murray, T. H. Runcorn, E. J. R. Kelleher, and J. R. Taylor, Highly efficient mid-infrared difference-frequency generation using synchronously

pulsed fiber lasers , Optics Letters, Vol. 41, (11), 2446-2449 (2016)

[2]. S. Guha, J. O. Barnes, and L. P. Gonzalez, Multiwatt-level continuous-wave midwave infrared generation using difference frequency mixing in periodically poled MgO-doped lithium niobate, Optics Letters, Vol. 39, (17), 5018-5021 (2014)

[3]. L. E. Myers, R. C. Eckardt, M. M. Fejer, R. L. Byer, W. R. Bosenberg, and J. W. Pierce, "Quasi-phase-matched optical parametric oscillators in bulk periodically poled LiNbO3," J. Opt. Soc. Am. B 12(11), 2102–2116 (1995).

[4]. Hwan Hong Lim, Sunao Kurimura, and Nan Ei Yu, Parasitic-light-suppressed quasi-phase-matched optical parametric oscillation device, Optics Express Vol. 22, No. 5, 5209-5215, (2014)

10088-27, Session 6

Growth and processing of OP-GaAs and OP-GaP waveguides for mid-IR frequency conversion

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Orientation-patterned semiconductor waveguides are promising devices for mid-infrared frequency conversion, combining the high nonlinear coefficient of quasi-phase-matched (QPM) materials such as GaAs and GaP with the tight power confinement offered by the waveguide geometry. The ability to maintain high nonlinear gain along the entire optical path in such a waveguide is expected to result in orders of magnitude reduction in pump power requirements for optical parametric oscillation over bulk orientation-patterned gallium arsenide (OPGaAs) and phosphide (OPGaP) devices. A main obstacle to the utilization of efficient OPGaAs and OPGaP waveguide devices has been the relatively high losses of the waveguides produced to date. Here we describe the design, MBE growth, and fabrication of OPGaAs and OPGaP rib waveguide structures based on AlxGa1-xAs and AlxGa1-xP cladding layers respectively. The best available dispersion data for GaAs, AlxGa1-xAs, GaP, and AlxGa1-xP were used to calculate the phase-matching periods for the desired frequency interaction, which were in turn modified by the specifics of the structure, composition, and geometry of the waveguides. QPM OPGaAs and OPGaP template structures were grown by polar-on-nonpolar MBE using established techniques, followed by growth of cladding, core, cladding, and cap layers that were subsequently patterned and etched to produce rib structures. Details of the growth and processing parameters, waveguide structure, and preliminary loss data and frequency conversion results will be presented.

10088-40, Session PTue

Third order optical nonlinearities in Gorilla Glass

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Given its excellent mechanical and optical properties, Gorilla glass (Corning) has been widely used in tablets and smartphones. Its technological appeal has prompted studies on its use as a platform for advanced photonic devices. In this direction, studies on the third-order optical nonlinearities of Gorilla glass are of foremost importance. Here, we report a study of the nonlinear index of refraction of Gorilla glass, using the closed aperture Z-scan technique with femtosecond pulses (120 fs and 1 KHz) from the near UV to the telecom range (400 – 1500 nm). To the best of our knowledge, this is the first report of the nonlinear spectrum for this material. The Z-scan data reveal an approximately constant behavior for the nonlinear refractive index over the studied spectral range, with values two times higher than the ones obtained for fused silica, which is related to the high concentration of alkaline ions in this sample, particularly potassium. Optical Kerr Gate experiments were also carried out, using excitation wavelengths at 520, 650 and 900 nm. Such results revealed that the induced nonlinear process presents a response time shorter than the pulse duration. Such results show that Gorilla glass present optical properties compatible with its use in photonic devices, such as waveguides. Financial support from FAPESP, CAPES, CNPq and the USP-Princeton partnership are acknowledged.

10088-41, Session PTue

Nonlinear mode conversion for intermodal four-wave mixing Stokes and anti-Stokes in a multimode fiber

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Intermodal four-wave mixing (IM-FWM) results in definite transverse modes for Stokes and anti-Stokes beams. For some applications it may be needed to have these beams in other spatial modes. Here, we generate anti-Stokes beam in a specific mode and convert it to another transverse mode all in a short multimode optical fiber . Conversion is achieved by an optically induced long-period grating (OLPG) generated via multi-mode interference of different pump modes in SMF-28.

With both 532nm pump photons in the fundamental LP01 mode, Stokes and anti-Stokes beams are generated at 656 and 447nm and in LP02 and LP01 modes, respectively. By adjusting the laser coupling into the fiber another pump mode besides the fundamental is excited and beats with the fundamental mode to generate an OLPG, which efficiently couples the anti-Stokes to LP02 and LP11.

Notable aspects of this work:

1) Excitation of excessive pump modes result in observation of anti-Stokes beam in transverse mode that does not satisfy phase-matching or even conservation of optical angular momentum (C-OAM).

2) Modal evolution of anti-Stokes beam generated via IM-FWM in the presence of OLPG by propagation in fiber has been studied experimentally and theoretically.

3) Experimental results suggest an improved OLPG-based conversion efficiency.

4) Single pump laser configuration is used for both writing and probe beams and is a more robust and less complicated setup for mode conversion which alleviates the need for temporal synchronization of writing and probe beams.

5) Our observations give a plausible explanation to reported inconsistency in C-OAM.

10088-42, Session PTue

Generation of 70 ps pulses at 280 nm and 295 nm freely triggerable between single shot and 80 MHz

Thomas Schönau, Dietmar Klemme, André Kaltenbach, Kristian Lauritsen, Rainer Erdmann, PicoQuant GmbH (Germany)

Laser pulses from diode based laser systems in the UV range are of great interest in the fields of microscopy and spectroscopy. Providing UV wavelength pulses at variable repetition frequencies or on demand

requires nonlinear frequency conversion in single pass arrangement for example in a crystal featuring a high effective nonlinear coefficient. In recent years, Raman-shifted fiber lasers and amplifiers enabled the generation of fundamental signal in the range from 1100 nm and above and give access to cascaded frequency conversion towards new UV wavelengths, especially 280 – 295 nm, highly demanded from the life sciences.

Our approach presented here is based on a freely triggerable distributed feedback (DFB) laser diode to create sub-100 ps seed pulses. After a two-stage fiber amplifier, pulses at 30 nJ and peak power of 0.5 kW are launched into commercial PM-Raman fiber to create 1120 nm and 1180 nm signal respectively. The spectral linewidth and central wavelength of the Raman signal was controlled and optimized via co-propagating CW signal from a FBG-stabilized laser diode at 1122 nm or 1178 nm.

The Raman-shifted pulsed signal is separated from residual fundamental light and two times frequency doubled in a single pass cascade of MgPPLN and beta-BBO crystals with optimized focal conditions and spectral filtering. High dynamic range filter clean up the UV signal from fundamental signal background.

The power level of >1 mW average power at 80 MHz is sufficient for a wide range of applications in the life sciences, such as fluorescence spectroscopy and confocal microscopy.

10088-43, Session PTue

Compact pulsed frequency convertor for 355 nm generation for sensing application by using monolithic PP-Mg:SLT device

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Compact third harmonic (355 nm) frequency convertor was demonstrated based on pulsed fiber laser for sensing application. Fundamental 1064 nm laser was fiber based laser with?repetition rate of 50 kHz, peak power of 25 kW, pulse width of 1 ns and average power of 1 W. The light was delivered by polarization maintain large mode area fiber and connected to the frequency convertor. In the frequency convertor, SHG-THG monolithic PP-Mg:SLT device was used. Each device length area was 4 mm and 11 mm, respectively. By optimizing periodicities for both SHG and THG, we found the optimum phase matching condition for both conversion in one device. We succeeded to generate more than 10 % of conversion efficiency with more than 100 mW of output power. We integrated this device into frequency convertor. The convertor size of less than 125cc was demonstrated. More than 100 mW with circular beam 355nm was obtained from this convertor. Since the convertor is consisted with one nonlinear device, it is required less number of optics (such as focusing lenses) and electric parts (only one TEC elements). Therefore, it was realized palmtop size convertor. With this size, it is possible to realize affordable laser module for easy to integrate into the portable sensing system such as LIDAR systems on the airplane and could be attractive to characterize much smaller particle sensing by 355 nm light.

10088-44, Session PTue

Modulation of frequency doubled DFB-tapered diode lasers for medical treatment

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The use of visible lasers for medical treatment is increasing, especially within ophthalmology where they are used for photocoagulation on the retina. Most lasers used today are diode pumped solid state lasers or optically pumped semiconductor lasers, but recently there has been an interest to move to direct frequency doubling of high power infrared diodes instead.

We present an investigation of how the second harmonic light can be modulated by perturbations to the laser diode. The laser used is a monolithic master oscillator (MO) power amplifier (PA) structure consisting of a single mode distributed feedback laser and a tapered amplifier mounted p-side up. This mounting allows for individual control of the current over the MO and the PA allowing for greater decoupling of the wavelength and the power. Pulse modulation of the visible light up to several kHz is achieved by detuning the infrared wavelength by changing the current over the MO. Furthermore, a high modulation depth above 95 % can be achieved.

This type of system is ideal for medical treatment since it gives full control over the pulse train without the need for extra components such as fast shutters, choppers or acousto-optic modulators, thereby further reducing the size and cost of the system compared to the current technologies.

10088-28, Session 7

Development of orientation-patterned GaP grown on foreign substrates for QPM frequency conversion devices

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Thick hydride vapor phase epitaxially grown orientation-patterned gallium phosphide (OPGaP) is a leading material for quasi-phase matching (QPM) frequency conversion in the mid- and longwave IR. This is due to its negligible two-photon absorption (2PA) in the convenient pumping range 1 – 1.7 μm, compared with the 2PA of some traditional QPM materials, such as GaAs. In this presentation, we describe homo- and heteroepitaxial growth techniques aimed to produce hundreds of microns thick OPGaP on: 1) OPGaP and OPGaAs templates both fabricated by using a molecular beam epitaxy (MBE) for sub-lattice polarity inversion, but one with and one without MBE regrowth after the inversion; 2) OPGaAs templates fabricated using an improved wafer-fusion process. Some of the advantages of the heteroepitaxial growth of OPGaP on OPGaAs templates include: 1) achieving good domain fidelity as a result of the significantly higher OPGaAs template quality; 2) eliminating the needs of using the poor quality commercially available GaP in the production of thick OPGaP material, and 3) suppression of the additional absorption band between 2 – 4 μm (which is due to incorporation of n-type impurities) and, in general, improvement of the IR transmittance in the entire IR region. Combining the advantages of the two most promising nonlinear materials, GaAs and GaP, will accelerate the development of high power, broadly tunable laser sources in the IR which, in addition, will be offered with higher device quality and at a reasonably lower unit cost. Optical characterization that will demonstrate frequency conversion will also be presented.

10088-29, Session 7

Broadband midinfrared from fiber laser difference frequency generation in OP-GaP

Kevin F. Lee, Christopher J. Hensley, IMRA America, Inc. (United States); Peter G. Schunemann, BAE Systems (United States); Martin E. Fermann, IMRA America, Inc. (United States)

We generate up to 52 mW of broadband pulses at 8 μm wavelength by difference frequency generation (DFG) in orientation-patterned GaP (OP-GaP). With the broad transparency range of OP-GaP, from visible to 12 μm, near infrared fiber laser output can be converted to the midinfrared. An

Er fiber oscillator at 1.5 μm and 90 MHz repetition rate provides pulses for direct amplification to 1.45 W, and Raman shifting to 1.9 μm followed by amplification to 0.45 W in Tm doped fiber. The two beams are then mixed in OP-GaP with up to 20% photon conversion efficiency. The wavelength can be tuned from 5 to 11 μm wavelength by changing the quasi-phase matching period by translating the multi-period crystal, or by changing pumping to control the Raman wavelength shifting.

Given the meters of optical fiber in the two arms, thermal drifts cause temporal mismatches when focusing the two beams into the nonlinear crystal. We actively stabilize the path lengths by monitoring a coincidentally generated sum frequency signal as an indicator of timing overlap, and feeding back to a piezoelectric delay stage. Using relatively slow feedback correction, the intensity variation is reduced from 100% to 1%.

We have combined the new nonlinear crystal OP-GaP with femtosecond fiber lasers to create a compact, high-powered midinfrared pulse source that will drive new technologies in chemical sensing and imaging.

10088-30, Session 7

Continuous-wave difference frequency generation in the mid-infrared with orientation-patterned gallium phosphide (OP-GaP) crystals

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Tunable and spectrally pure coherent sources in the mid infrared (IR) are required for both high-sensitivity and high-precision molecular spectroscopy. Mid-IR difference-frequency generation (DFG) of two visible/near-IR lasers in a nonlinear crystal can be a convenient choice because of the possibility of direct referencing of the pump and signal laser to the absolute frequency standard via a comb, leading to an intrinsically metrological DFG source.

Commercial crystals such as LiNbO3 and LiTaO3 are transparent only below 5 ?m. For longer wavelengths, quasi-phase-matched (QPM) OP-GaAs or OP-GaP are preferable for DFG over birefringence phased-matched chalcogenides for their higher nonlinear coefficients and because they are free from spatial walk-off, which dramatically reduces the nonlinear interaction length. The advantages of OP-GaP over OP-GaAs are the larger thermal conductivity and the larger bandgap energy that is better suited for pumping at the convenient Nd:YAG wavelength of 1064nm.

Here we report on the first continuous-wave DFG source around 5.85?m wavelength using two OP-GaP crystals, with 11.5 and 24.6mm lengths. A Nd-YAG laser at 1064nm and a diode-laser at 1301nm are used as pump and signal, respectively. Up to 65?W of single-frequency idler at was generated from ~10W of pump and ~40mW of signal in the longer crystal, limited by thermal dephasing effects arising from the non-negligible absorption at the pump and signal wavelengths. Following the cw Gaussian beam DFG theory, both the linear and nonlinear properties of OP-GaP have been characterized.

10088-31, Session 7

Advances in large aperture single crystal CdSiP2 for high energy mid-infrared generation

Kevin T. Zawilski, Peter G. Schunemann, BAE Systems (United States)

Recent growth advances have enabled large-aperture CdSiP2 (CSP) crystals which are useful for high energy mid-infrared generation. CSP is a new non-linear material which is a high temperature analog to ZnGeP2 (ZGP) with a larger bandgap and promising characteristics for IR frequency conversion. CSP has the highest nonlinear coefficent (d36=84.5 pm/V) of any bulk birefringent material for producing mid-infrared pulses from high-energy 1-, 1.5-, or 2-micron laser sources. Crystals are birefringent and are transparent from 0.5 to 9 microns. Its thermal conductivity (13.6 W/mK) is higher than that of YAG, and 10-15 times higher than existing NLO crystals AgGaS2 (1.4 W/mK) and AgGaSe2 (1.0 W/mK) used for shifting 1.06-micron and 1.55-micron lasers into the mid-IR. Laser damage thresholds similar to those for ZGP have been measured. CSP growth presents significant crystal growth challenges compared to ZGP including: a higher melting point and vapor pressure that push the limits of fused silica based growth technology, a higher reactivity with boat materials and fused silica ampoules, an increased incidence of twin formation, and a negative c-axis thermal expansion coefficient making it prone to cracking. Despite these difficulties, recent advances in growth using the horizontal gradient freeze (HGF) technique from stoichiometric melts have resulted in scaling boules to 28mm diameter. In addition, efforts to minimize impurity contamination as well as more precise stoichiometry control continue to reduce extrinsic absorption losses in CSP.

10088-32, Session 8

Molecular spectroscopy from 5-12 μm using an OP-GaP OPO *(Invited Paper)*

Derryck T. Reid, Luke Maidment, Heriot-Watt Univ. (United Kingdom); Peter G. Schunemann, BAE Systems (United States)

We report a femtosecond optical parametric oscillator (OPO) based on the new semiconductor gain material orientation patterned gallium phosphide (OP-GaP) and being the first example of a broadband OPO operating across the molecular fingerprint region. OP-GaP crystals with lengths of 1 mm and several patterning periods were diced, polished, and anti-reflection (AR) coated for near- to mid-infrared wavelengths. We configured a synchronously pumped OP-GaP OPO in a 101.2-MHz resonator with high reflectivity from 1.15–1.35 μm, pumped with 150-fs pulses from a 1040-nm femtosecond laser (Chromacity Spark). The coating of one spherical mirror was optimized for transmission at the pump wavelength of 1040 nm and for high reflectivity at the resonant signal wavelength in a range from 1.15–1.35 μm, while the other spherical mirror collimated the idler beam emerging from the OP-GaP crystal and was silver coated to provide high reflectivity for all idler wavelengths. This collimated idler beam was output-coupled from the cavity by transmission through a plane mirror coated with high transmission for the idler wavelengths (5–12 μm) and high reflectivity for the signal wavelengths (1.15–1.35 μm) on an infrared-transparent ZnSe substrate. Idler spectra centered from 5.4–11.8 μm and extending to 12.5 μm were collected. The maximum average power was 55 mW at 5.4 μm with 7.5 mW being recorded at 11.8 μm. Details of Fourier transform spectroscopy using water vapor and a polystyrene reference standard will be presented.

10088-33, Session 8

Single-frequency tunable long-wave infrared OP-GaAs OPO for gas sensing *(Invited Paper)*

Julie Armougom, Quentin Clément, Jean-Michel Melkonian, Jean-Baptiste Dherbecourt, Myriam Raybaut, ONERA (France); Arnaud Grisard, Eric Lallier, Thales Research & Technology (France); Bruno P. Gérard, III-V Lab. (France); Basile Faure, Grégoire Souhaité, Teem Photonics (France); Antoine Godard, ONERA (France)

Optical parametric oscillators (OPOs) are very attractive sources to deliver the high-peak-power, narrow-linewidth, and tunable pulses required for standoff detection of gases by the differential absorption lidar (DIAL) technique. Orientation-patterned GaAs (OP-GaAs) is a nonlinear crystal that offers unique advantages to enable DIAL in the long-wave infrared (7–13 µm), which is of high interest for the detection of various hazardous gas species. In this talk, we present our results on single-frequency emission in OP-GaAs using a nested cavity OPO (NesCOPO) configuration emitting in the long-wave infrared (LWIR) and its use for preliminary DIAL experiments.

The OP-GaAs NesCOPO is pumped by a pulsed nanosecond single-frequency Tm:YAP microlaser. This laser emits 36 ns pulses with a repetition rate of 100 Hz at 1938.5 nm and delivers a maximum output energy of 170 µJ. Various OP-GaAs samples, with lengths of 5 or 10 mm, were used to implement the OPO, leading to an oscillation threshold spanning from 2 to 10 µJ. Using quasi-phase-matching periods of 64.8, 66.0, and 72.6 µm, temperature-tuning of the OPO was carried out in the 8–8.8 µm and the 10.3–10.9 µm spectral bands. Stable single-longitudinal mode emission of the OPO is obtained owing to Vernier spectral filtering provided by the NesCOPO scheme.

Short-range standoff detection of ammonia vapor around 10.4 ?m is performed with this source. All the components fit within a 45 cm?60 cm breadboard. We believe that this achievement paves the way to DIALs in the LWIR with increased robustness and reduced footprint.

10088-34, Session 8

Frequency down-conversion of 1 µm laser radiation to the mid-IR using non-oxide nonlinear crystals in a cascaded intracavity configuration *(Invited Paper)*

Valentin P. Petrov, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany); Andrey A. Boyko, Nadezhda Y. Kostyukova, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany) and Special Technologies, Ltd. (Russian Federation) and Novosibirsk State University (Russian Federation); Georgi M. Marchev, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany); Valdas Pasiskevicius, Royal Institute of Technology (Sweden); Dmitry B. Kolker, Novosibirsk State University (Russian Federation); Valeriy Badikov, Dmitrii Badikov, Galina Shevyrdyaeva, Kuban State University (Russian Federation); Andrius Zukauskas, Royal Institute of Technology (Sweden); Vladimir Panyutin, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany)

Cascaded optical parametric oscillators (OPOs) for down conversion of laser radiation into the mid-IR spectral range using non-oxide nonlinear crystals in the second stage have rarely been realized with intracavity pumping. Such compact and robust schemes profit from the higher intracavity pump power for the second stage provided by the signal or idler wave of an oxide crystal based first stage, in turn pumped as a rule at 1.064 µm by a Nd:YAG laser system. We investigated a singly-resonant OPO (SRO) based on AgGaSe2 (AGSe) intracavity pumped at ~1.85 µm by the signal pulses of a Rb:PPKTP doubly-resonant OPO (DRO). With two AGSe samples cut for type-I and II phase-matching, an extremely broad tuning range for the non-resonated idler was achieved, extending from 5.8 to ~18 µm.

In a similar set-up with the same nonlinear crystals and a dichroic half-wave plate, we studied also intracavity difference-frequency generation (DFG). This simpler scheme, which enables more efficient extraction of the mid-IR radiation, delivered pulse energy of 0.67 mJ at 7 µm, equivalent to an overall conversion efficiency from the 1.064 µm pump of 1.2%. Substituting AGSe by the new monoclinic nonlinear crystal BaGa4Se7 (BGSe) we achieved similar conversion efficiency and energy of 0.71 mJ. Heating the Rb:PPKTP crystal provided tuning of the DFG output up to ~8.2 µm. The main advantage of BGSe is its damage resistivity up to the maximum pump levels applied at 100 Hz. On the contrary, cumulative surface damage effects were observed in AGSe already at 10 Hz.

10088-35, Session 8

Efficient cascaded half-harmonic generation of mid-IR frequency combs *(Invited Paper)*

Alireza Marandi, Marc Jankowski, Ryan Hamerly, Stephen J. Wolf, Stanford Univ. (United States); Evgeni Sorokin, Technische Univ. Wien (Austria); Irina T. Sorokina, Norwegian Univ. of Science and Technology (Norway); Peter G. Schunemann, BAE Systems (United States); Martin M. Fejer, Robert L. Byer, Stanford Univ. (United States)

Half-harmonic generation is the reverse of second harmonic generation that happens in optical parametric oscillators (OPOs) at degeneracy. It is an intrinsically phase-locked down-conversion process, which can be used to efficiently transfer well-developed near-IR frequency combs to the mid-IR.

We overview recent experimental progress in cascading multiple stages of half-harmonic generation of femtosecond frequency combs starting from a 1-?m pump. We have achieved stable operation with efficiencies as high as ~64%, pulses as short as three optical cycles at 4 ?m, and output powers as high as 2.6 W at 2 ?m. Our recent numerical and analytical studies of nonlinear dynamics and different operation regimes of femtosecond OPOs indicate a path toward achieving even higher efficiencies and shorter pulses.

10088-36, Session 9

Large-scale artificial spin network based on time-multiplexed degenerate optical parametric oscillators for coherent Ising machine *(Invited Paper)*

Hiroki Takesue, Takahiro Inagaki, Kensuke Inaba, NTT Basic Research Labs. (Japan); Ryan Hamerly, Stanford Univ. (United States); Kyo Inoue, Osaka Univ. (Japan); Yoshihisa Yamamoto, Stanford Univ. (United States) and Japan Science and Technology Agency (Japan)

Solving the Ising model using artificial spin systems is now drawing attention as a promising approach to solve NP-hard combinatorial optimization problems. Such artificial spin systems include the superconducting qubit systems by D-Wave and the CMOS device system by Hitachi. Unlike those systems based on solid-state devices, a coherent

Ising machine (CIM) is a photonic system that employs lasers or degenerate optical parametric oscillators (DOPO) as artificial spins. In this talk, we describe our efforts to produce a large-scale DOPO network for a CIM that solves complex combinatorial optimization problems. We used dual-pump four-wave mixing in a 1-km highly nonlinear fiber (HNLF) to obtain phase-sensitive amplification in the 1.5-um band. By pumping the HNFL placed in a fiber cavity with dual-wavelength pulses at a 2-GHz repetition frequency, we generated more than 10,000 DOPOs multiplexed in the time domain. At well above the oscillation threshold, we observed that the DOPO phases were discretized to {0, pi}, indicating that they could be used as stable Ising spins. We also implemented one-dimensional (1D) Ising model with the DOPOs. We inserted a 1-bit delay Mach Zehnder interferometer into the fiber cavity so that nearest-neighbor coupling between the DOPOs was achieved. The experimental result showed that the behavior of the optically coupled DOPOs well matched the theory of the 1D Ising model, confirming that the DOPOs well simulated the characteristics of low-temperature spins.

10088-37, Session 9

Nonlinear frequency conversion of structured beams and Airy beam optical parametric oscillator *(Invited Paper)*

Goutam K. Samanta, A Aadhi, N. Apurv Chaitanya, M.V. Jabir, Physical Research Lab. (India)

Nonlinear optics have provided powerful means to generate tunable optical radiation inaccessible to ordinary lasers. While nonlinear frequency conversion processes are mostly dealt with laser beams in Gaussian spatial distribution, many of the scientific and technological applications require optical beams in various spatial structures. For example, optical vortices, having phase singularity (phase dislocation) in the wavefront, carries orbital-angular-momentum (OAM) per photon. The optical vortices are important for high resolution microscopy, quantum information, particle micro-manipulation, and lithography. Similarly, Airy beam, a non-diffraction waveform, has peculiar properties of non-diffraction, self-healing and self-acceleration. Due to such unique properties, the Airy beam finds many applications including curved plasma wave-guiding, long distance communication, and nonlinear frequency conversion. In this talk, we will discuss our recent results on nonlinear generation and interaction of various structured optical beams including optical vortices, perfect vortices, and hollow Gaussian beam and development of continuous-wave and ultrafast Airy beam optical parametric oscillators.

[1] N. Apurv Chaitanya, A. Aadhi, M. V. Jabir, and G. K. Samanta, Optics Letters, 40, 2614-2617 (2015).

[2] N. Apurv Chaitanya, S. Chaitanya Kumar, K. Devi, G. K. Samanta, and M. Ebrahim-Zadeh, Optics Letters 41, 2715-2718 (2016).

[3] M. V. Jabir, N. Apurv Chaitanya, A. Aadhi, and G. K. Samanta, Scientific Reports, 6, 21877 (2016).

[4] A. Aadhi, N. Apurv Chaitanya, M. V. Jabir, Pravin Vaity, R. P. Singh, and G. K. Samanta, Scientific Reports, 6, 25245 (2016).

[5] Apurv Chaitanya N., S. Chaitanya Kumar, A. Aadhi, G. K. Samanta, and M. Ebrahim-Zadeh, Scientific Reports 6, 30701 (2016).

10088-38, Session 9

Dispersion tuning of a narrow-linewidth picosecond OPO based on chirped quasi-phase matching with a volume Bragg grating

Delphine Descloux, Guillaume Walter, Jean-Baptiste Dherbecourt, Guillaume Gorju, Jean-Michel Melkonian, Myriam Raybaut, ONERA (France); Cyril Drag, Lab. Aimé-Cotton (France); Antoine Godard, ONERA (France)

We report on a new widely tunable synchronously-pumped optical parametric oscillator (SPOPO) architecture that exploit an axially chirped volume Bragg grating (VBG) to carry out dispersion tuning. Owing to the high dispersion induced by the chirped VBG, only a narrow spectral band, corresponding to a thin slice of the VBG, satisfies the synchronous-pumping condition. At a fixed position, the VBG is thus a narrow-band filtering element; the variation of its position along the cavity axis enables to tune the wavelength.

Owing to an aperiodic quasi-phase matching (QPM) nonlinear crystal providing a broad parametric gain spectral bandwidth, the OPO can be tuned by the simple axial translation of the VBG without moving any other part or changing the crystal temperature.

The SPOPO is singly resonant for the signal (~1.47 μm) and is pumped by a Nd:YVO4 mode-locked laser (76 MHz pulse repetition rate and 8 ps pulse duration). The nonlinear crystal is 60-mm long and is based on MgO-doped aperiodically poled lithium niobate containing a chirped QPM grating with a gain bandwidth of 40 nm for signal (and of 270 nm for idler). The VBG is 38 mm long and chirped (~10 ps/nm) with a reflection bandwidth of 40 nm for the signal around 1470.3 nm.

This approach enables us to tune the idler wavelength over 215 nm with a nearly Fourier-transform-limited linewidth. Rapid continuous tuning over 150 nm in 100 ms is also demonstrated by use of a direct-drive translation stage to rapidly move the VBG.

10088-39, Session 9

Combined visible and near-infrared OPA for wavelength scaling experiments in strong-field physics

David T. Lloyd, Univ. of Oxford (United Kingdom); Kevin O'Keeffe, Swansea Univ. (United Kingdom); Adam S Wyatt, Central Laser Facility, STFC Rutherford Appleton Laboratory (United Kingdom); Patrick N. Anderson, Daniel J. Treacher, Simon M. Hooker, Univ. of Oxford (United Kingdom)

We report the operation of an optical parametric amplifier (OPA) capable of producing gigawatt peak-power laser pulses with tunable wavelength in either the visible or near-infrared spectrum. Switching between the differing output wavelengths is simple and automatable, requiring only the rotation of a crystal and swapping of a dichroic mirror. We envisage this work will allow researchers to modify extant OPAs present in ultrafast laboratories to increase the wavelength coverage from these systems.

The three-stage OPA is synchronously pumped by 3 mJ, 40 fs, 800 nm wavelength pulses from a Ti:Sapphire chirped pulse amplification system. The first two stages produce an amplified, wavelength-tunable, near-infrared signal beam. The final stage has two distinct configurations. Configuration a) is optimized for further power amplification of the signal beam, producing >250 uJ, 80 fs pulses, tunable between 1250 and 1550 nm. In configuration b), >100 uJ, sub 100 fs pulses tunable between 490 - 530 nm are produced by optimization of sum-frequency generation between the pump and the amplified signal beam.

The OPA was used to generate high-order harmonics in noble gases with photon energies up to 85 eV. By switching between configurations, harmonic spectra were recorded over a wide range of driving wavelengths. The results are shown to agree well with numerical simulations of the wavelength scaling of high harmonic generation. This flexible source of femtosecond pulses presents an ideal tool for exploring the wavelength-dependence of strong-field phenomena, in both the multi-photon and tunnel ionization regimes.

Conference 10089: Real-time Measurements, Rogue Phenomena, and Single-Shot Applications II

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Part of Proceedings of SPIE Vol. 10089 Real-time Measurements, Rogue Phenomena, and Single-Shot Applications II

10089-1, Session 1

Analog gearbox for real-time metrology

Bahram Jalali, Jacky C. K. Chan, Ata Mahjoubfar, Daniel R. Solli, Mohamad H. Asghari, Univ. of California, Los Angeles (United States)

Time stretch accelerator is a powerful engine designed to assist in acquisition, feature extraction and storage of fast optical data. It has enabled the discoveries of optical rogue waves and the soliton explosion phenomena, observation of the birth of laser mode locking, detection of relativistic electron structures in accelerators, and identification of rare cancer cells in blood. A new paradigm known as warped (anamorphic) stretch promises to create yet unprecedented capabilities. Functioning as a self-adaptive information gearbox, this analog engine reshapes the evolution of a wideband streaming data based on the local entropy such that the instantaneous bandwidth is within Nyquist bandwidth of the digitizer. The instantaneous bandwidth adapts itself to the signal speed leading to real-time optical data compression. Nonlinear group delay dispersion modes form primitive building blocks to create information gearboxes that match the speed of the incoming optical waveform to that of the analog to digital converter and digital processor. These nonlinear dispersion primitives function as time-stretch wavelets, the properties of which is governed by their symmetry. Dispersion basis functions synthesize gearbox functions that are reconfigurable and can be implemented in analog optical domain for processing of real time optical data. Two dimensional version of these operations have been implemented in digital domain and have created a new class of digital image processing algorithms with powerful functionalities ranging from data compression to edge detection, feature enhancement and machine learning. Additional applications of these physics inspired algorithms include coding, signal classification, and enhancement of signal-to-noise during ultrafast analog-to-digital conversion.

10089-2, Session 1

Single-shot observation of optical rogue waves in integrable turbulence using time microscopy *(Invited Paper)*

Pierre Suret, Rebecca El Koussaifi, Lab. de Physique des Lasers, Atomes et Molécules (France); Alexey M. Tikan, Lab. de Physique des Lasers, Atomes et Molécules (France); Clement Evain, Lab. de Physique des Lasers, Atomes et Molécules (France); Christophe Szwaj, Serge Bielawski, Stéphane Randoux, Univ. des Sciences et Technologies de Lille (France)

We present the first direct single-shot recordings of optical rogue waves by using a specially-designed Time Microscope ultrafast acquisition system [1,2,3]. The signal under consideration is nonlinear random light that is neither periodic nor pulsed. Our homemade time microscope is divided in two parts : a time lens and a single-shot spectrum analyzer. The time lens is provided by sum frequency generation between the signal and a 25 ps chirped pulse. The 250 fs temporal resolution of our time microscope allows us to investigate the fast dynamics underlying integrable turbulence [4,5] arising in optical fibres. In our experiments, partially coherent waves emitted by a amplified spontaneous emission light source experience nonlinear propagation in a single mode optical fibre. Observations performed with the time microscope at the output of the fibre immediately reveals the emergence of

intense peaks, with powers frequently exceeding the average power < P> by factors of 10-50. Starting from random fluctuations having typical time scale around 5-10ps, those extreme peaks are also found to be extremely narrow, with time scales of the order of several hundreds of femtoseconds. The probability density function of optical power is found to evolve from exponential distribution that corresponds to linear superposition of waves to heavy tailed distribution. The experiments are very well reproduced by numerical simulations of the one dimensional nonlinear Schrödinger Equation. Moreover the experimental data analysis reveals the emergence of coherent structures that are locally extremely well fitted by the Peregrine solitons.

[1] Suret et al., arXiv:1603.01477, (2016)

[2] Kolner, B. H. and Nazarathy, M. Opt. Lett. 14, (1989)

[3] Bennett, C. & Kolner, B. Opt. Lett. 24, (1999)

[4] Agafontsev, D. & Zakharov, Nonlinearity 28, 2791 (2015)

[5] Walczak, P., Randoux, S. & Suret, P., Phys. Rev. Lett. 114, 143903 (2015)

10089-3, Session 1

Real-time observation of hidden multi-soliton dynamics in a few-cycle Ti:Sapph oscillator *(Invited Paper)*

Georg Herink, Felix Kurtz, Georg-August-Univ. Göttingen (Germany); Daniel R. Solli, Bahram Jalali, Univ. of California, Los Angeles (United States); Claus Ropers, Univ. of California, Los Angeles (United States) and Georg-August-Univ. Göttingen (Germany)

Mode-locked lasers are a prominent example of dissipative nonlinear systems which support soliton bound-states. However, rapid dynamic interactions between such soliton complexes with pico- to femtosecond separation are mostly invisible to standard laser characterization techniques, including scanning interferometric autocorrelation, temporally-averaged spectroscopy, and single-shot measurements at low repetition rates. Here, we apply the time-stretch dispersive Fourier transform (TS-DFT) and high-speed real-time sampling to resolve fast intracavity soliton dynamics.

The multi-soliton complexes are induced in a common broadband commercial laser oscillator (~10 fs pulse width) by applying external perturbations. The optical spectrum of a multi-pulse complex corresponds to a spectral interferogram, encoding both the distances and the relative phase of its constituents. In order to access this information for fast bound-state dynamics, rapid spectral detection is essential. The presented single-shot spectroscopy is enabled via the transformation of spectral information to the time-domain via group-velocity-dispersion in a long optical fiber, and subsequent high-bandwidth real-time acquisition [1]. By recording such single-shot spectral interferograms, we can resolve a diverse set of dynamic bound-states, and identify unprecedented rapid dynamics of bound-states with regular, periodic and aperiodic behavior in a state-of-the-art broadband Kerr-lens oscillator.

[1] G. Herink, B. Jalali, C. Ropers, D.R. Solli, “Resolving the buildup of femtosecond mode-locking with single-shot spectroscopy at 90 MHz frame-rate” Nat. Photon. 10, 321–326 (2016).

10089-4, Session 1

Single-shot spectroscopy of broadband Yb fiber laser *(Invited Paper)*

Masayuki Suzuki, Shin Yoneya, Hiroto Kuroda, Saitama Medical Univ. (Japan)

Nonlinear polarization evolution is an efficient technique for achieving the passive mode-locking in fiber laser oscillator, which can produce a broadband spectrum and ultrafast pulses. This passive mode-locking fiber laser oscillator dynamics depends strongly on a nonlinear effect. The induced nonlinear effect in the fiber of the cavity brings a spectral broadening of laser pulse, and the broadband spectrum and ultrafast pulse generates from the fiber oscillator as results. Simultaneously this nonlinear effect causes the transition of laser pulse structure stochastically and non-periodically. This phenomena timescale is from nanoseconds to milliseconds, and therefore this particular event of single pulse spectrum cannot be detected by using a conventional spectrometer which consists on a grating and a linear array detector. Recent progress of a time stretch dispersive Fourier transform technique is enabling the single-shot spectral measurement of a femtosecond laser pulse in real time at a frame rate of ~100 MHz. To understand the dynamics of Yb fiber laser oscillator, we measure the single-shot spectrum by using Roguescope which is based on the time stretch dispersive Fourier transform. In this presentation, we report on an experimental study of the single-shot spectrum transition in the mode-locking and noise-like pulse from a home-made broadband Yb fiber laser oscillator. The spectral evolution of the mode-locking and noise-like pulse can be observed by adjusting the LD current, the polarization of waveplates angle, and the net of cavity dispersion. The details of experimental results will be discussed in the conference.

10089-5, Session 1

Real time measurements of spontaneous breathers generated by modulation instability in optical fibre *(Invited Paper)*

John M. Dudley, FEMTO-ST (France); Mikko Närhi, Tampere Univ. of Technology (Finland); Benjamin Wetzel, Institut National de la Recherche Scientifique (Canada); Cyril Billet, Univ. de Franche-Comté (France) and FEMTO-ST (France); Jean-Marc Merolla, Shanti Toenger, Thibaut Sylvestre, FEMTO-ST (France); Roberto Morandotti, Institut National de la Recherche Scientifique (Canada); Goëry Genty, Tampere Univ. of Technology (Finland); Frédéric Dias, Univ. College Dublin (Ireland)

Modulation instability is a fundamental process of nonlinear physics, leading to the unstable breakup of a constant amplitude solution of a particular physical system. There has been particular interest in studying modulation instability in the cubic nonlinear Schr"{o}dinger equation (NLSE) which models a wide range of nonlinear systems including superfluids, fiber optics, plasmas and Bose-Einstein condensates. Modulation instability in the NLSE is also a significant current area of study in the context of understanding the emergence of high amplitude or high intensity events that satisfy "rogue wave" statistical criteria. Here, exploiting recent advances in real time ultrafast optical metrology via an optical time lens system, we perform real-time measurements in an NLSE optical fibre system of the unstable breakup of a continuous wave field, simultaneously characterising emergent modulation instability breathers, and their associated statistics. Our results allow quantitative comparison between experiment, modelling, and theory, and we show very good agreement in both extracted intensity profiles and associated statistics.

10089-6, Session 1

Hidden amplitude-phase correlations in the carrier-envelope noise of mode-locked lasers *(Invited Paper)*

Günter Steinmeyer, Nils Raabe, Tianli Feng, Mark Mero, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany); Haochen Tian, Tianjin University (China) and Tianjin University (China); Youjian Song, Tianjin University (China); Wolfgang Hänsel, Menlo Systems (Germany) and Menlo Systems GmbH (Germany); Ronald Holzwarth, Menlo Systems GmbH (Germany); Alexander Sell, Toptica Photonics AG (Germany) and Toptica Photonics AG (Germany); Armin Zach, Toptica Photonics AG (Germany)

Rogue waves in optical fiber supercontinua emerge because quantum noise induces a modulation instability, which creates large shot-to-shot variations in the output spectra of the fiber. These variations are seeded by amplified spontaneous emission noise of the driver laser. Apart from the pulse energy variations that induce rogue waves, quantum noise also causes timing jitter variations and phase noise in the driver laser, which are all expected to be mutually uncorrelated. As we will show by experimental verification, the absence of correlations typically holds at frequencies above the inverse upperstate lifetime, as expected. Our experimental analysis is based on measuring the carrier-envelope beat note of 5 different femtosecond oscilators, including three commercial Er:fiber lasers, one Yb:fiber laser, and one Ti:sapphire laser. A long beat note time series is then numerically demodulated to isolate amplitude and frequency modulations. While we do not observe much variation in the analysis for different gain media, one of the Er:fiber lasers shows markedly different behavior and exhibits a correlation between frequency and amplitude noise at megahertz frequencies. We convinced ourselves that both noise components are of stochastic origin, i.e., they clearly relate to quantum noise. It is striking that among the 5 lasers under test, the laser with the high-frequency correlation is the only one that utilizes a semiconductor saturable absorber mirror (SESAM). In an attempt explain the high-bandwidth correlation, we used the Kramers-Kronig relation to theoretically compute intracavity phase variations that would result from pulse energy variations on the quantum noise level. In fact, the computed coupling effects of an exciton resonance in the SESAM appear strong enough to explain the findings.

10089-7, Session 1

Unveiling relativistic electron bunch microstructures and their dynamical evolutions, using photonic time-stretch *(Invited Paper)*

Clément Evain, Christophe Szwaj, Marc Le Parquier, Serge Bielawski, Univ. des Sciences et Technologies de Lille (France); Eléonore Roussel, Elettra-Sincrotrone Trieste S.C.p.A. (Italy); Marie-Agnès Tordeux, Laurent Manceron, Jean-Blaise Brubach, Jean-Paul Ricaud, Lodovico Cassinari, Marie Labat, Marie-Emmanuelle Couprie, Pascale Roy, Synchrotron SOLEIL (France); Andrii Borysenko, Karlsruher Institut für Technologie (Germany); Nicole Hiller, Karlsruher Institut für Technologie (Germany) and Paul Scherrer Institut (Switzerland); Anke-Susanne Mueller, Patrik Schoenfeld, Johannes L. Steinmann, Karlsruher Institut für Technologie (Germany)

Relativistic electrons emit light at various wavelength (from the terahertz to the X-ray domains) when they are deviated by magnetic fields. This process is at the basis of the light sources called synchrotron radiatation facilities.

Operation of these machines requires to understand and/or master various dynamical instabilities, that can be of very fundamental nature. In particular, above a given charge threshold, interaction between an electron bunch and its own emitted radiation leads to the so-called microbunching instability. This is characterized by the spontaneous appearance of longitudinal structures – or patterns – in the charge density distribution, at millimeter/sub-millimeter scale, that evolve in a complex way. These microstructures

are responsible for the emission of powerful coherent light pulses in the terahertz domain.

Up to recently, these structures have been particularly challenging to observe, because of their millimeter/sub-millimeter wavelength (i.e., picosecond time-scale), and their short revolution time in the accelerator (microseconds or less).

Here we show that the microstructures and their dynamics are now experimentally accessible. The principle consists in using the so-called photonic time stretch for "slowing-down" the THz information, so that it can be recorded by an oscilloscope. Two complementary approaches have been used. At SOLEIL we monitored the THz pulses of coherent radiation emitted in the far field. At ANKA, we directly probed directly the near field in the vicinity the electron bunch. Direct comparison with theoretical models (based on the Vlasov-Fokker-Planck equation) are also presented.

10089-8, Session 2

Optical pulse waveform profiling through real-time stamping to corresponding characteristic spectra *(Invited Paper)*

Tsuyoshi Konishi, Yu Yanasaki, Tomotaka Nagashima, Osaka Univ. (Japan)

We report an optical pulse profiling method which has a potential to enable real-time stamping of optical pulse waveforms to corresponding characteristic spectra without any user's expertise and skills. The profiling process performs the following 4 steps: First, we acquired both an input power spectrum and an output one suffered from nonlinear optical phenomena in a high nonlinear fiber (HNLF). Secondly, random trial spectral phase data are fed to HNLF propagation calculation based on a nonlinear Schrödinger equation and calculated output power spectrum data are provided. Thirdly, the algorithm compares the difference between the original output power spectrum and the calculated one. The algorithm re-tunes a trial spectral phase data and repeat propagation calculation when the difference is not enough small relative to the target level. Finally, the algorithm stops and provides a spectral phase information of the input optical pulse when the difference is enough small relative to the target level and a temporal profile can be easily calculated after inverse Fourier transform of retrieved spectrum. Its performance was confirmed by comparison with conventional instruments. With the current HNLF which has a nonlinear coefficient of ?=23(/W/Km), the profiling sensitivity can be estimated to at least less than 20 pJ (average power). In addition, its polarization free characteristic could make it more attractive. The concept can be extended for real-time measurement of pulse-by-pulse phenomena provided the use of fast spectrum analyzers enable to acquire and storage pulse-by-pulse spectrum in real-time.

10089-9, Session 2

Billion frames per second spectrum measurement for high-repetition-rate optical pulses based on time stretching technique *(Invited Paper)*

Hideaki Furukawa, Takeshi Makino, National Institute of Information and Communications Technology (Japan); Mohammad H. Asghari, Paul Trinh, Time Photonics, Inc. (United States); Bahram Jalali, Univ. of California, Los Angeles (United States); Xiaomin Wang, Tetsuya Kobayashi, Optoquest Co., Ltd. (Japan); Wai S. Man, Kwong Shing Tsang, Amonics Ltd. (Hong Kong, China); Naoya Wada, National Institute of Information and Communications Technology (Japan)

Recently, ultra-fast optical pulses with femtosecond or picosecond pulse width have been utilized for elucidating ultra-fast phenomena of substances, manufacturing fine-structure and measuring object shape in optical measurement field. On the other hand, in optical communication field, the capacity expansion of a single channel using ultra-fast optical pulses has been studied in order to increase the capacity of optical fiber transmission. Therefore, the characteristic measurement for ultra-fast optical pulses has become increasingly essential.

One of the challenges is the development of high-speed spectrum measurement technologies for high-repetition-rate optical pulses. Since conventional spectrum analyzers take time to do wavelength sweeping, the number of measured spectrum in one second (frame rate) is low. Therefore, the spectral analysis for individual pulse is difficult and the important information might be lost at high repetition-rate.

In this study, in order to achieve a high-speed spectrum measurement, we exploit a fiber chromatic dispersion-based wavelength-to-time mapping and time stretching technique for high-repetition-rate optical pulses. By receiving the stretched optical pulses with a digital oscilloscope, it is possible to measure the spectrum of individual pulse. Moreover, by using a higher-speed digital oscilloscope and/or increasing the amount of chromatic dispersion, the wavelength resolution can be improved in this measurement.

We experimentally demonstrate the spectrum measurement for an optical pulse train with 1 GHz repetition rate. The pulse width and the wavelength bandwidth are 1.6 ps and 2.0 nm at a central wavelength of 1550 nm, respectively. As a result of applying a chromatic dispersion of -100 ps/nm and receiving stretched optical pulses with a 16 GHz bandwidth 50 Gsample/s digital oscilloscope, the processing for 1 GHz optical pulse train and one billion frame rate measurement are achieved with the wavelength resolution of approximately 150 pm.

10089-10, Session 2

Real-time spatiotemporal measurement of ultrafast fields from multimode optical fibers *(Invited Paper)*

Rick Trebino, Zhe Guang, Michelle Rhodes, Georgia Institute of Technology (United States)

Multimode fiber (MMF) is receiving increasing attention. This is in part because MMF could play an important role in expanding the transmission volume in optical telecommunications. With their larger core areas, MMFs allow mode-division multiplexing and hence a significant increase in the number of available data channels

Essentially all applications of MMFs depend on information in the transmitted optical fields, in particular, the different spatial and temporal behaviors of the various modes in the MMF. The output fiber fields are, in general, spatiotemporally complex, especially when ultrashort pulses are involved, as the various spatial modes can separate in time and spread due to dispersion, often by differing amounts.

To measure the complete spatiotemporal intensity and phase of ultrashort pulses with arbitrary shape, we have recently developed a compact, single-camera-frame technique called Spatially and Temporally Resolved Intensity and Phase Evaluation Device: Full Information from a Single Hologram (STRIPED FISH). STRIPED FISH requires a spatially filtered reference pulse measured temporally by frequency-resolved optical gating (FROG), whose complete spatiotemporal intensity and phase are thus known. STRIPED FISH then simultaneously generates multiple holograms at different frequencies on a single camera frame, yielding the unknown pulse completely in space and frequency. We use STRIPED FISH to measure pulses emerging from several MMFs. We have also plotted intuitive movies of the emerging pulse trains to display their spatial, temporal, and spectral field variations as the eye would, in principle, see them.

10089-11, Session 2

Roguescope: Single-shot high-throughput spectroscopy at billion frames per second *(Invited Paper)*

Mohammad H. Asghari, Time Photonics, Inc (United States); Paul D. Trinh, Time Photonics, Inc. (United States); Bahram Jalali, Univ. of California, Los Angeles (United States)

The real-time measurement of fast non-repetitive events is arguably the most challenging problem in the field of instrumentation and measurement. These instruments are needed for investigating rapid transient phenomena such as chemical reactions, fast physical phenomena, phase transitions, protein dynamics in living cells and impairments in data networks. Optical spectrometers are the basic instrument for performing sensing and detection in chemistry, physics and biology applications. Unfortunately, the scan rate of a spectrometer is often too long compared with the timescale of the physical processes of interest. In terms of conventional optical spectroscopy, this temporal mismatch means that the instrument is too slow to perform real-time single-shot spectroscopic measurements. Single-shot measurement tools such as frequency-resolved optical gating (FROG) and spectral phase interferometry for direct electric-field reconstruction (SPIDER) are, although powerful, therefore unable to perform pulse-resolved spectral measurements in real time.

Roguescope is a commercially available single-shot optical spectrometer with a frame rate of up to Billion frames per second, at least tens of thousand times faster than the next fastest spectrometer. The Roguescope real-time capability is enabled by photonic time-stretch implemented by Time-Stretch Dispersive Fourier Transform. The Roguescope can capture large data sets to reveal rare events with meaningful accuracy. Applications include optical rouge waves, laser transients, chemical reactions, and nonlinear dynamics. RogueScope is an essential tool for measurements of fast stochastic processes such as laser transients, rare events and outliers in optical systems. RogueScope is ideal for capturing non-Gaussian statistics that are signatures of complex dynamics.

10089-12, Session 2

88 MHz pixel-rate multi-photon imaging with swept-source FDML laser *(Invited Paper)*

Sebastian N. Karpf, Bahram Jalali, Univ. of California, Los Angeles (United States)

In this talk we present a new instrument for rapid point-scanning in laser imaging. We circumvent the inertia limit of galvanometric mirrors by employing passive, diffraction-based scanning. A wavelength-swept FDML laser is modulated to short pulses and amplified in order to reach high peak powers for multi-photon microscopy. The FDML laser light is modulated to pulses by an electro-optical modulator (EOM), generating 100ps pulses at up to 88MHz repetition rate (programmable). The peak power can be adjusted by ytterbium-doped fiber amplifiers (YDFAs). By sending these spectrally swept pulses on a diffraction grating, a spectral brush is generated. Thus, pixels along a line are addressed sequentially in time at typically 88MHz pixel rate. The line-rate is given by the sweep-rate of the FDML (342kHz) and can go beyond MHz rates. We discuss applications for fast imaging, especially when a fast pixel-wise illumination is desired. In one application, we show non-linear excitation in multi-photon imaging, where both two-photon excited fluorescence microscopy (TPM) and fluorescence lifetime imaging (2P-FLIM) are acquired in parallel. Therefore, the pixel-wise generated fluorescence signal is recorded on a fast photomultiplier tube (PMT) and digitized using a fast oscilloscope. Both imaging modalities are recorded at line–rates of 342kHz and frame rates in excess of 1 kHz. Additionally, the flexibility inherent in the direct modulation is harnessed to achieve non-linear mapping and warped sampling of the field-of-view. In all, this new instrument, coined Two-Photon Imaging by diffracted swept-laser excitation (TIDE), surpasses the speeds of inertia-based scanning mechanisms and opens up new applications for real-time measurements in non-linear imaging.

10089-14, Session 3

Broadband laser ranging development at the DOE Labs *(Invited Paper)*

Corey V. Bennett, Lawrence Livermore National Lab. (United States); Brandon M. La Lone, National Security Technologies, LLC (United States); Patrick W. Younk, Los Alamos National Lab. (United States); Edward P. Daykin, National Security Technologies, LLC (United States); Michelle A. Rhodes, Lawrence Livermore National Lab. (United States)

Broadband Laser Ranging is a new diagnostic being developed in collaboration across multiple USA Dept. of Energy facilities. Its purpose is to measure the precise position of surfaces and particle clouds moving at km/s. The diagnostic uses spectral interferometry to encode distance into a modulation in the spectrum of a mode-locked fiber laser, and dispersive Fourier transformation to map the spectral modulation into time, thereby enabling recording of range information in the time-domain on a fast oscilloscope every 50-80 ns. This talk will present some of the hardware design issues, system tradeoffs, calibration issues, and experimental results.

BLR is being developed as an add-on to conventional Photonic Doppler Velocimetry (PDV) systems because PDV often yields incomplete information when lateral velocity components are present, or when there are drop-outs in the signal amplitude. In such case integration of the velocity from PDV can give incorrect displacement results. Experiments are now regularly fielded with over 100 channels of PDV, and BLR is being developed in a modular way to enable high channel counts of BLR and PDV recorded from the same probes pointed at the same target location. In this way instruments will independently record surface velocity and distance information along the exact same path.

10089-15, Session 3

Broadband laser ranging: Signal analysis and interpretation *(Invited Paper)*

Natalie Kostinski, Michelle A. Rhodes, Lawrence Livermore National Lab. (United States); Jared Catenacci, Marylesa Howard, Brandon M. La Lone, National Security Technologies, LLC (United States); Corey V. Bennett, Lawrence Livermore National Lab. (United States); Patrick J. Harding, Los Alamos National Lab. (United States)

Broadband Laser Ranging (BLR) is essentially a spectral interferometer used to infer distance to a moving target. A BLR record is a sequence of pulses representing consecutive target positions. Generally speaking, the chromatic dispersion in the fiber maps spectral information into the time domain, yielding chirped beat signals at the detector. In order to infer distance to a target, the underlying pulses must be consistently registered and subtracted despite environmentally-induced pulse shape variability. Then, nonlinear transformation of the quadratic phase, the subsequent FFT peak frequency, and the relationship determined by the calibration data result in a target position. Approaches include low pass filters for estimates of the pulse envelope and zero crossings and a quadrature method for determining the phase of the chirped signal. Data acquired on explosively-driven experiments is presented and the relative merits of the methods are discussed. BLR has been recently fielded on explosively driven experiments at Lawrence Livermore National Laboratory, National Security Technologies, and Los Alamos National Laboratory.

10089-16, Session 3

Velocity measurement using frequency domain interferometer and chirped pulse laser *(Invited Paper)*

Katsuhiro Ishii, Yasuhiko Nishimura, Yoshitaka Mori, Ryohei Hanayama, Yoneyoshi Kitagawa, The Graduate School for the Creation of New Photonics Industries (Japan); Takashi Sekine, Nakahiro Sato, Takashi Kurita, Toshiyuki Kawashima, Hamamatsu Photonics K.K. (Japan); Atsushi Sunahara, Osaka Univ. (Japan); Yasuhiko Sentoku, Univ. of Nevada, Reno (United States); Eisuke Miura, National Institute of Advanced Industrial Science and Technology (Japan); Akifumi Iwamoto, Hitoshi Sakagami, National Institute for Fusion Science (Japan)

An ultra-intense short pulse laser induce a shock wave in material and compress it. The pressure of shock compression is stronger than a few tens GPa. To characterize shock wave, time-resolved velocity measurement in nano- or pico-second time scale. Velocity Interferometer System for Any Reflector (VISAR) has been widely used to reference light are fed to the spectrometer and the spectral interferogram is recorded. From the spectral fringes, the measure the velocity of shock wave in material.

Frequency domain interferometer and chirped pulse laser also provide single-shot time-resolved velocity measurement. We have developed a laser-driven shock compression system and frequency domain interferometer with CPA laser. The pulse width and the chirp rate of the probe beam are 640 ps and 25.6 ps /nm, then temporal resolution is about 10 ps.

In the presentation, we explain the principle of velocity measurement using a frequency domain interferometer and a chirped pulse laser and show the numerically calculated spectral interferograms. Moreover we demonstrate the laser driven shock wave generation and shock velocity measurement. The main part from CPA laser is compressed and irradiate a single crystal yttria-stabilized zirconia (s-YSZ) with a thickness of 150mm. The peak intensity and the pulse width of the main pulse are 5x1016 W/cm2 and 180 fs, respectively. A part of main pulse is used as a probe beam and illuminates the sample from the back surface of the sample. The reflected light from the back surface and the temporal profile of the velocity is analyzed.

10089-30, Session 3

Single-shot time stretch stimulated Raman spectroscopy *(Invited Paper)*

Francesco Saltarelli, Vikas Kumar, Daniele Viola, Francesco Crisafi, Fabrizio Preda, Giulio Cerullo, Dario Polli, Politecnico di Milano (Italy)

No Abstract Available

10089-17, Session 4

Spatiotemporal coupling effects in ultrashort pulses and their visualization

Michelle Rhodes, Zhe Guang, Rick Trebino, Georgia Institute of Technology (United States)

Our recently developed general theory of first-order spatiotemporal distortions in ultrashort laser pulses provides a helpful framework for understanding beam couplings in ultrashort pulses. The theory describes both amplitude and phase couplings between spatial, temporal, angular, and spectral coordinates. While the four amplitude coupling terms (spatial chirp, angular dispersion, pulse-front tilt, and the ultrafast lighthouse effect) are generally understood, the four phase coupling terms are much more difficult to understand and visualize. This is most likely because phase couplings are difficult to plot in a meaningful way. In general, visualizing both pulse amplitude and phase couplings completely in space and time is a difficult problem.

In this work, we present an unprecedented approach to understanding and visualizing an arbitrary pulse in time and space, revealing, in particular, its spatiotemporal couplings, especially for the elusive phase couplings. Specifically, we have developed a 4D movie-plotting approach to display the complete spatiotemporal electric field, including diffraction effects. Our resulting 4D movies show a pulse as it would appear to the eye if one could slow time by a factor of ~1012. From the propagated electric field, we generate a movie of the pulse propagating in time and space. Using this technique, the effects of spatiotemporal amplitude and phase couplings of pulses can be readily and intuitively displayed, which is a long-overdue capability, essential for ultrashort-pulse measurements and applications.

10089-18, Session 4

Measuring the dynamic of Rogue waves by unique time-lens configuration

Moti Fridman, Avi Klein, Bar-Ilan Univ. (Israel)

We developed a unique time-lens configuration for measuring in real time the temporal evolution of Rogue waves in optical fibers. Our time-lens configuration is based on array of several time-lens and we obtain the temporal evolution of Rogue waves by super-resolution techniques similar to a 3D imaging by a lens array.

The experimental and calculated results as well as the theoretical background will be presented.

10089-19, Session 4

Spatio-temporal extreme events in a laser system

Cristina Rimoldi, Institut Non Linéaire de Nice Sophia Antipolis (France) and Institut Non Linéaire de Nice Sophia Antipolis (France); Stéphane Barland, Institut Non Linéaire de Nice Sophia Antipolis (France) and Univ. Côte d'Azur (France); Franco Prati, Univ. degli Studi dell'Insubria (Italy); Giovanna Tissoni, Institut Non Linéaire de Nice Sophia Antipolis (France)

In this contribution, we show numerical results about extreme events occurring in the transverse section of the field emitted by a broad-area semiconductor laser (VCSEL) with an intra-cavity saturable absorber, as the one used in some experiments.

The system under study may present multiple stable solutions such as stationary cavity solitons, chaotic cavity solitons, and a global turbulent solution, that are all coexisting below the laser threshold with the non-lasing zero-intensity solution. Unlike the previous literature about optical rogue waves in spatially extended optical systems, we developed a numerical method for the individuation of the spatio-temporal maxima of the transverse field intensity: each maximum appearing in the space profile is followed during its time evolution, and an "event" is counted only when its peak intensity reaches the maximum value also in time. Studying the statistics of these events both below and above the laser threshold, we identify extreme events according to different definitions and indicators, and indicate the best parameter set to observe them in experiments.

A comparison with the existing methods of statistical analysis of extreme events in other transverse systems has been also developed.

Below the laser threshold the rogue waves may coexist, depending on the

parameters, with stationary or self-pulsing cavity solitons. We compare the spatial profile of the rogue waves and that of the stationary solitons and the spatial and temporal profiles of the rogue waves and those of self-pulsing solitons.

10089-20, Session 4

Polarization extinction ratio and polarization dependent intensity noise analyses in long-pulse supercontinuum generation

Catherine Chin, NKT Photonics A/S (Denmark); Rasmus Dybbro Engelsholm, DTU Fotonik (Denmark); Peter M. Moselund, Thomas Feuchter, Lasse Leick, NKT Photonics A/S (Denmark); Adrian Podoleanu, Univ. of Kent (United Kingdom); Ole Bang, DTU Fotonik (Denmark)

We investigate the polarization of supercontinuum generated in nominally non-birefringent silica photonic crystal fibers over the entire spectrum of the source (450-2400 nm). We demonstrate that the degree of polarization varies over the spectrum but that some parts of the spectrum show stable polarization extinction ratios (PER) of over 10 dB. We experimentally demonstrate how the spectrally resolved polarization develops with increasing power and along the length of the nonlinear fiber. The experimental results are compared to numerical simulations of coupled polarization states mimicking the experimental conditions. Subsequently, a single-shot pulse-to-pulse polarization dependent relative intensity noise (PD-RIN) was measured and the noise characteristics were analyzed using long-tailed and rogue wave statistics. To do this, we used a range of 10 nm narrow bandpass filters (BPF) between 550 nm to 2200 nm, and fast photo detectors, to record 800 consecutive pulses. Peaks from these pulses are first extracted, then distribution of their pulse height histogram (PHH) is constructed. Analysis using higher-order moments about the mean (variance, skewness and kurtosis) showed that: (1) around the pump wavelength of 1064nm, the PD-RIN is lowest, PHH exhibits a Gaussian distribution, and higher order moments are zero, (2) further away from pump, PD-RIN increases in parabolic fashion, PHH follows a left-skewed long-tailed Gamma distribution, and higher-order moments increase. Spectrally, the difference of the PD-RIN in the two orthogonal axes increases with PER.

10089-21, Session 4

Wavelength-multiplexed ghost imaging in time

Piotr Ryczkowski, Margaux Barbier, Goëry Genty, Tampere Univ. of Technology (Finland); Ari T. Friberg, Univ. of Eastern Finland (Finland); John M. Dudley, FEMTO-ST (France)

Ghost imaging is an optical technique that produces the image of an object by correlating the total amount of light transmitted through the object with the random intensity pattern that the object is irradiated with. When the technique is used with incoherent light sources, characterized by random temporal intensity fluctuations, it requires recording a very large number of distinct realizations to obtain a faithful image reproduction. In order to significantly reduce the number of realizations, one can use pre-programmed known patterns, so-called computational ghost imaging.

Recently, ghost imaging was transposed into the time-domain to image ultrafast varying waveforms. Here, we report on a novel proof-of-concept experiment of computational ghost imaging in the time domain using wavelength multiplexing. By encoding different time-varying intensity patterns onto separate wavelength channels, we can perform simultaneous measurement of multiple realizations. This allows us to perform ghost imaging in real-time, without the need of probing the time-varying object repeatedly. Specifically, we use a programmable spectral filter to encode a set of 32 Hadamard-like time-varying intensity patterns onto a broadband LED light source. An electro-optic intensity modulator driven by an electrical waveform is used to create the time-varying object to be measured. The object is then reconstructed “blindly” by correlating the time-averaged transmission of each wavelength channels with the digitized form of the time-varying Hadamard patterns that illuminate the object. The temporal resolution of the measurement is currently to 0.5 s limited by the speed at which the variable spectral filter can be manipulated.

10089-22, Session 5

Extreme events and phase dynamics in a forced semiconductor ring laser

François Gustave, Lab. de Physique des Lasers, Atomes et Molécules (France) and Univ. des Sciences et Technologies de Lille (France); Lorenzo L. Columbo, Univ. degli Studi di Bari Aldo Moro (Italy); Massimo Brambilla, Politecnico di Bari (Italy); Franco Prati, Univ. degli Studi dell’Insubria (Italy); Giovanna Tissoni, Institut Non Linéaire de Nice Sophia Antipolis (France); Cristina Rimoldi, Institut Non Linéaire de Nice Sophia Antipolis (France) and Univ. Côte d’Azur (France); Stéphane Barland, Institut Non Linéaire de Nice Sophia Antipolis (France)

In this contribution, we analyse the nucleation of extreme events in a fast (nanosecond time scale) spatially extended oscillatory medium with coherent forcing. In particular, we focus on the predictability of individual events and their analysis in terms of the (spatio-temporally resolved) phase dynamics of the system.

The experimental system is a strongly multimode ring semiconductor laser consisting of a millimetric semiconductor active medium enclosed in a 1-m long optical cavity under coherent external forcing. While similar experiments have often been performed in single mode lasers (described by lowdimensional dynamical systems) the description of this particular experiment requires the use of partial differential equations taking into account the propagation of the electric field.

In the single-mode case, the many accessible dynamical regimes are well documented both experimentally and theoretically and include frequency and phase locking, bistability, excitability and chaos. In the multimode case (and especially with the geometrical characteristics of this particular experiment), the system is much less documented in particular due to the stiffness of the model equations and its very large number of degrees of freedom.

We analyze our results thanks to a set of partial differential equations describing the field and semiconductor medium evolution. Here, we analyze the impact of phase dynamics in the formation of coherent structures in this system, from phase solitons to extreme events. In phase-unstable regimes, where usually strong multimode competition occurs, we attempt the prediction of extreme events based on local phase space reconstruction.

10089-23, Session 5

Suppression of noise of soliton pulses using a polarization-imbalanced nonlinear loop mirror

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The generation of clean solitons is important for a number of applications such as optical analog-to-digital conversion (ADC) based on soliton self-frequency shift. In real sources the quality of the pulses is deteriorated by dispersive waves, continuous wave (CW), and amplified spontaneous emission (ASE). The dispersive waves appear in the spectral profile as side-lobe components that would limit the resolution of ADC. Spectral compression techniques cause the appearance of a pedestal on the spectrum. All of these pulses imperfections have to be eliminated to improve the performance of all-optical systems. The nonlinear optical loop mirror (NOLM) is a good candidate for these tasks. In the present work we report the implementation of a polarization-imbalanced NOLM for soliton cleaning. The NOLM consists of a nearly symmetrical coupler with a 51/49 coupling ratio, 100 m of twisted OFS Truewave fiber whose dispersion value is 9 ps/nm/km at 1550 nm, and a tunable in-line fiber polarization controller (PC) asymmetrically inserted inside the loop. The use of the nearly symmetrical coupler allows very low transmission for low power components of radiation. At the same time adjustment of the PC allows the adjustment of the nonlinear characteristic to have a maximum transmission for solitons with different durations. We used two sources of pulses, SESAM-based and a ring fiber laser. For appropriate PC adjustment, we obtained a rejection of ASE by 220 times, and rejection of the dispersion waves and pedestal by more than 200 times. The maximum transmission reached 70%.

10089-25, Session 5

High dynamic range single shot diagnostic for ultrashort pulses from optical parametric oscillator

Ning Hsu, Jean Claude M. Diels, The Univ. of New Mexico (United States)

A diagnostic method is presented that enables a single shot characterization in amplitude and phase of the ultrashort, weak pulses that are generated in synchronously pumped Optical Parametric Oscillators (OPO). The need for single shot characterization arises from the instability often associated with these devices, and errors introduced by trying to average a nonlinear detection process. The particular challenge associated with synchronously pumped OPO is that the signal wave is too weak for nonlinear single shot correlations as required in most method such as SPIDER, FROG and MOSAIC. However, a nonlinear by-product of the OPO signal is the sum frequency of pump and signal, which is easily detectable and spectrally resolvable. The method presented here is to use an amplitude and phase characterization of the pump pulse (Ti:sapphire in this case), by a single shot version of the MOSAIC method [1], the spectrum of the sum frequency of pump and signal, and the signal spectrum to achieve a complete reconstruction of the signal wave in amplitude and phase with very few iterations. The method is shown to have a larger dynamic range than other amplitude and phase reconstruction methods such as FROG.

References

[1] D. A. Bender, Precision Optical Caracterization on Nanometer Length and Femtosecond Time Scales. Ph.D dissertation, University of New Mexico, 2002

10089-26, Session 5

Investigation of the effect of dispersion on the dynamics of fiber-based ring cavity laser

Svetlana Slepneva, Cork Institute of Technology (Ireland) and Tyndall National Institute (Ireland); Aleksandr Pimenov, Weierstrass-Institut für Angewandte Analysis und Stochastik (Germany); Guillaume Huyet, Cork Institute of Technology (Ireland) and Tyndall National Institute (Ireland) and ITMO Univ. (Russian Federation); Andrei G. Vladimirov, Weierstrass-Institut für Angewandte Analysis und Stochastik (Germany)

We investigate both experimentally and numerically the effect of dispersion on a dynamical system with delocalised chromatic dispersion and nonlinearity. Experimentally such system is realised as a fibre-based ring cavity laser with the unidirectional light propagation. The laser cavity incorporates a semiconductor optical amplifier and a tunable narrow bandwidth optical band pass Fabry-Perot filter. We show that when the transmission wavelength of the filter sets the laser operation below 1320nm, the laser demonstrates bistability between a stable and a turbulent regimes and at longer wavelengths only turbulent behaviour is observed. The wavelength at which the transition between the bistable and turbulent regimes occurs depends on dispersion which can be controlled by including fiber delays of different lengths into the cavity. Theoretically, we consider a system with linear dispersion line and a localised nonlinearity. We describe the chromatic dispersion of the fiber as a Lorentzian absorption line with the central frequency detuned from the laser frequency. This enables us to model the light propagation by two partial differential equations describing the evolution of the electric field and the polarisation of the absorption line. The optical amplifier and the tunable filter enable us to obtain the boundary equation for these partial differential equations. We show that these equations can be reduced to differential equations with distributed delay that can recover many of the features observed experimentally and that are also comparable to features observed in the Complex Ginzburg Landau or Non-Linear Schoedinger equations.

10089-24, Session PTue

Analysis and Enhancement of 3D Shape Accuracy in a Single-shot LIDAR Sensor

Munhyun Han, Univ. of Science & Technology (Korea, Republic of); Gudong Choi, Minhyup Song, Hong Seok Seo, Bongki Mheen, Electronics and Telecommunications Research Institute (Korea, Republic of)

The accuracy of timing jitter is of prime importance at the magnificent utilization of recognition arena using LiDAR (Light Detection and Ranging) technology for the real-time high-resolution three-dimensional image sensor, especially for a moving object detection in various applications such like the fully automated car navigation. To asset the accuracy of the timing, in other words, the accuracy of the distance or three-dimensional shape, the standard deviation method is widely used in the time-of-flight (TOF) LiDAR technology. While the most timing jitter analysis are mainly based on the fiber-network or open space in a relatively short range distance, more accurate analyses are required to have more information about the timing jitter at a long-range free space conditions for the extended LiDAR-related applications.

In this paper, utilizing eye-safe wavelength based Single Shot LiDAR System(SSLs) based on a 400MHz wideband InGaAs Avalanche Photodiode and a 1550 nm 2 nsec of full width at half maximum MOPA fiber laser for a single light source and a single detection. The precise timing jitter for the implemented SSLs was analyzed to characterize the measurement results, and the enhanced results was also reported by adopting a wide bandwidth

receiver and spline interpolation for the measurement. Additionally, the timing jitter performances of SSLs were compared in day light and indoor condition, and multiple shot averaging technique was used to analyze the enhancement in the various conditions. Finally, the obtained high-resolution three-dimensional image from the SSLs were obtained and analyzed for each given condition.

10089-27, Session PTue

Towards autonomous photonic reservoir computer based on frequency parallelism of neurons

Akram Akrout, Piotr Antonik, Marc Hälterman, Serge Massar, Univ. Libre de Bruxelles (Belgium)

Reservoir Computing is a bio-inspired computational paradigm particularly well adapted to time-dependent signal processing. The past years have seen the realisation of photonic reservoir computers with performance comparable to digital algorithms. Most of these works are based on delay dynamical systems in which the « photonic neurons » are treated sequentially. We have recently realised an experimental system based on the concept of frequency multiplexing, in which the neurons are materialised as the amplitude of light at different frequencies (A. Akrout et al., « Parallel photonic reservoir computing through frequency multiplexing of neurons », under review). In this systems the neurons are processed in parallel, making it in principle much faster than the sequential systems. In most of the works up to now the output of the reservoir is implemented using slow digital offline post-processing. This is also the case of our recent experiment on frequency parallelism. Here we demonstrate, using numerical simulations, the possibility of an analogue electronic readout layer for this system. Our simulations take into account all the experimental limitations of the setup, e.g. sampling rates, device bandwidths, resolutions, and noise. The results obtained are comparable to those produced with the same architecture and a digital output layer. The proposed setup is thus an important step towards analog, low footprint, all-optical information processing. Moreover parallel processing will be necessary for high bandwidth applications.

10089-28, Session PTue

Encoding technology for fast single wavelength measurement

Jianan Tang, Wenge Zhu, Lei Yuan, Hai Xiao, Clemson Univ. (United States)

Wavelength measurement is common in modern optical industry and research, like laser output calibration, dense wavelength division multiplexing (DWDM), and fiber Bragg grating sensors. In these systems, wavelength measurement is preferred to be high-speed and high-precision at low cost. Ratiometric edge filters are one common approach, which map wavelength to energy and compare the measured signal with a reference signal. By analysis the spectra of the filters and the measured ratio, the wavelength of the measured signal could be determined. Ratiometric edge filters are small volume, simple configuration and eliminate mechanical movement. However, the complicated signal process limits the speed and increases the cost.

In this article, we proposed an encoding digital single wavelength meter based on a series of fiber Fabry-Perot interferometers (FFPI). The N FFPIs are fabricated by femtosecond laser machining, with their optical path difference (OPD) arranged in the form of 2-times increments (i.e., OPDi = 2OPDi-1). When the measured signal goes through the N FFPIs respectively, the reflection spectra exhibit sinusoidal waveforms with their free spectrum range (FSR) arranged in the form of 2-times decrements (i.e., 2FSRi = FSRi-1). After compared with the threshold, the sinusoid spectra are transformed to rectangular digital signals. In the view point of digital signals, the combination of these rectangular signals manifest N-bit Grey codes, which uniquely map to the 2^N corresponding wavelength segments. As such, a single wavelength meter is achieved with low cost, high speed, flexible range and resolution. We use 3 FFPIs to demonstrate the concept and a wavelength meter is achieve with 1nm resolution in the range of 1556nm to 1564nm.

10089-29, Session PTue

Chiral extreme events in forced semiconductor lasers

François Gustave, PhLam (France)

No Abstract Available

Conference 10090: Laser Resonators, Microresonators, and Beam Control XIX

Monday - Thursday 30–2 February 2017

Part of Proceedings of SPIE Vol. 10090 Laser Resonators, Microresonators, and Beam Control XIX

10090-1, Session 1

Q-factor enhancement of integrated lithium-niobate-on-insulator ridge waveguide whispering-gallery-mode resonators by surface polishing

Richard Wolf, Ingo Breunig, Hans Zappe, Univ. of Freiburg (Germany); Karsten Buse, Univ. of Freiburg (Germany) and Fraunhofer-Institut für Physikalische Messtechnik (Germany)

Lithium niobate (LN) whispering-gallery-resonators (WGRs) are most promising for frequency-conversion due to their high field enhancement by small mode volumes and high Q-factors. By traditional fabrication-techniques like diamond-blade-cutting with subsequent mechanical polishing, bulk-WGRs in millimeter size and Q-factors in the range of 10^9 have been demonstrated. The integration of WGRs into LN substrates, especially lithium-niobate-on-insulator (LNOI) material has the potential of low-cost mass production, but in contrast to their bulk counterparts, LNOI-based WGRs provide three orders of magnitude lower Q-factors due to residual surface roughness. Q-factor enhancement by annealing, like it has been demonstrated for glass resonators, does not work for mono-crystalline materials, especially for LNOI. Therefore, the efficiencies for, e.g., second harmonic generation in integrated WGRs are low and optic parametrical oscillation was not yet realized by this approach.

We report on integrated WGRs based on LNOI, made by lithography and reactive-ion-etching . Light is guided in waveguide-rings with ridge-like cross-sections. We employed a linear ridge-waveguide, also made out of LNOI, to couple light into the WGRs by evanescent field coupling. By changing the distance between the coupling waveguide and the WGRs, we were able to measure the Q-factor for different coupling-regimes. For Q-factor-enhancement, we developed a polishing process to reduce the roughness of the waveguide-side-walls. Our devices reach unloaded Q-factors higher than 10^6 at 1550 nm wavelength . Wavelength-dependent Q-factor measurements indicate that still Rayleigh-scattering limits the Q-factor. Further improvement of this polishing process is feasible and will enable efficient low-cost frequency converters.

10090-2, Session 1

Experimental analysis of amplitude fluctuations in a Er:ZBLALiP whispering gallery mode laser *(Invited Paper)*

Patrice Féron, Jean-Baptiste Ceppe, Yannick Dumeige, Ecole Nationale Supérieure des Sciences Appliquées et de Technologie (France); Michel S. Mortier, Ecole Nationale Supérieure de Chimie de Paris (France)

Micro spherical resonators have attracted significant attention in recent years due to their interesting optical properties and the range of applications for which they can be used. Most of the publications dedicated to micro spherical Laser are devoted to lasing effects in different materials where the spectral properties of the emission depends on (i) the choice of dopant (e.g. Er^{3+}, Yb^{3+}, Tm^{3+}) and (ii) the host matrix (e.g. silica, fluoride, phosphate or telluride glass) in which the dopant is embedded. Yet, the dynamics of theses Lasers are still to be studied. This paper shows experimental results on the amplitude fluctuations of a Whispering Gallery Mode Laser, also known as relative intensity noise (RIN). It gives information about the dynamics inside the cavity, such as photon lifetime, effective pumping rate and noise sources. We use as active medium Er^{3+} doped fluoride ZBLALiP glass and also industrial IOG-1 Yb^{3+}- Er^{3+} co-doped phosphate glass. Theses glasses are well adapted to the development of micro spherical Laser operating in the infrared region, in particular with emission wavelengths falling respectively in the C-band and C+L band. We have observed that the RIN can provide insurance about the emission of the Laser. Moreover, we have shown that a single-mode emission comes with the presence of multiple harmonics of the relaxation frequency, which is the signature of a Laser with high noise levels. In this particular case, the second and higher orders of intensity fluctuations cannot be neglected any longer in the small-signal analysis.

10090-3, Session 1

Lithium niobate microdisk resonators on a chip *(Invited Paper)*

Fang Bo, Jie Wang, Zhenzhong Hao, Guoquan Zhang, Jingjun Xu, Nankai Univ. (China)

Microresonators with high quality factors have recently attracted much attention due to their ability to dramatically enhance light intensity by confining light within a small mode volume for a long period of time. They provide a versatile platform for researching on fundamental physics and practical applications ranging from nonlinear and quantum optics to ultrasensitive sensing. Lithium niobate (LN) is a artificial crystalline material with large electro-optical coefficients and high second-order nonlinearity, therefore, it is a good candidate for active photonic devices. Here, we report on our recent progresses on the mass fabrication of monocrystalline LN microdisk resonators with Q factors higher than 1e6 and LN-silica hybrid microdisk resonators with Q factors of the order of 1e5. The active tunable characteristics of the resonance wavelengths of the fabricated LN microdisk resonators and its based transmission modulations were demonstrated based on the electro-optic and thermo-optic effects of LN crystal.

10090-4, Session 1

Engineering of dissipation to break reciprocity of light in modes-coupling system *(Invited Paper)*

Fangjie Shu, Washington Univ. in St. Louis (United States); Changling Zou, Yale Univ. (United States); Xu-Bo Zou, Univ. of Science and Technology of China (China); Lan Yang, Washington Univ. in St. Louis (United States)

Mode coupling is a important issue in a resonant system. A concept of dissipative coupling is proposed in the frame of coupled mode theory. This is a indirect coupling based on coupling of both modes to a highly lossy mode. It is shown that the lossy mode provide a equivalent coupling between two coherent modes. As an example, the theory is applied to a micro-ring to break its chiral symmetry. By carefully designing dissipation and scattering coupling we break chial symmetry of light in the modes-coupling system. The resonant frequencies and modes both in theoretical and numerical results show good agreements. The reflection spectrum show also asymmetry feature. Moreover, the dissipation is usually considered to be harmful for applications and should be avoid in the designation of photonic systems. We believe our finding of symmetry breaking by dissipation coupling will provoke people to utilizing dissipations as a tool for manipulating photons.

10090-5, Session 1

Cavity designs for GHz frequency combs *(Invited Paper)*

Jean Claude M. Diels, The Univ. of New Mexico (United States); Ladan Arissian, National Research Council Canada (Canada)

Frequency comb generation is relatively straightforward with large laser cavities, giving more time for the gain to recover after a round-trip of the intracavity pulse. Typical Ti:sapphire lasers generate pulses of less than 50 fs at a repetition rate of 100 MHz. Increasing the repetition rate – hence the spacing between teeth of the frequency comb that is generated -- is desirable for numerous applications in communication, astronomy and spectroscopy. The option generally used is to decrease the size of the resonator, implying considerably tighter design restrictions since the average power is usually maintained, hence a smaller energy/pulse and a reduction in the nonlinear mechanisms creating the mode-locking. A comprehensive modeling of a Ti:sapphire cavity is presented to answer this design challenge. There are however other solutions to create GHz spaced frequency combs that will be reviewed. These include nested frequency combs by insertion of an intracavity Fabry-Perot, and injection mode-locking by using master oscillator – slaved injected oscillator with resonator length having a common multiple. Design consideration of these solutions will be discussed.

10090-6, Session 2

Stable regimes in filter-driven FWM optical microcombs *(Invited Paper)*

Marco Peccianti, Andrew Cooper, Luigi Di Lauro, Hualong Bao, Univ. of Sussex (United Kingdom); Sai T. Chu, City Univ. of Hong Kong (China); Brent E. Little, State Key Lab. of Transient Optics and Photonics (China); David J. Moss, Swinburne Univ. of Technology (Australia); Roberto Morandotti, Institut National de la Recherche Scientifique (Canada); Alessia Pasquazi, Univ. of Sussex (United Kingdom)

The Filter-Driven FWM is a specific microcomb laser design which exploits large free spectral range nonlinear filters, such as integrated micro-ring resonators, inserted in a main long amplifying cavity. Thanks to its characteristic multi-cavity configuration, it is capable to support the propagation of multiple soliton pulses per main cavity round-trip. It inherits several characteristics from the seminal operating principle known as dissipative four wave mixing (DFWM), that exploits resonant filters in an “intracavity” configuration. However, the FD-FWM can exhibit stable operating regimes as opposed to the strong amplitude instabilities normally observed in the DFWM.

We will report here a novel investigation of different stable operating conditions which can continuously accessed and controlled by tuning the cavity parameters. This make this design particularly suitable as platform for optical microcombs. We will discuss the observed regimes, the performance and their relation with the cavity parameters carrying out a specific modelling of this multiple nonlinear cavity system.

10090-7, Session 2

Whispering gallery mode stabilization of quantum cascade lasers for infrared sensing and spectroscopy *(Invited Paper)*

Simone Borri, Istituto Nazionale di Ottica (Italy); Mario Siciliani de Cumis, Istituto Nazionale di Ricerca Metrologica (Italy); Giacomo Insero, Lab. Europeo di Spettroscopie Non-Lineari (Italy); Gabriele Santambrogio, INRIM (Italy) and LENS (Italy); Anatoliy A. Savchenkov, Danny Eliyahu, Vladimir S. Ilchenko, Andrey B. Matsko, Lute Maleki, OEwaves, Inc. (United States); Paolo De Natale, Istituto Nazionale di Ottica (Italy)

Tunable and spectrally pure laser sources in the mid infrared (IR) are required for a variety of applications, including high-sensitivity and high-precision spectroscopy. Quantum cascade lasers (QCLs) are attractive coherent sources for these applications thanks to their mW to W optical power level and their high intrinsic frequency stability [1]. If combined with mid-IR Whispering Gallery Modes microResonators (WGMRs) they can form compact and portable narrow-linewidth sources. Mid-IR WGMRs are at the very beginning of their story, and their already high Q-factors (~107 at mid-IR wavelengths) are expected to further increase with the improvement of materials and fabrication techniques.

Here, we describe our results on frequency-stabilized mid-IR QCLs to crystalline WGMRs, successfully tested on a compact apparatus for sub-Doppler molecular spectroscopy [2,3]. Both optical and electronic locking have been implemented, achieving ~10-kHz level linewidth over 1 s timescale. The possibility of Pound-Drever-Hall stabilization has also been tested and the results are discussed.

The low sensitivity to environmental noise is one of the strengths of this approach and leads to good stability levels even over long timescales. This method is expected to show all its potentiality when the integration time grows from the present few seconds to hours or days. In this latter case we can take advantage of high long-term relative frequency stability which may be better than 10-10 per day [4]. This approach allows to get narrow-linewidth tunable lasers in a compact and robust configuration, paving the way to portable, spectrally pure mid-IR spectrometers for high-resolution molecular spectroscopy.

10090-8, Session 2

Ultrafast dynamics and stabilization in chip-scale optical frequency combs *(Invited Paper)*

Shu Wei Huang, Univ. of California, Los Angeles (United States)

Optical frequency comb technology has been the cornerstone for scientific breakthroughs such as precision frequency metrology, re-definition of time, extreme light-matter interaction, and attosecond sciences. Recently emerged Kerr-active microresonators are promising alternatives to the current benchmark femtosecond laser platform. These chip-scale frequency combs, or Kerr combs, are unique in their compact footprints and offer the potential for monolithic electronic and feedback integration, thereby expanding the already remarkable applications of optical frequency combs.

In this talk, I will first report the generation and characterization of low-phase-noise Kerr frequency combs. Measurements of the Kerr comb ultrafast dynamics and phase noise will be presented and discussed. Then I will describe novel strategies to fully stabilize Kerr comb line frequencies towards chip-scale optical frequency synthesizers with a relative uncertainty better than 2.7?10-16. I will show that the unique generation physics of Kerr frequency comb can provide an intrinsic self-referenced access to the Kerr comb line frequencies. The strategy improves the optical frequency stability by more than two orders of magnitude, while preserving the Kerr comb’s key advantage of low SWaP and potential for chip-scale electronic and photonic integration.

10090-9, Session 2

Mid-infrared crystalline supermirrors with ultralow optical absorption

Christoph Deutsch, Crystalline Mirror Solutions GmbH (Austria); Garrett D. Cole, Crystalline Mirror Solutions, LLC (United States) and Crystalline Mirror Solutions GmbH (Austria); David Follman, Paula Heu, Crystalline Mirror Solutions, LLC (United States); Bryce J. Bjork, JILA (United States) and National Institute of Standards and Technology (United States); Chris Franz, Alexei L. Alexandrovski, Stanford Photo-Thermal Solutions (United States); Oliver H. Heckl, Jun Ye, JILA (United States) and National Institute of Standards and Technology (United States); Markus Aspelmeyer, Univ. Wien (Austria)

Substrate-transferred crystalline coatings are a groundbreaking new concept for the fabrication of ultralow-loss mirrors. The single-crystal lattice structure of these substrate-transferred GaAs/AlGaAs Bragg mirrors exhibits the lowest mechanical losses and hence unmatched Brownian noise performance, which nowadays limits the stability of precision optical interferometers. Another outstanding feature of these coatings is the wide spectral coverage of the GaAs/AlGaAs material platform. Limited by interband absorption at short wavelengths and the reststrahlen band at long wavelengths, crystalline coatings can be employed as low-loss multilayers from approximately 900 nm up to 5 μm and beyond. Excellent optical performance has been demonstrated in the near-infrared with excess optical losses (scatter + absorption) as low as 3 parts per million (ppm), enabling cavity finesse values up to 360,000 at 1.55 μm. Our first attempts at applying crystalline coatings in the mid-infrared has resulted in mirrors with excess optical losses of 159 and 242 ppm at 3.3 and 3.7 μm, respectively. Remarkably, these results are already on par with current state-of-the-art amorphous mirror coatings. Absorption measurements based on photothermal common-path interferometry (PCI) reveal that the optical losses are largely dominated by optical scatter. Via, PCI, we have confirmed absorption losses below 10 ppm at 3.7 μm, showing the enormous potential of GaAs/AlGaAs Bragg mirrors at mid-infrared wavelengths. An optimized fabrication process, which is currently under development, can efficiently suppress optical scatter due to accumulated growth defects on the surface. Ultimately, we foresee excess losses significantly less than 50 ppm in the mid-infrared spectral region.

10090-10, Session 3

Nanomaterial-enhanced frequency combs *(Invited Paper)*

Andrea M. Armani, The Univ. of Southern California (United States); Rigoberto Castro-Beltran, The Univ. of Southern California (Mexico); Vinh Diep, Eda Gungor, Xiaoqin Shen, Soheil Soltani, The Univ. of Southern California (United States)

Optical cavities are able to confine and store specific wavelengths of light, acting as optical amplifiers at those wavelengths. Because the amount of amplification is directly related to the cavity quality factor (Q) (or the cavity finesse), frequency comb research has focused on high-Q and ultra-high Q microcavities fabricated from a range of materials using a variety of methods. In all cases, the comb generation relies on a nonlinear process known as parametric frequency conversion which is based on a third order nonlinear interaction and which results in four wave mixing (FWM). Clearly, this approach requires significant optical power, which was the original motivation for using ultra-high-Q cavities. In fact, the majority of research to date has focused on pursuing increasingly high Q factors. However, another strategy is to improve the nonlinearity of the resonator through intelligently designing materials for this application. In the present work, a suite of nanomaterials (organic and inorganic) have been intelligently designed with the explicit purpose to enhance the nonlinearity of the resonator and reducing the threshold for frequency comb generation in the near-IR. The nanomaterials do not change the structure of the comb and only act to reduce the comb threshold. The silica microcavity is used as a testbed for initial demonstration and verification purposes. However, the fundamental strategy is translatable to other whispering gallery mode cavities.

10090-11, Session 3

Soliton dynamics in optical micro resonators *(Invited Paper)*

Maxim Karpov, Hairun Guo, Erwan Lucas, Victor Brasch, Martin H. P. Pfeiffer, John J. Jost, Ecole Polytechnique Fédérale de Lausanne (Switzerland); Michael L. Gorodetsky, Russian Quantum Ctr. (Russian Federation); Tobias J. Kippenberg, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

Dissipative Kerr solitons (DKS) generated in optical microresonators have attracted significant attention over recent years in the areas of optical frequency metrology, spectroscopy and coherent communication. DKS allow for fully coherent, high repetition rate broadband optical frequency combs (soliton combs) and provide access to stable ultrashort pulses of tunable duration. The formation process and the dynamics of such dissipative solitons strongly depend on the interplay of high-order nonlinear and thermal properties of the microresonator, and in many aspects significantly deviate from the behavior of solitons in optical fibers. This talk will focus on the fundamental principles of DKS dynamics, and cover the range of various unique phenomena discovered in such systems.

10090-12, Session 3

Dissipative Kerr solitons and microcavity frequency combs *(Invited Paper)*

Kerry J. Vahala, California Institute of Technology (United States)

Dissipative Kerr soliton mode locking in high-Q silica micro cavities is reviewed including resonator dispersion optimization. Phenomena relating to soliton propagation in the micro cavity are studied including dispersive wave generation and soliton trapping. Applications of the soliton comb are described.

10090-13, Session 3

Kerr combs from normal and anomalous dispersion silicon nitride microresonators *(Invited Paper)*

Andrew M. Weiner, Minghao Qi, Purdue Univ. (United States); Xiaoxiao Xue, Tsinghua Univ. (China)

Nonlinear wave mixing in optical microresonators offers a route to chip-level optical frequency combs. The properties of the combs generated depend crucially on the interaction between nonlinearity and dispersion. This presentation will discuss research at Purdue University on comb generation in silicon nitride chip-scale microresonators, with an emphasis on distinct features observed in the anomalous and normal dispersion regimes. Time permitting, we will also discuss our efforts to bring Kerr combs to bear on applications such as radio-frequency photonic filtering.

10090-14, Session 3

Effect of Raman scattering and mode coupling in Kerr comb generation in a silica whispering gallery mode microcavity *(Invited Paper)*

Takasumi Tanabe, Takumi Kato, Shun Fujii, Ryo Suzuki, Atsuhiro Hori, Keio Univ. (Japan)

We will first discuss on the effect of Raman scattering in Kerr comb generation in a whispering gallery mode (WGM) microcavity. Silica exhibit broad Raman gain which enable broad comb formation. Although four-wave mixing excites only the same longitudinal mode family, Raman scattering enable the nonlinear coupling between the higher order modes. We will discuss on the condition required to excite different longitudinal family. With the help of Raman scattering, we obtained very broad spectrum, with which we demonstrated broad visible light generation via third-harmonic generation. Next we will discuss on the effect of mode-coupling such as clock-wise -- counter clock-wise (CW/CCW) mode coupling. We discuss that by a carefully design of the CW/CCW coupling, we are able to obtain a pair of counter-propagating soliton pulse. We also discuss that a cross phase modulation enables the injection like behavior between TM/TE modes upon Kerr comb generation in a WGM microcavity system.

10090-15, Session 4

Chip-Scale Frequency Comb Generators for High-Speed Communications and Optical Metrology *(Invited Paper)*

Christian Koos, Karlsruher Institut für Technologie (Germany); Tobias J Kippenberg, Ecole Polytechnique Fédérale de Lausanne (EPFL) (Switzerland); Liam P Barry, Dublin City University (Ireland); Abderrahim Ramdane, Laboratoire de Photonique et Nanostructures, CNRS (France); Francois Lelarge, III-V Labs (France); Wolfgang Freude, Pablo-Palomo Marin, Juned N Kemal, Claudius Weimann, Stefan Wolf, Philipp Trocha, Joerg Pfeifle, Karlsruher Institut für Technologie (Germany); Maxim Karpov, Arne Kordts, Victor Brasch, Ecole Polytechnique Fédérale de Lausanne (EPFL) (Switzerland); Regan T Watts, Dublin City University (Ireland); Anthony Martinez, Vivek Panapakkam, Laboratoire de Photonique et Nanostructures, CNRS (France); Nicolas Chimot, III-V Labs (France)

Chip-scale frequency comb sources are key elements for a variety of applications, comprising massively parallel optical communications and high-precision optical metrology. In this talk, we give an overview on our recent progress in the area of integrated optical comb generators and of the associated applications. Our experiments cover modulator-based comb sources, injection locking of gain-switched laser diodes, quantum-dash mode-locked lasers, as well as Kerr comb sources based on cavity solitons. We evaluate and compare the performance of these devices as optical sources for massively parallel wavelength division multiplexing at multi-terabit/s data rates, and we report on comb-based approaches for high-precision distance metrology.

10090-16, Session 4

Soliton Kerr combs: From chaos to order and from theory to experiment *(Invited Paper)*

Michael L. Gorodetsky, Russian Quantum Ctr. (Russian Federation) and M.V. Lomonosov Moscow SU (Russian Federation); Valery E. Lobanov, Grigory Lihachev, Nikolay Pavlov, Russian Quantum Ctr. (Russian Federation); Sergey N. Koptyaev, SAMSUNG R&D Institute Rus. (Russian Federation)

Kerr frequency combs in optical passive microresonators promise new breakthroughs in photonics. Such combs result from multiple hyper-parametric four-wave mixing processes when reaching a threshold of modulational instability. These combs however have chaotic nature. It was revealed in recent experiments, theoretical and numerical analysis that transition form these chaotic states to highly ordered states associated with dissipative Kerr solitons is possible. In this report we discuss theoretical approaches to analyze these soliton states and reveal methods of reliable transition to single soliton states. Latest expaerimental results with soliton combs are reported.

10090-17, Session 4

Integrated optical frequency comb generator with chip-scale prism-waveguide coupled high-Q crystalline WGM resonator *(Invited Paper)*

S. J. Ben Yoo, Guangyao Liu, Tiehui Su, Univ. of California, Davis (United States); Vladimir S. Ilchenko, Andrey B. Matsko, Lute Maleki, OEwaves, Inc. (United States)

We discuss design, fabrication, and experimental results of optical frequency comb generation from a high-Q crystalline WGM resonator with on-chip prism-waveguide couplers. < 2 dB insertion loss and superb optical frequency comb generation comparable to the conventional prism coupled method.

10090-20, Session 5

Kerr frequency combs generated by hybrid microcavities

Rigoberto Castro, Vinh Diep, Eda Gungor, Soheil Soltani, Andrea M. Armani, The Univ. of Southern California (United States)

Due to their high quality factors, which result in large circulating optical intensities, microcavities are an attractive platform for creating frequency combs. Over the past decade, in an attempt to achieve both a high Q and a high third order susceptibility, many different material systems have been explored including silica, silicon, silicon nitride, and fluorides. However, these devices are ultimately limited by the material's fundamental performance. In contrast, entirely new physical phenomena have been realized with nanomaterials. One strategy to leverage these emerging nanomaterials to enhance frequency comb generation is to create hybrid optical cavities in which novel nanomaterials are coated on or attached to the surface of a microresonator.

In the present work, we demonstrate a hybrid platform consisting of a gold nanoparticle coated whispering gallery mode silica microsphere. The hybrid device supports Q factors above 10 million at 1550nm, indicating that the nanoparticles are interacting with the optical field. Additionally, we

demonstrate that the nanoparticles enhance the optical field in comparison to a plain silica optical cavity-based frequency comb, further reducing the comb threshold and increasing the comb span. The effect is studied over a range of gold nanoparticle concentrations. The mechanism and enhancement is further elucidated with finite element method modeling.

10090-21, Session 5

PCSELs with lateral optical feedback

Richard J. E. Taylor, The Univ. of Tokyo (Japan); Guangrui Li, Pavlo Ivanov, David T. D. Childs, Univ. of Glasgow (United Kingdom); Benjamin J. Stevens, The Univ. of Sheffield (United Kingdom); Nasser Babazadeh, Olesya Ignatova, Richard A. Hogg, Univ. of Glasgow (United Kingdom)

All-semiconductor photonic crystal surface-emitting lasers (PCSELs) operating in CW mode at room temperature and coherently coupled arrays of these lasers are reviewed. These PCSELs are grown via MOVPE on GaAs substrates and include QW active elements and GaAs/InGaP photonic crystal (PC) layer situated above this active zone.

Atoms of triangular shapes have been shown to increase optical power from the PCSEL but are also shown to result in a competition between lasing modes. Simulation shows that the energy splitting of lasing modes is smaller for triangular atoms, than for circles making high power single-mode devices difficult to achieve.

In this work we experimentally investigate the effect of lateral optical feedback introduced by a facet cleave along one or two perpendicular PCSEL edges. This cleavage plane is misaligned to the PC resulting in a periodic variation of facet phase along the side of the device.

Results confirm that a single cleave selects the lowest threshold 2D lasing mode, resulting in a ~20% reduction in threshold current and favours single-mode emission. The addition of a second cleave at right-angles to the first has no significant effect upon threshold current.

The virgin device is shown to have a symmetric far-field (1 degree) whilst a single cleave produces a 1 degree divergence perpendicular to cleave and 5 degree parallel to cleave. The second orthogonal cleave results in the far field becoming symmetric again but with a divergence angle of 1 degree indicating that single-mode lasing is supported over a wider area.

10090-22, Session 5

On-chip ultrahigh-Q packaged microresonator and applications

Guangming Zhao, Sahin K. Özdemir, Washington Univ. in St. Louis (United States); Tao Wang, Tsinghua Univ. (China); Linhua Xu, Eshan S. King, Washington Univ. in St. Louis (United States); Yunqi Hu, Gui Lu Long, Tsinghua Univ. (China); Lan Yang, Washington Univ. in St. Louis (United States)

Whispering gallery mode (WGM) microresonators have been intensively studied in many areas such as sensing, lasing, and fundamental study. WGM microresonators are always coupled by a tapered fiber, and the coupling is controlled by a 3D nanotranslation stage. We always suffer from the instability of coupling condition, which means it is difficult to put microresonators in practical applications. Hence, we present an efficient way to package on-chip ultrahigh-Q microresonators. Stimulated Raman Scattering is achieved in this packaged microresonator, which means we have a portable, narrow linewidth laser and it can be used to expand the working wavelength of a laser. In addition, by coupling two whispering-gallery modes (WGM), which is simultaneously excited in the packaged microtoroid resonator, we can observe an electromagnetically induced transparency (EIT) effect for the first time in a portable WGM structure. This packaged microresonator can be used for real quantum communication applications. Furthermore, highly sensitive sensing can benefit from the high Q-factor and its stability.

10090-23, Session 5

Nanofiber Bragg grating cavities

Andreas W. Schell, Hideaki Takashima, Hironaga Maruya, Atsushi Fukuda, Shigeki Takeuchi, Kyoto Univ. (Japan)

Funnelling the light emitted from quantum emitters like atoms, molecules, or defect centers into the guided mode of a single mode optical fiber is highly important for scaling up quantum optics experiments, since it provides the possibility to interconnect experiments at different locations and ensures high mode overlap of photons from different sources. Here, we present a photonic nanocavity on a tapered optical fiber. The cavities are formed by two Bragg mirrors fabricated by an ion beam [1]. Characterization in terms of transmission, reflection, and polarization are performed and compared with numerical simulations [2]. The quality factors of the fabricated devices can reach values over 300 while the mode volume is smaller than the cubic wavelength. Simulations indicate that a Purcell enhancement of 19.1 with 82 % coupling efficiency can be reached using this cavities. A comparison of cavities fabricated using a gallium beam is compared with cavities made using a helium beam giving insights about implantation of gallium in the ion beam milling fabrication of resonators. Using the knowledge from experiment and simulation, new designs for nanofiber Bragg grating cavities are developed and tested.

[1] A W Schell et al. Sci. Rep. 5, 9619 (2015)

[2] H Takashima et al. Opt. Express 24, 15050-15058 (2016)

10090-24, Session 5

All-optical control of silica microresonators *(Invited Paper)*

Lei Shi, Huazhong Univ. of Science and Technology (China)

Wavelength tuning of optical microresonators is of great importance in enhancing their flexibility. Especially, all-optical control of a silica microresonator is highly attractive, but it is difficult to realize because of the relatively weak Kerr effect and the absence of a plasma dispersion effect of silica. Here, we present three schemes for broadband all-optical wavelength tuning of silica microsphere resonators, silica optofluidic ring resonators and silica microbottle resonators, respectively. Iron-oxide nanoparticles embedded silica microsphere resonators, magnetic-fluid-filled silica optofluidic ring resonators, and graphene-coated silica microbottle resonators are proposed and experimentally demonstrated for the first time. The maximum wavelength tuning sensitivity and tuning range could reach 0.2 nm/mW and 13nm, respectively. For the graphene-coated silica microresonator an high Q factor of the microresonator is maintained with all-optical tuning, and this is very important for its many applications. With such excellent performances, these three all-optical schemes show great potential of silica microresonators in optical signal processing, sensing, nonlinear optics, microwave photonics, and quantum optics applications.

10090-67, Session 5

Creation and control of transient tunable arbitrary-shaped photonic elements at the surface of an optical fiber

Artemiy Dmitriev, Misha Sumetsky, Aston Univ. (United Kingdom)

The propagation of whispering gallery modes along an optical fiber is fully controlled by nanoscale variation of the effective fiber radius. In the present work we demonstrate the possibility of the creation, tuning, translation and annihilation of arbitrary-shaped transient photonic elements, such as miniature slow light delay lines, dispersion compensators and dispersionless optical buffers, at the surface of an initially regular optical fiber. This is achieved by means of local heating of the fiber with low-power focused CO2 laser radiation, which introduces nanoscale change to the effective radius of the fiber because of thermo-refractive coupling and thermal expansion. The CO2 laser beam is swept along the fiber, with its position and intensity programmably controlled by an acousto-optical deflector, so that the shape and the settling speed for these structures are constrained only by thermal relaxation processes inside the irradiated fiber. Possible realization of a similar technique on a chip, with laser beam heating substituted by on-chip DC heaters, is analysed. The potential application of this method to the on-the-fly fine tuning of the shape of pre-created Surface Nanoscale Axial Photonics (SNAP) elements, particularly providing gates for switching on and off coupling of optical delay elements to a photonic circuit, is also discussed.

10090-25, Session 6

Advances in microwave generation using Kerr optical frequency combs *(Invited Paper)*

Khaldoun Saleh, Yanne K. Chembo, FEMTO-ST (France)

Whispering-gallery mode (WGM) resonators are passive bulk cavities that have the capability to trap laser light by total internal reflection for a duration higher than a microsecond. Owing to their versatility in size, they can feature free-spectral ranges varying from few GHz to few THz depending on the resonator’s radius, while their quality factor (Q) can exceed a billion at telecom wavelengths. The small volume of confinement, high photon density and long photon lifetime contribute to enhance the light-matter interaction, thereby giving rise to many nonlinearities like Kerr, Raman, or Brillouin scattering. We here discuss recent advances in the understanding of the spatiotemporal behavior of the intracavity fields. We will also discuss some of the main challenges related to the understanding of nonlinear and quantum phenomena in these WGM resonators.

10090-26, Session 6

Piezo-optomechanical transducers as a link between radio frequency, optical, and acoustic waves *(Invited Paper)*

Kartik Srinivasan, National Institute of Standards and Technology (United States)

We demonstrate a nanoscale device platform in GaAs that establishes a link between the radio frequency (RF) and optical domains through acoustic waves, mediated by the piezoelectric and photoelastic effects. First, interdigitated transducers (IDTs) convert 2.4 GHz RF photons into 2.4 GHz propagating surface acoustic waves. These acoustic waves are routed through phononic crystal waveguides and are coupled to a nanobeam optomechanical cavity that supports both a highly localized 2.4 GHz breathing mechanical mode and a high quality factor 1550 nm optical mode. In contrast to non-resonant excitation of photonic structures with IDTs, here the phononic waveguide preferentially excites a localized mechanical mode, which in turn strongly interacts with the optical mode through the photoelastic effect. Finally, the optical mode can be out-coupled or excited via an optical fiber taper waveguide. Using this platform, we demonstrate preparation of the breathing mode in a coherent state at any location in phase space, and optically read out an average coherent intracavity phonon number as small as one-twentieth of a phonon. In the time-domain, we show that RF pulses are mapped to optical pulses, forming a resonant acousto-optic modulator with a sub-Volt half-wave voltage. We also observe a novel acoustic wave interference effect in which RF-driven motion is completely cancelled by optically-driven motion, enabling the demonstration of interferometric opto-acoustic modulation in which acoustic wave propagation is gated by optical pulses. Efforts to improve upon the efficiency of the different transduction processes and integration with quantum dot gain media will be discussed.

10090-27, Session 6

Non-reciprocal transmission in the microresonators *(Invited Paper)*

Chunhua Dong, Univ. of Science and Technology of China (China)

Non-reciprocal devices, such as circulators and isolators, are indispensable components in classical and quantum information processing in an integrated photonic circuit. Aside from those applications, the non-reciprocal phase shift is of fundamental interest for exploring exotic topological photonics, such as the realization of chiral edge states and topological protection. However, incorporating low optical-loss magnetic materials into a photonic chip is technically challenging. In this study, the non-reciprocal transmission in an optomechanical resonator is experimentally demonstrated for the first time. The underlying mechanism of the non-reciprocity demonstrated in this study is actually universal and can be generalized to any traveling wave resonators with a mechanical oscillator, such as the integrated disk-type microresonator coupled with a nanobeam. Considering that higher cooperativity and cascading of the optical devices have been reported in a photonic integrated chip, non-reciprocity in such an microresonator has applications for integrated photonic isolators and circulators, which will play important roles in a hybrid quantum Internet.

10090-28, Session 6

Exploring optical isolation with silica microresonators *(Invited Paper)*

Seunghwi Kim, JunHwan Kim, Gaurav Bahl, Univ. of Illinois at Urbana-Champaign (United States)

Microscale resonators that simultaneously exhibit high-Q optical and mechanical resonances are routinely used to study the coupling between light and vibration. We have learned recently that Brillouin scattering (traveling-wave light-sound interactions) within these resonators can enable nonreciprocal optical transmission through a waveguide, which can be reconfigured optically and on demand. In this talk, we describe the basic theory and experimental demonstrations of Brillouin Optomechanics, and describe how it allows the breaking of time-reversal symmetry by means of traveling phonon modes. We experimentally demonstrate ultra-low loss optical isolation using a simple resonator system. Our results demonstrate that chip-scale optical isolation is much more accessible than previously thought.

10090-29, Session 7

High-resolution high-reflective LCOS spatial light modulator for beam manipulation beyond visible spectrum

Grigory Lazarev, Jarek Luberek, Fabian Kerbstadt, HOLOEYE Photonics AG (Germany)

We present the high-resolution high-efficiency LCOS-based spatial light modulators for near IR and for near UV band. The samples show reflectivity over 95% for the IR and over 94% for UV band, achieved with help of the high-reflective dielectric stack, implemented within the wafer-scale fabrication process. The panels show an improved laser-induced damage threshold in comparison with reference panels without dielectric stack. Furthermore the dielectric stack modified the electrical, mechanical and electro-optical properties of the panels. The flatness, electro-optical response and temporal behavior were analyzed. The optimal driving parameters were determined and diffraction efficiencies for typical beam manipulation patterns were measured.

10090-30, Session 7

Super narrow beam shaping system for remote power supply at long atmospheric path

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Wireless power transmission technology based on high power diode and fiber lasers have a high potential for Earth and space applications. Narrow infrared laser beam can deliver up to 1 kW of electrical power to a photoelectric receiver with dimensions 10-20 cm at distance 1-10 km. To achieve high efficiency it is necessary to fit the beam to the dimension of receiver moving with angular velocity in range 0.5-3 °/sec in all range of distance. Thus beam shaping system has to provide fast control of shape, dimensions and positon of the beam with high accuracy in condition of atmosphere which distorts the beam.

We consider multi-wavelength 135-mm off-axis beam forming system with fast 3-axis positioning of focusing lens and 1 um precision. The system allows to meet rigid requirements of system performance for both fiber and diode laser beams. We present a model for the three channel beam forming system based on matrix with stochastic element. Results of experiment at 1.5 km atmospheric path are also presented. Local and temporal characteristics of the beam for various atmospheric conditions are considered. Comparing simulation and experimental results we demonstrate an adequacy of models and theoretical assumption. For the beam atmospheric distortion correction we propose a new design of axis and off-axis beam forming system, which includes an adaptive mirror and a beam characterization unit. The advantages and disadvantages of the design are discussed.

Results of the research provide the basis for manufacturing of high efficiency system for remote power supply of UAV.

10090-31, Session 7

Generation of an ultra-flexible focused top-hat beam profile with aspheres

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The demand for a uniform intensity distribution in the focal region of the working beam is growing steadily, especially in the field of laser material processing, lithography or optical data storage. To generate such a Top-Hat beam profile it was shown in the past that it is a promising approach to use refractive beam shaping solutions, since they are quite more efficient, have a relatively simple structure and consequently, are easier to manufacture. Furthermore they are more insensitive to wavelength changes compared to diffractive solutions. For the practical application of this top-hat beam profile it is desired not only to generate a high quality beam profile but to have a high flexibility with respect of the application area. Usually a balance between these requirements must be achieved.

It is subject of this work to present a compact refractive beam shaping system, which transforms a collimated Gaussian beam into a focused Top-Hat beam. The resulting beam profile has a high optical performance and a high level of flexibility as well. The system can be matched with either a collimated laser beam with different size or a fiber coupled source. Due to the modular approach the size of the Top-Hat beam profile can be chosen arbitrary depending on the application area. Furthermore, the system can be handled and adjusted easily, since it can be combined with SPA™ Beam Expanders or SPA™ AspheriColl. In the following some selected design investigations as well as some valuable results of the practical testing are presented.

10090-32, Session 7

New adaptive optics strategy to optimize ultra intense laser focalization

Xavier Levecq, Guillaume Beaugrand, Imagine Optic SA (France)

The development in ultra-intense lasers aims at achieving the highest laser intensity on the target.

To ensure highest intensity, one has to accurately control spatial phase to get the smallest focused spot. The spatial phase is controlled using adaptive optics systems with a wavefront sensor to measure spatial phase and a deformable mirror to correct it. This adaptive optics system is commonly placed at the output of the laser chain (just before or just after the compressor) and it now becomes a standard feature on high-power laser chains. The usual strategy of adaptive optics correction is to separate a small fraction of the main beam and to measure its wavefront using a wavefront sensor. However such strategy only ensures that the laser beam is free from aberrations at the location of the wavefront sensor. Aberrations induced by the optical elements located downstream of the wavefront sensor, for instance focusing optics, are not measured and therefore are not corrected by the adaptive optics loop. These aberrations contribute to final focal spot degradation. In order to get the highest intensity on the target, an aberration-free wavefront in the interaction chamber after the focusing optics is required.

We will present a simple, direct and automated method using a standard focal spot camera and phase retrieval algorithms in order to measure and correct wavefront directly on the focal spot itself. This method is simple as it does not require additional hardware and can be used with spectral bandwidth larger than 200 nm.

10090-33, Session 7

Monolithic fiber coupler for high power diode laser bars: Results of prototype

Thomas Mitra, Klaus Bagschik, LIMO Lissotschenko Mikrooptik GmbH (Germany)

First experimental results and simulations of a unique monolithic fiber coupler allowing coupling of light from several emitters of a laser diode bar into an optical fiber at high brightness will be presented.

Fiber coupled laser modules of up to 50 W output power from a 100 ?m fiber and NA 0.15 are feasible with just a single mini bar of 10 emitters and the monolithic fiber coupler as only optical element for beam shaping and focusing. Standard configurations for fiber coupling of laser diodes bars require typically optical elements for a) collimation in the fast axis, b) collimation in the slow axis, c) rearrangement of beamlets and d) focusing to the fiber facet. The optic comprises all these functions into a single element.

The beam lets are rearrangement to generate a symmetrized beam parameter product which suits to the optical fiber. The optic is designed with individual free form segments on its front and back for each emitter of the laser diode bar.

The originally horizontally arranged emitters are rearranged by displacements/tilts of the segments to end up with a vertical stacking of the emitters in angular space at the fiber facet.

By means of the monolithic fiber coupler, very cost effective fiber coupled laser diode modules based on bars are feasible. There are several advantages compared to current designs due to the very small number of components s and mounting steps per laser module and the resulting small package size. Thus, approaches based on laser diodes bars can also compete with single emitter solutions for pumping application due their superior power per pump module.

Further applications are direct material processing, projection and illumination systems.

Compared with previous presentations on this topic, new results of the prototype will be presented.

10090-34, Session 8

Numerical design of gradient index beam shapers *(Invited Paper)*

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Gradient index (GRIN) optics are routinely used for simple lenses and multi-mode optical fiber communications. These quadratic index profiles are easily modelled and relatively easy to fabricate. However, with the advent of 3D printing and other additive methods as well as femtosecond laser direct writing, it will soon be possible to fabricate optics with arbitrary refractive index profiles. In this paper, we explore techniques to design GRIN optics that transform a particular spatial field profile into the desired distribution. One approach uses ray theory based on the eikonal equation, and is suitable for high Fresnel numbers. A second approach uses a split-step wave propagation method to compensate for the effects of diffraction. The design methods are applicable to a wide variety of beam shaping problems. As an example, we have designed a GRIN element that converts three mutually coherent Gaussian beams into a single Gaussian with a theoretical efficiency of 100 percent and M-squared less than 1.01. Further, we point out and justify a simple method to yield GRIN profiles in multi-mode waveguides that have an arbitrary transverse eigenmode. We explore the potential and limitations of these new methods.

10090-35, Session 8

Multiplexing the spatial modes of light in the mid-IR region

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Traditional optical communication systems optimize multiplexing in the polarization and the wavelength of light to attain a high bandwidth data communication link. Yet despite these technologies, we are expected to reach a bandwidth ceiling in the near future. Communication using orbital angular momentum (OAM) carrying modes which provides infinite dimensional states, provides a way to increase link capacity by multiplexing spatially overlapping modes as independent data channels both in the azimuthal and radial degrees of freedom. Spatial modes are multiplexed and de-multiplexed by the use of spatial light modulators. Implementation of complex amplitude modulation is employed on a laser beam's phase and amplitude to generate spatial modes. Modal decomposition is employed to detect spatial modes due to the orthogonality of the modes as they propagate in space. We demonstrate data transfer by sending images as a proof-of concept in a lab-based scheme. We demonstrate the creation and detection of spatial modes in the mid-IR region as a precursor to a mid-IR free-space communication link.

10090-36, Session 8

Integrated Optical Design for Highly Dynamic Laser Beam Shaping with Membrane Deformable Mirrors

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The integration of active optics like deformable mirrors exhibits significant innovative capacity for the development of actively controlled and adaptive optical systems for highly flexible laser materials processing within a wide field of applications. To take full advantage of the highly dynamic spatial and temporal beam shaping, the huge amount of degrees of freedom has to be considered and optimized already within the early stage of the optical design. Since the functionality of commercial available ray-tracing software has been mainly specialized on geometric dependencies and their optimization within constraints, the complex system characteristics of deformable mirrors cannot be sufficiently taken into account yet. The main reasons are the electro-mechanical-optical interdependencies of electrostatic membrane deformable mirrors namely inter-actuator coupling and saturation that result in nonlinear deformation.

This motivates the development of an integrative design approach. The functionality of the ray-tracing program ZEMAX® is coupled with a model of a commercial membrane mirror. This way, the internal optimization routines of ZEMAX® can be used for computing the appropriate actuator voltages of the deformable mirror. The model of the mirror is based on experimentally determined influence functions. Furthermore, software routines are derived and integrated that allow for the compilation of optimization criteria for the most relevant beam shaping problems. Finally, passive (lenses) as well as active (mirror) optical components can be parameterized to solve a given beam shaping problem under consideration of the mirror´s characteristics. The mirror´s parameters (control voltages) are reused for the control of the real optical set-up. The comparison of simulated and experimentally determined intensity distributions shows that the integrative approach enables the reliable prediction of the behavior of active optical systems based on membrane mirrors.

10090-37, Session 8

Mode profiles and Airy distributions of Fabry-Pérot resonators with frequency-dependent mirror reflectivity

Nur Ismail, Cristine Calil Kores, Dimitri Geskus, Markus Pollnau, KTH Royal Institute of Technology (Sweden)

Lasers that rely on waveguide geometries with tight optical confinement produce high optical gain, and their laser slope efficiency can be optimized by significantly increasing the transmission of the outcoupling mirror. At such low reflectivities, the concepts of linewidth and finesse of the Airy distribution of a Fabry-Pérot resonator break down and commonly applied approximations turn invalid. We thoroughly investigate the Fabry-Pérot resonator, avoid approximations, and derive its generic Airy distribution, equaling the internal resonance enhancement, and all related Airy distributions, such as the commonly known transmission. We verify that the sum of the mode profiles of all longitudinal modes is the fundamental physical function characterizing the Fabry-Pérot resonator and generating the Airy distributions. We point out that the spectral linewidth of the underlying Lorentzian-shaped mode profiles quantifies the resonator losses and introduce a new parameter, the Lorentzian finesse, which describes

the resolution of these Lorentzian lines, whereas the usually considered Airy finesse only quantifies the performance of the Fabry-Pérot resonator as a scanning spectrometer. We investigate the influence of frequency-dependent mirror reflectivities, as well as frequency-dependent penetration depth of light into the mirrors, on the mode profiles and the resulting Airy distributions. The mode profiles then deviate from simple Lorentzian lines and exhibit peaks that are not located at resonant frequencies. Our simple, yet accurate analysis greatly facilitates the characterization of Fabry-Pérot resonators with low reflectivity, high loss, or strongly frequency-dependent mirror reflectivities and/or resonator lengths, as typically applied in distributed-Bragg-reflector (DBR) and distributed-feedback (DFB) narrow-linewidth lasers.

10090-19, Session PTue

Precise manufacturing of SNAP devices using whispering gallery modes of a reference optical fiber

Artemiy Dmitriev, Misha Sumetsky, Aston Univ. (United Kingdom)

Surface Nanoscale Axial Photonics (SNAP) technique opens the possibilities for development of photonic devices based on whispering gallery modes (WGMs) in optical fibers. Nanoscale modulation of optical fiber's effective radius introduced by local partial annealing of fiber by CO2 laser radiation allows one to make the photonic devices with extremely high precision. Characterisation of a SNAP element is performed by measuring the transmission spectra of a microfiber that is coupled to the WGMs in different points along the fiber. Recent results show that the precision of manufacturing of SNAP elements is constrained by the excess frequency noise introduced into the measured data during the scanning along the fiber. In this paper we analyse the main sources of this noise: technical noise because of drift of reference frequency of the measuring device (spectrum analyser) and drift of resonant frequencies caused by changes of ambient temperature. A method of compensation of noise coming from both of these sources is proposed. It is based on use of reference WGMs of a regular optical fiber which is put close to the SNAP element parallel to it. The same tapered microfiber is used to couple light to WGMs of both fibers. It is shown experimentally that the instrumental frequency noise is suppressed by more than an order of magnitude using this method. Potential developments of the proposed technique, such as low-frequency temperature drift elimination by self-referencing and moving the reference optical fiber together with scanning tapered microfiber, are also analysed.

10090-66, Session PTue

Micro-refractive element stabilized plane-parallel resonators incorporating solid-state and colloidal gain media

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The fabrication and characterization of a microsphere-stabilized optical resonator is presented here. Two plane-parallel mirrors comprise the critically stable cavity and, before sealing the cavity with the top mirror, we deposit a monolayer of polystyrene microspheres onto the surface of the bottom mirror along with a solution of colloidal quantum dot gain media. Upon optical excitation with a pulsed pump laser, the lasing action from the planar cavity is stabilized at individual microsphere locations. Notably, we can toggle between single and multi-transverse mode operation, without complicated fabrication steps, by tuning the cavity length and/or changing the sphere size.

The resonator design presented here removes the need for bottom-up fabrication and lateral spatial confinement of individual emitters to achieve single mode operation. In addition to the passive method for arranging spheres described above, we can also direct the microspheres to specific locations via convective assembly. The procedure consists of drawing the meniscus of a colloidal microsphere suspension over a PDMS template of holes by translating the substrate with a linear stage. After assembling the spheres, array patterns were replicated by pressing the microsphere-filled PDMS templates onto a mirror coated with a 50 μm thick film of optically transparent adhesive. The transferred pattern was integrated into an optical cavity by placing a high reflector on top after dispensing the colloidal quantum dot gain medium. Our method of producing microlaser arrays is promising for cost-effective, scalable beam shaping with tunable spectral properties.

10090-68, Session PTue

Optical characterization of transition metal ions doped ZnO microspheres synthesized via ablation in air

Parvathy Anitha Sukkurji, NILESH J VASA, Indian Institute of Technology Madras (India)

ZnO is a direct-transition semiconductor with a band gap energy of 3.37 eV at room temperature and large exciton binding energy of ZnO about 60 meV [1]. Recent studies have shown that the doping of the transition metal(TM) ions like Mn into ZnO offers a feasible means of realizing p-type ZnO because the delocalized transition metal d-levels provides more vacancies, which give rise to hole conduction [2]. Microspheres with high sphericity and symmetry exhibit unique functionalities which makes them excellent omnidirectional optical resonators [3]. Hence there is an advent interest in fabrication of single crystalline semiconductor microspheres especially magnetic ZnO microspheres, as ZnO is a promising material for semiconductor device applications. Also, ZnO is non-toxic and biocompatible, implying it is a potential material for biomedical applications [4]. Room temperature Photoluminescence (PL) spectra of the fabricated ZnO microspheres were measured, at an excitation wavelength of 325 nm. The ultraviolet (UV) luminescence observed is attributed to the room-temperature free exciton related near-band-edge (NBE) emission in ZnO. Besides the NBE luminescence, weak and broad visible luminescence (~560nm) was also observed. In transition metal (TM) ion doped ZnO, 3d levels emissions of TM ions is expected to modify the inherent characteristic emissions of ZnO. In our study, highly smooth spherical shaped micro particles with different diameters ranging from ~3 to 6 ?m were grown in different substrates by using a pulsed Nd3+: YAG laser. SEM (Scanning Electron Microscopy) and AFM (Atomic Force Microscopy) images show the presence of uniform smooth surfaced spheres. Raman scattering measurements from the samples at 488 nm light excitation provide confirms the wurtzite structure of the fabricated undoped and TM doped ZnO microspheres. WGM lasing studies from TM doped ZnO microparticles using a continuous wave laser are in progress.

REFERENCES

[1]. Bagnall, D. M., Chen, Y. F., "Optically pumped lasing of ZnO at room temperature," Applied Physics Letters 70,2230-2234 (1997).

[2]. Soni, B. H., and Deshpande, M. P., "Studies on ZnO nanorods synthesized by hydrothermal method and their characterization, " Journal of Nano- and Electronic Physics 5.4, Vol. 42, 328–334 (2013).

[3]. Okamoto, S., Inaba, K., Iida, T., Ishihara, H., Ichikawa, S., Ashida, M., "Fabrication of single crystalline microspheres with high sphericity from anisotropic materials", Scientific Reports 5186, 1-4 (2014).

[4]. Janotti, A., and Van de Walle, C.G., "Fundamentals of zinc oxide as a semiconductor, "Rep. Prog. Phys., 72 , 126501-126539 (2009)

[5]. Chaaya, A. A.,Viter, R., Bechelany, M., Alute, Z., Erts, D., Zalesskaya, Kovalevskis, K., Rouessac, V., Smyntyna, V., and Miele, P., " Evolution of microstructure and related optical properties of ZnO grown by atomic layer deposition," Beilstein J. Nanotechnol. 4, 690–698 (2013).

[6]. Singh Moirangthem, R., Ju Cheng,P., Hang Chien, P., C., Trong Huynh Ngo, B., Chang, S.,W., Chung Hao Tien, Chang, Y. C.,"Optical cavity modes of a single crystalline zinc oxide microsphere," OSA Optics Express 3, Vol. 21, 1-11 (2013).

10090-69, Session PTue

Laser simulation applying Fox-Li iteration: Investigation of reason for non-convergence

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Fox-Li iteration is often used for the numerical simulation of lasers. If a solution is found, the complex field amplitude at the output plane is often a good indication of the laser output beam, providing estimates for the power and beam quality. What does it mean if no solution is found? An example for which the medium possesses a self-focusing nonlinearity is investigated. The complex field amplitude is found for the laser for which the strength ?, of the self focusing nonlinearity, is zero. A Fox-Li iterative calculation for the laser with nonzero ? is started, with initial complex field amplitude corresponding to the mode for ?=0. The field amplitude is evaluated as it propagates back and forth in the laser. Thus insight is gained regarding the evolution of a beam as it propagates round trips in the laser. If the beam develops small-scale filaments, we conclude that the laser output beam would suffer from filamentation.

10090-70, Session PTue

New generation of deformable mirror dedicated to ultra high intensity laser

Xavier Levecq, Guillaume Beaugrand, Imagine Optic SA (France)

Like in astronomy, Adaptive Optics (AO) is now a standard feature at the actual ultra-high intensity lasers facilities. AO helps in reaching both maximum peak energy and intensity in correcting both aberrations induced by the optical components and the thermal effects induced in the amplification stages. The new generation of ultra-high intensity femto-second petawatt and above class lasers requires new features of wavefront corrections. AO needs a new breath to overcome potentially bigger diameter, larger aberrations, faster optics, higher risk of damaging optical components and faster and easier maintenance.

Imagine Optic is a pioneer company in the development of AO solutions, wavefront sensors and deformable mirrors, dedicated to ultra-high intensity lasers. Here, we will present the new generation of deformable mirror, ILAO Star, which is using a new design mechanical actuators.

We will present these new actuators and their improvements compared to the previous generation. Principles of actuation, design of deformable mirror and its complete characterization will be presented in this article. We will also present the advantages brought by these new actuators when integrated in the ILAO Star deformable mirror :

- Custom design : from 20 mm to 500 mm useful diameter, from 0° to 45° angle of incidence
- Faster speed (up to 10Hz)
- Correction capabilities
- Better mechanical efficiency
- Better thermal stability
- Longer life time
- Easier and safer maintenance
- etc.

10090-38, Session 9

Optomechanical oscillations in asymmetric whispering gallery mode optical cavities

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Ultra high quality optical resonators have enabled accumulation of exceptionally high intensities of light from low input powers. This feature opens new horizons in low power observation of physical phenomena such as lasing, sensing and radiation pressure driven oscillations. Radiation pressure instability facilitates transfer of energy from photons to mechanical degree of freedom in optical resonators. In high quality toroidal micro cavities, radiation pressure is demonstrated in the form of "dynamic back action" and results mechanical oscillations with sub-Hz linewidth. Since the toroidal cavities are symmetrical in nature, the exerted radiation pressure can mainly excite radially symmetric modes such as the first cantilever mode and the radially breathing mode. Study of these modes reveals important information about interaction of light and mechanical mode as well as intrinsic properties of the resonator as a mechanical oscillator. However, there are some unexcited mechanical modes that in some cases have even higher mechanical quality factors compared to the usually excited ones. Most of the properties of these mechanical modes remain unknown because the radially symmetric force does not provide a component to excite them. In this research, we have developed a novel method to fabricate asymmetric toroidal resonators (minor and major diameters), which enables us to regeneratively excite unobserved asymmetric modes. One key feature is that the optical quality factor is relatively high despite the asymmetry. As a result, we are able to excite the asymmetric modes with sub-mW threshold powers. Complementary modeling is also performed, confirming the experimental findings.

10090-39, Session 9

High-throughput real-time sensing with microfluidic electro-opto-mechanical resonators

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Resonant optical sensors have enabled the label-free measurement of nanoparticles suspended in liquids, down to the resolution of individual viruses and large molecules, but are only able to quantify optical properties (refractive index, scattering, fluorescence). Additionally, these sensors are fundamentally limited by the random diffusion of particles to the sensing region, and thus only quantify a tiny fraction of the analyte. We have developed a microfluidic optomechanical resonator capable of sensing flowing nanoparticles using the action of phonons that are coupled to light. The phonon mode of the system casts a nearly perfect net for measuring density, viscoelasticity, and compressibility of the particles that flow through, without being limited by random diffusion. Information on the particle mechanical properties is encoded in the light scattered from the thermal fluctuations of the phonon mode, and measurements at a timescale of below 20 milliseconds have been demonstrated previously. In this work, we develop a new experimental method for improving the signal-to-noise ratio (SNR) and sensing speed achievable with this technique, by implementing electro-opto-mechanical transduction. We demonstrate real-time particle transit measurements as fast as 400 microseconds, a factor of 50x improvement in speed, without any post-processing. We discuss how this novel technique can be used for ultra-high throughput analysis of mechanical properties of biological particles in liquids, enabling a new form of flow cytometry.

10090-40, Session 9

The linewidth of distributed feedback resonators: the combined effect of thermally induced chirp and gain narrowing

Cristine Calil Kores, Dimitri Geskus, Nur Ismail, KTH Royal Institute of Technology (Sweden); Meindert Dijkstra, Univ. Twente (Netherlands); Edward H. Bernhardi, Markus Pollnau, KTH Royal Institute of Technology (Sweden)

Distributed-feedback (DFB) laser resonators are widely recognized for their advantage of allowing laser emission with extremely narrow linewidth. Our investigation concerns y tterbium-doped amorphous Al2O3 channel waveguides with a corrugated homogeneous Bragg grating inscribed into its SiO2 top cladding, in which a ?/4 phase-shift provides a resonance and allows for laser emission with a linewidth as narrow as a few kHz. Pump absorption imposes a thermal chirp in the grating period, which has implications for the spectral characteristics of the resonator, given the asymmetric nature of the resulting period. The propagation of light in periodic or quasi-periodic stratified media may be described by several different approaches, such as the coupled-mode theory (CMT), the index-matching technique, and the transfer-matrix method.

We investigate the effect of the thermal chirp on the spectral response of a DFB laser resonator, experimentally and by simulations using the CMT. A controlled temperature gradient is imposed upon the waveguide in the propagation direction and the spectral response of the unpumped resonator is investigated by use of a scanning narrow-linewidth laser. By comparison with the spectrum while pumping the resonator, we investigate i) the shift in the central wavelength of the resonance, which provides information about the fraction of pump power that is converted to heat, and this knowledge can be extended for the above laser operation, ii) the linewidth of the resonance, which is studied under the scope of gain narrowing, along with the expected values obtained directly from gain measurements.

10090-41, Session 9

Dissipative interaction with a high-Q microcavity for single nanoparticle detection *(Invited Paper)*

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Ultrasensitive optical detection of nanoparticles is highly desirable for applications in early-stage diagnosis of human diseases, environmental monitoring and homeland security, but remains extremely difficult due to ultralow polarizabilities of small-sized, low-index particles. Optical whispering-gallery-mode (WGM) microcavities, with high Q factors up to 108, provide a promising platforms for label-free detection of nano-scaled objects, due to significantly enhanced light-matter interaction. The mechanisms of the conventional WGM sensors, based on the reactive (or dispersive) interaction, measure the mode shift induced by the environmental variations of refractive index, which may fail to detect low-index nanoparticles. In this work, we propose a different dissipative sensing scheme, reacting as linewidth change of WGMs, to detect single nanoparticle using a silica toroidal microcavity fabricated on a silicon substrate. In experiment, detection of single gold nanorods in aqueous environment is realized by monitoring simultaneously the linewidth change and shift of cavity mode. Besides a good consistent with the theoretical predictions, the experimental result shows that the dissipative sensing achieves a better signal-to-noise-ratio compared to the dispersive mechanism. Remarkably, by setting the probe wavelength on and off the surface plasmon resonance of the gold nanoparticles, the great potential of the dissipative sensing method to detect single lossy nanoparticles is demonstrated. This dissipative sensing method holds great potential in detecting lossy nanoparticles, and may become a promising lab-on-a-chip platform for detecting small-sized, low-index particles with ultralow polarizabilities.

10090-42, Session 9

High-resolution temperature sensor through measuring the frequency shift of single-frequency Erbium-doped fiber ring laser

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Though many temperature sensors have been designed with high sensitivities by monitoring the thermal-induced wavelength shifts in the optical fiber devices, the low resolution of the optical spectrum analyzer and the broad bandwidth of the output laser may decrease the accuracy of the direct detected wavelength shifts and make the sensors have no response to a very small temperature drift. In order to the sensing resolution, we propose a principle to achieve a temperature sensor with high resolution through employing the optical heterodyne spectroscopy method to measure the thermal-induced frequency shift in the single-frequency Erbium-doped fiber ring laser. The small temperature drift can be calculated using the amount of frequency shift by tracing out the heterodyne spectra with different temperature. Owing to the narrow linewidth of the output single-frequency signal and the high accuracy of the optical heterodyne spectroscopy method in measuring the frequency shift in the single-frequency ring laser, the temperature sensor can be employed to resolve a temperature drift up to ~5.5?10-6 °C theoretically when the single-frequency ring laser has a linewidth of 1 kHz and a 10-kHz frequency shift is achieved from the heterodyne spectra. Moreover, not only can the proposed principle improve the sensing accuracy by enhancing the resolution, but also it is compatible with the measurement of other physical quantities, such as strain, vibration and pressure.

10090-43, Session 10

Impact of zirconium dopants on the lasing efficiency of Raman microcavity lasers

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Despite having low Raman gain coefficients, silica microcavities have demonstrated exceptionally low Raman lasing thresholds in a wide range of environments. One reason for their success is their ability to support ultra-high quality factors (Q) which result in high circulating optical powers. However, because the lasing efficiency of these devices is governed by the Raman coefficient of the lasing media, only moderate efficiencies have been demonstrated in silica devices due to silica's low Raman gain coefficient.

In the present work, we synthesize a suite of silica sol-gels doped with a range of Zirconium (Zr) concentrations. The intrinsic Raman gain of the Zr-doped silica is measured using Raman spectroscopy, and the values show a clear dependence on Zr dopant concentrations. Subsequently, ultra-high-Q silica toroidal microcavities are coated with the different Zr-doped sol-gels. To enable comparison across devices, the Q factors of all devices and the device diameters are held constant. The lasing performance is characterized using a 765 nm pump source, and the Raman emissions for the coated devices are detected at 790 nm and longer. The lasing emission

and characteristic threshold curves are quantified using both an optical spectrum analyzer and an optical spectrograph. The lasing slope efficiency exhibits a marked increase from 3.37% to 47.43% as the Zr concentration increases due to the Raman gain improvement. These values are particularly notable as they are the unidirectional, not bidirectional, lasing efficiencies. Therefore, they are more accurate representations of the expected performance of the device in a real-world setting.

10090-44, Session 10

Gyroscope based on a crystalline optical WGM microresonator

Wei Liang, Vladimir S. Ilchenko, Danny Eliyahu, Anatoliy A. Savchenkov, Andrey B. Matsko, Lute Maleki, OEwaves, Inc. (United States)

We report on a study of performance of both active and passive optical gyroscopes based on high finesse crystalline whispering gallery mode (WGM) resonators. We show that the sensitivity of the devices is ultimately limited due to the nonlinearity of the resonator host material. A gyroscope characterized with 0.02 deg/hr^1/2 angle random walk and 2 deg/hr bias drift is demonstrated.

10090-45, Session 10

A simple method to characterize thermal property of an optical microresonator

Weijian Chen, Washington Univ. in St. Louis (United States); Jiangang Zhu, Washington Univ. in St. Louis (United States) and Los Alamos National Lab. (United States); Sahin K. Ozdemir, Washington Univ. in St. Louis (United States); Bo Peng, Washington Univ. in St. Louis (United States) and IBM Thomas J. Watson Research Ctr. (United States); Lan Yang, Washington Univ. in St. Louis (United States)

Thermal properties of a photonic resonator, determined by both intrinsic properties of materials and the geometry and structure of the resonator, play important roles in various applications including radiation detection, biosensing, and microlaser. In this work, we propose and demonstrate a method to measure the thermal relaxation time and thermal conductance of an optical microresonator. The method utilizes the optothermal effect of two nearby optical modes in the transmission spectrum of the same resonator to extract the thermal properties of the resonator. We show that the thermal relaxation time, as well as thermal conductance, can be tailored by changing the geometric parameters of the resonator. Furthermore, we provide an analytical model that can be used to estimate the thermal relaxation time of a microtoroid resonator given its geometric parameters. The experimental results agree well with the analytical predictions. Our method can be exploited to characterize and optimize the thermal properties of other types of optical microresonators.

10090-46, Session 10

The study of polarization mode selection and coupling efficiency of optofluidic ring resonator lasers

Xiaoyun Pu, Yuanxian Zhang, Yunnan Univ. (China)

The polarization mode selection and the dependence of coupling efficiency on the polarization state of pump light have been demonstrated for an optofluidic ring resonator (OFRR) laser in the present work. An optical fiber is chosen to serve as the ring resonator and surrounded by rhodamine 6G dye solution of lower refractive index as the fluidic gain medium. The lasing emission of whispering gallery mode (WGM) is a transverse magnetic mode (TM mode) when pumped by s-polarized light, while it is a transverse electric mode (TE mode) when pumped by p-polarized light. TE and TM mixed emission are found in lasing spectra if pump light contains both p- and s-polarized lights. The lasing intensity of TM mode is nearly twice as that of TE mode for the same pump energy density, meaning an obvious difference of coupling efficiency on polarization state of pump light. A model of induced dipole moment is set up in which a dye molecule is treated as an radiant dipole, the calculated coupling efficiency for s-polarized dipole moments is just two twice as that of p-polarized dipole moments. Based on the model, the lasing intensity formulae for both TM and TE mode are derived, the calculated results match the experimental data very well. Our work may be further applied to lower threshold detection, such as detecting a single molecular layer of gain in optofluidic lasers for lab-on-chip.

10090-47, Session 11

Enhanced sensitivity in PT-symmetric coupled resonators

Hossein Hodaei, Absar U. Hassan, Hipolito Garcia Gracia, William E. Hayenga, Demetrios N. Christodoulides, Mercedeh Khajavikhan, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

In the recent years, the notion of parity-time symmetry has received a considerable attention in the field of optics and photonics [1-2]. Utilizing this concept, several integrated photonic devices have been proposed and demonstrated such as lasers, amplifiers, and demultiplexers [3-4]. Among the possible PT-symmetric arrangements, coupled resonators provide a versatile platform in order to attain new functionalities. In such configurations, the interplay between gain/loss contrast and coupling can introduce non-Hermitian degeneracies or exceptional points in the spectrum. An intriguing feature associated with such points is that the eigenfrequencies around these degeneracies are strongly dependent on the parameters of the system [5,6] (frequency detuning, gain, coupling, etc.). This aspect can be fruitfully utilized to enhance the responsivity of resonator-based sensors [7]. In this fashion, one can surpass the typical limitations of a single-cavity sensing device dictated by the Q-factor and the spectroscopic resolution.

Here, we experimentally investigate the sensitivity of PT-symmetric microring lasers with respect to perturbations when biased close to an exceptional point. The coupled microrings are fabricated on an InP-based gain medium and the PT-symmetry is established through selective pumping of the structure. Perturbations are induced thermally using metallic heaters fabricated on top of each microring. Our results show that the resonance frequency of the lasing modes change in a square root fashion, thus leading to ~10X enhancement in the sensitivity. Our work provides a new avenue in enhancing the detection limit of resonator-based integrated sensors through PT-symmetric coupled cavities.

References

[1] K. G. Makris, R. El-Ganainy, and D. N. Christodoulides, Phys. Rev. Lett. 100, 103904 (2008).

[2] C. E. Rüter, K. G. Makris, R. El-Ganainy, D. N. Christodoulides, M. Segev, and D. Kip, Nat. Phys. 6, 192-195 (2012).

[3] H. Hodaei, M.-A. Miri, M. Heinrich, D. N. Christodoulides, and M. Khajavikhan, Science 346, 975-978 (2014).

[4] H. Benisty, A. Lupu, and A. Degiron, Phys. Rev. A, 91, 053825 (2015).

[5] W. D. Heiss, J. of Phys. A: Mathematical and Theoretical 45, 444016 (2012).

[6] J. Wiersig, Phys. Rev. Lett. 112, 203901 (2014).

[7] A. M. Armani, R. P. Kulkarni, S. E. Fraser, R. C. Flagan, K. J. Vahala, Science 317, 783-787 (2007).

10090-48, Session 11

Coupled mode analysis of micro-disk resonators with an asymmetric-index-profile coupling region

Clément Arlotti, Guilhem Almuneau, Olivier Gauthier-Lafaye, Stéphane Calvez, Lab. d'Analyse et d'Architecture des Systèmes (France)

Over the last two decades, integrated whispering-gallery-mode resonators have been increasingly used as the basic building blocks for selective filters, high-sensitivity sensors, switch nodes in photonic chips or even as nonlinear converters. Irrespective of the application, the performance of these integrated micro-resonators is generally governed by the evanescent coupling of the light between its constitutive cavity and bus waveguides. It is therefore of crucial importance to be able to assess the dependence of the coupler characteristics based on the chosen structural layout. The coupled-mode theory, which derives the response of the full coupler from the linear superposition of a number of constitutive decomposition fields, has been shown to be one of the most efficient methods to describe this coupling interaction for devices with simple and often symmetric refractive index distributions.

Here, following our recent experimental demonstration, we extend the coupled-mode analysis to vertically-coupled racetrack resonators presenting not only an asymmetric distribution of refractive index but also a multilayer separation region between the two waveguide cores, generally resulting in mismatched propagation constants in the coupling region. In doing so, we introduce a criterion which, given the coupler overall permittivity distribution, clarifies how to best choose the individual decomposition index profiles among the various possible solutions. We subsequently exploit the derived decomposition to evaluate the theoretical transmission characteristics of an AlGaAs/AlOx-based structure as function of wavelength and as function of the position of the resonator relative to the access waveguide.

10090-49, Session 11

New spherical optical cavities with non-degenerated whispering gallery modes

Tsutaru Kumagai, Tokyo Institute of Technology (Japan); Giuseppe Palma, Francesco Prudenzano, Politecnico di Bari (Italy); Tetsuo Kishi, Tetsuji Yano, Tokyo Institute of Technology (Japan)

Modified spherical resonator is proposed to show splitting of the degenerated Whispering Gallery Modes (WGMs). Highly spherical optical cavity has high Quality factor to behave as resonator to have high photon density with low threshold of excitation energy. However, it also restricts the conditions of excitation (quite narrow bandwidth to introduce the excitation photon).

This paper proposed the modification of spherical cavity by the introduction of defect inside to split degenerated WGMs for excitation. A single bubble or hollow ring is introduced inside the sphere. Generally, resonance using WGM in sphere is determined by the mode number, l, and the mode order, n, but not be the mode order, m. From the symmetry of cavity, WGMs are degenerated concerning with m. The placement of the defect like single bubble or hollow ring breaks this symmetry, and induces the variety of the excitation modes of spherical cavity. A couple of simulations using eigenmode analysis and transient analysis are applied to observe the effect of the defect on the WGM resonance in the spherical cavity. Concerning with the sphere with a single bubble defect is compared with the experimentally observed resonance in Nd-doped tellurite glass microsphere with a single bubble. Splitting of resonance modes comes from the non-degeneration of WGMs (NDWGMs) in sphere, and opens the optical windows for excitation light to couple with NDWGMs to pump Nd^{3+} in sphere efficiently.

10090-51, Session 11

Automatic channel-switched intracavity-absorption acetylene sensor based on mode-competition via Sagnac loop filter

Wei Shi, Haiwei Zhang, Liangcheng Duan, Ying Lu, Quan Sheng, Jianquan Yao, Tianjin Univ. (China)

Multipoint intracavity-laser-absorption sensor networks have also been realized by substituting the high-cost optical components with low-cost passive fiber devices, such as fiber Bragg grating and dense wavelength division multiplexing filter. However, the narrow bandwidths and fixed operating wavelengths of the fiber Bragg grating and the dense wavelength division multiplexing filter may limit the multiplexing capability of intracavity-laser-absorption sensor network. Here, we report a flexible and high sensitivity multipoint intracavity-laser-absorption acetylene sensor via mode-competition in a ring laser based on Sagnac loop filter. It spends 50 seconds when the voltage gradient method is employed to scan the absorption spectra. When the gas cells are filled with 1% acetylene, the absorption sensitivities are 398 ppmV and 1905 ppmV at 1532.83nm and 1534.01nm, respectively. To the best of our knowledge, it is the first time that realizing an automatic channel-switched intracavity-laser-absorption via the mode-competition in the ring laser based on a Sagnac loop filter. Compared with fiber Bragg grating and dense wavelength division multiplexing filter, the flexible tuning of transmission spectrum of the Sagnac loop filter makes it more compatible for hybrid gas detection by adjusting the polarization controller applied to the polarization maintained fiber. The principle can be employed to enhance the capacity of an intracavity hybrid gas sensor network combining with other multiplexed technique.

10090-52, Session 11

Generation of nearly degenerate and ultrastable bi-frequency signal twins and idler twins based on nonlinear crystal twins

Yujie J. Ding, Lehigh Univ. (United States)

We have investigated the novel coupled optical parametric oscillators based nonlinear crystal twins as ultrastable resonators. Our scheme for quasi-phase-matching is fundamentally different from all the previous ones. Indeed, when one of the nonlinear crystals is placed in the cavity, parametric oscillation is phase-matched based on birefringence. Only after the second crystal, having the sign of its nonlinear coefficient being the opposite of that of the first crystal, is placed next to the first crystal inside the resonators, a single pump wave generates a pair of signals and a pair of idlers. These signal twins (also idler twins) exhibit ultrastability, i.e. their frequency difference is insensitive to the fluctuations of the crystal temperature and pump frequency. As a result, these twins can be used to realize variety of the applications including coherent link from optical to microwave frequencies, optical generation and control of millimeter waves, and detection based on optical heterodyning with ultrahigh sensitivity.

10090-71, Session 11

Control the flow of light in Whispering-gallery-mode resonators *(Invited Paper)*

Lan Yang, Washington Univ. in St. Louis (United States)

Due to resonance enhanced light-matter interactions, whispering-gallery-mode (WGM) resonators have become an excellent platform to explore interesting physical phenomena that might enable innovative ways to control light. In this talk, first I will discuss exceptional points in WGM resonators. EPs are non-Hermitian degeneracies that occur in open

physical systems. Such counterintuitive phenomena as loss-induced lasing and enhanced sensors have occurred in systems operating around EPs. I will show that we can develop a new route to control lasing direction by operating whispering-gallery-mode (WGM) resonators around EPs. Specifically, close to an EP, a strong spatial chirality can be imposed on the WGMs, which is equivalent to a switchable direction of light rotation inside the resonator. By directly establishing the essential link between the non-Hermitian scattering properties of the WGM resonator and a strong asymmetric backscattering in the vicinity of an EP, we can dynamically control the chirality of resonator modes. This enabled us to tune the direction of a WGM microlaser from a bidirectional emission to a unidirectional emission in the preferred direction. Then I will discuss chaos-induced stochastic resonance in an opto-mechanical WGM resonator, and optomechanically-mediated transfer of chaos between two largely detuned optical fields (i.e., no direct talk between the fields) such that a very weak optical field (probe), which cannot create chaos itself, experiences periodic, quasi-periodic and finally chaotic oscillations due to the optomechanical oscillations created by a strong optical field (pump): the probe follows the same route to chaos as the pump.

10090-53, Session 12

Parameter optimization of a vectorial optical field generator for precise spatial polarization control

Jian Chen, Univ. of Electronic Science and Technology of China (China) and Univ. of Dayton (United States); Guanghao Rui, Southeast Univ. (China); Lingjiang Kong, Univ. of Electronic Science and Technology of China (China); Qiwen Zhan, Univ. of Dayton (United States)

Based on two liquid crystal spatial light modulators (SLM), a vectorial optical field generator (VOF-gen) is capable of controlling the phase, amplitude, and polarization (ellipticity and orientation) of an optical field on a pixel-by-pixel basis to generate arbitrarily complex optical field. Due to the different responses of the non-polarizing beam splitter to the S- and P- components of polarized beam, gamma curve error and fringe field effect of the SLMs and other factors, the polarization of the output beam from the VOF-gen could depart from the desired results, leading to adverse effects on the performance and application of the designed complex beam. In this work, we report on the realization of precise spatial polarization control of light via a priori optimization of the polarization rotation and retardation modulation in the generated patterns. To obtain the modification coefficient for the polarization rotation, we design patterns to generate linearly polarized light at 45˚, measure the intensities of the vertical and horizontal components of the output beam and calculate the ratio of them. After several iterations, the method converges to an accurate coefficient based on the criterion that the measured intensities are equal. For the modification of the retardation, we design patterns to generate circularly polarized light and let the modulated beam propagate through a circular polarization analyzer. We iteratively adjust the modification value until the intensity of the output beam approaches extinction. Finally, we generate complex polarized beam with these optimized coefficients and the measured Stokes parameters demonstrate the validity of this method.

10090-54, Session 12

The investigation of iodine cell temperature control in frequency stabilized Nd:YAG laser system

Prayut Potirak, King Mongkut's Institute of Technology Ladkrabang (Thailand); Monludee Ranusawud, National Institute of Metrology (Thailand) (Thailand); Pichet Limsuwan, King Mongkut's University of Technology Thonburi (Thailand); Prathan Buranasiri, King Mongkut's Institute of Technology Ladkrabang (Thailand)

In this research, the temperature characteristics of a 10 cm long iodine cell used in diode-pumped Nd:YAG laser system has been investigated. Here, the laser system were frequency stabilized by locking their frequency-doubled output at 563 THz. The absolute frequency measurement of the a10 hyperfine component of molecular Iodine R(56) 32-0 line with effect to various temperatures is reported. With the iodine cell temperature control, the output frequency is tuned in the range of standard frequency at 563.2602235 THz with about 10-9 of stability.

10090-55, Session 12

The use of modified hill-climbing algorithm for laser beam focusing through the turbid medium

Alexis V. Kudryashov, Institute of Atmospheric Optics (Russian Federation) and Institute of Geosphere Dynamics (Russian Federation); Alexander N. Nikitin, Ilya Galaktionov, Julia V. Sheldakova, Active Optics Night N Ltd. (Russian Federation)

We investigated the ability to focus the laser beam (? = 0.65 um) propagated through the scattering suspension of polystyrene microspheres in distilled water. We built the closed-loop adaptive optical system and applied the hill-climbing algorithm to focus the laser beam passed through turbid medium. Shack-Hartmann sensor was used to measure the local slopes of the Poynting vector, while the CCD camera was used to measure the intensity and the diameter of the focal spot in the far-field. We compare the beam focusing improvement using bimorph deformable mirror (50 mm in diameter) with 48 electrodes and stacked-actuator mirror (30 mm in diameter) with 19 actuators, that were applied in order to compensate for the local slopes of Poynting vector based on the feedback signal from the CCD camera.

10090-56, Session 12

Photonic crystal microchip laser

Darius Gailevicius, Vilnius Univ. (Lithuania); Volodymyr Koliadenko, The National Academy of Sciences of Ukraine (Ukraine); Vytautas Purlys, Martynas Peckus, Vilnius Univ. (Lithuania); Victor B. Taranenko, The National Academy of Sciences of Ukraine (Ukraine); Kestutis Staliunas, Univ. Politècnica de Catalunya (Spain) and Institució Catalana de Recerca i Estudis Avançats (Spain)

Microchip lasers, being very compact and efficient sources of coherent light, suffer from one serious drawback: low spatial quality of the beam, strongly reducing the brightness of emitted radiation. Attempts to improve the beam quality, such as pump-beam guiding, external feedback, either strongly reduce the emission power, or drastically increase the size and complexity of the lasers. Here we proposed that a specially designed photonic crystal in the cavity of a microchip laser can significantly improve the beam quality. Our experiments show that a microchip laser, due to spatial filtering functionality of the intracavity photonic crystal, has an improved beam quality factor M2, reducing it by a factor of 2, and increasing the brightness of radiation by a factor of 3. This comprises a new kind of laser, the "photonic crystal microchip laser", a very compact and efficient light source emitting high spatial quality high brightness radiation.

In the presentation, we will run a live numerical model of microchip laser, and will visually demonstrate that the intracavity photonic crystals indeed can strongly improve the beam spatial quality and brightness of the radiation. We will discuss the fabrication of Photonic Crystal spatial filters.

We will present the current experimental results on the development of Photonic Crystal Microchip Lasers [1], as well as the most recent observations.

[1] Darius Gailevicius, Volodymyr Koliadenko, Vytautas Purlys, Martynas Peckus, Victor Taranenko, and Kestutis Staliunas, Photonic Crystal Microchip Laser, resubmitted 2016, https://dl.dropboxusercontent.com/u/80903325/MicrochipPhCLaser%20SciRep%20final.pdf

10090-57, Session 12

Unstable resonators for high power diode pumped alkali lasers

Glen P. Perram, Athanasios Gavriedlides, LaVerne A. Schlie, Robert Loper, Michael R. Hawks, Air Force Institute of Technology (United States)

The diode-pumped alkali laser (DPAL) was first proposed in 2001 as an alternative to high-power, diode-pumped, solid-state lasers. The radiation from un-phased diode lasers is absorbed on the D2 line, 2S1/2 - 2P3/2, collisional relaxation populates the lower 2P1/2 state, and lasing is achieved on the 2P 1/2 - 2S1/2 transition. The DPAL system offers excellent thermal control, good beam quality, and a quantum efficiency of 95%– 99%. A high power, ~1 kW, cesium laser with 48% optical-to-optical efficiency was openly reported in 2012. More recently a 1.5 kW flowing potassium laser was reported. The rubidium – high pressure helium variant is also under strong investigation.

The high gain DPAL system will require an unstable resonator with high Fresnel number and high output coupling to achieve excellent beam quality. The design and analysis of the DPAL resonator and the influence of spatial variations in gain medium on far field beam quality are developed in this work. The relative advantages of longitudinal and transverse flow geometries to beam quality are evaluated.

In this project we develop a wave-optics simulation of unstable resonators for the DPAL gain media to assess the limitations on far field beam quality. A systematic study of the influence of gain medium aberrations, flow geometry, and resonator design on far field beam quality is reported. A path for model enhancements to address amplified spontaneous emission, parasitic modes and anomalous dispersion is also suggested

10090-58, Session 12

Control of pulse format in high energy per pulse all-fiber erbium/ytterbium laser systems

Michael Klopfer, The Univ. of New Mexico (United States); Leanne J. Henry, Air Force Research Lab. (United States); Ravinder K. Jain, The Univ. of New Mexico (United States)

We report for the first time the combination of high beam quality (M2 ~ 1.12) and single polarization output (PER ~ 15 dB) at mJ-pulse energy levels from a 100 ns pulsed 1550 nm fiber laser/amplifier system at repetition rates between 1 and 10 kHz. Pulses were generated from a continuous wave source through the opening and closing of an electro-optic modulator (EOM). To avoid prematurely reaching the damage threshold of the optical fiber of which the system is comprised, the front edges of the pulses were shaped by controlling the opening of the EOM via a Python driven home built arbitrary waveform generator. Various means were also utilized to minimize the energy between the pulses as well as the amplified spontaneous emission (ASE) to include the usage of a second EOM and/or an acousto-optic modulator (AOM) to block the interpulse power, pulsation of the pump diodes, as well as one or more ASE filters. For the higher power stages, because of damage threshold issues, only pulsing pumping can be used to control the interpulse energy and the spectrum. Our experimental results have shown a significant improvement in the fraction of the total energy intrapulse as well as a significant decrease in the intrapulse ASE for less than 100% duty cycle pulse pumping. Finally, the most recent experimental results on the ability to shape pulses as the energy per pulse is scaled upward will be presented for both the all fiber system as well as a hybrid fiber/solid state system.

10090-59, Session 13

Analysis of the emission characteristics of diode lasers by their wavefront structure

Inga-Maria Eichentopf, Martin Reufer, Hochschule Ruhr West (Germany)

In recent years wavefront measurements using a Shack-Hartmann Sensor became a fast and easy way to analyze the change of laser beam characteristics over a wide range of parameters. This method is well known for nearly Gaussian laser beams while the wavefront analysis of broadarea semiconductor lasers is still an open field of current research. Detailed analysis of the wavefront gives an additional path to get insight into the modal composition of semiconductor lasers, which has a dominant impact on the output parameters of the devices. For our investigations we utilize lasers based on the material system of GaAs emitting light in the near infrared. These types of laser emit typically more than one optical mode. The composition of these modal structures is highly affected by thermal and electric effects inside the active medium. By using a simulation software the intensity distribution at various diode currents can be associated with an assembly of Hermite Gaussian modes and thus gives insight into the basic modal structure. Additionally the change of modal composition can be recorded within the wavefront deflection. This delivers an extra track of information to the light emission. The aim of our research is to associate the wavefront with the modal structure gained by measuring the intensity distribution under changing working conditions. Furthermore we use a lens system to receive a magnified image of the beam and investigate the spatial evolution of the intensity and wavefront distribution of the laser emission along the propagating axis.

10090-60, Session 13

Characterising partially coherent optical fields

Prince Mredlana, Council for Scientific and Industrial Research (South Africa); Darryl Naidoo, CSIR National Laser Ctr. (South Africa); Cosmas Mafusire, Univ. of Pretoria (South Africa); Angela Dudley, CSIR National Laser Ctr. (South Africa); Tjaart Krüger, Univ. of Pretoria (South Africa); Andrew Forbes, Univ. of the Witwatersrand (South Africa)

Characterising optical fields is important in understanding their propagation and interaction with optical elements. Modal decomposition characterisation involves decomposing the optical field into its constituent coherent modes and determining their weights. We perform such a decomposition of an arbitrary beam and determine the beam size, beam divergence and curvature of each mode from the amplitude and phase information from the modal weights. We utilise the expressions for beam size, beam divergence and curvature for each mode to characterise the arbitrary beam. Phase-space optics has attracted interest as an alternative to Fourier optics, combining both wave and geometrical optics to give a more detailed field description. We also explore a novel approach in phase-space in which we characterise an aberrated partially coherent beam by the modal decomposition of its Wigner distribution function (WDF). The method is particularly efficient when dealing with fields with phase aberrations. The WDF method results show comparable accuracy when compared with modal decomposition performed on just optical field instead.

10090-61, Session 13

Self-calibrating, real-time M-square measurement system

Michael J. Scaggs, Gilbert J. Haas, Haas Laser Technologies, Inc. (United States)

M-square measurements since the inception of the ISO 11146-1 measurement standard of 1996 has been one that has been difficult even for a seasoned veteran of such measurements. Variations of more than 10% are not uncommon for the same measurement tool on the same laser being measured. Much of the variation comes from alignment, the motion involved (time averaged based), complex attenuation techniques which often include variable neutral density filters and the type of sensors employed. Moreover, setup times for the instrument can take hours and the measurements themselves many minutes. Measurement of a laser or a laser systems' M-square should be as simple as measuring the power of the laser. In that one aligns the laser to the device; put the device in self calibration mode; make a measurement.

In 2012 the authors developed a passive optical design that provided real-time M-square measurement of a laser or laser system but nevertheless still required calibration of the key optics within the system: a Fabry-Perot etalon pair and their spacing in order to obtain an accurate M-square result. Using existing data from the sensor along with a simple ray tracing technique, the etalon spacing can be determined with high accuracy through the deconvolution of the data from the sensor; thereby eliminating a separate time consuming calibration. The key calibration information can now be obtained in a fraction of a second without any effort on the part of the user.

10090-62, Session 13

Conical refraction of a high-M2 laser beam

Grigorii S. Sokolovskii, Ioffe Institute (Russian Federation); Valentin Y. Mylnikov, Saint-Petersburg State Polytechnical Univ. (Russian Federation) and Ioffe Institute (Russian Federation); Sergey N. Losev, Ioffe Institute (Russian Federation); Ksenia A. Fedorova, Aston Univ. (United Kingdom) and ITMO Univ. (Russian Federation); Edik U. Rafailov, Aston Univ. (United Kingdom)

We report on experiments with conical refraction of laser beams possessing a high beam propagation parameter M2. With beam propagation parameter values M2=3 and M2=5, unusual Lloyd distributions with correspondingly three and five dark rings were observed. In order to explain this phenomenon, we extend the dual-cone model of the conical refraction that describes it as a product of interference of two cones that converge and diverge behind the exit facet of the crystal. In the extended model, these converging/diverging cones are represented as the cone-shaped quasi-Gaussian beams possessing the M2 parameter of an original beam. In this formalism, a beam-waist of these cone-shaped beams is proportional to the M2 value and defines the area of their interference which is a width of the Lloyd ring. Therefore, the number of dark rings in the Lloyd distribution is defined by the M2 value and can be much greater than unity. The results of the numerical simulations within the extended dual-cone model are in excellent agreement with the experiment. The developed model offers a simple integral-free representation of the conical refraction and can be utilized for the calculation of laser cavities and optical traps involving conically-refracting crystals.

10090-63, Session 13

Beam shaping by means of different wavefront correctors

Alexis V. Kudryashov, Institute of Atmospheric Optics (Russian Federation) and Institue of Geosphere Dynamics (Russian Federation) and Active Optics Night N Ltd. (Russian Federation); Anna Lylova, Active Optics Night N Ltd. (Russian Federation) and Institute of Atmospheric Optics (Russian Federation); Julia V. Sheldakova, Active Optics Night N Ltd. (Russian Federation); Vadim Samarkin, Institute of Geosphere Dynamics (Russian Federation)

In the presentations we discuss the results of application of different types of deformable mirrors for laser beam formation.

10090-64, Session 13

Laser-beam characterization and measurement of laser-beam parameters including external optics with a fully automated twin hexapod operated beam expander and evaluation of the influence of optical components on beam quality with defined tilts and shifts

Markus Bohrer, Dr. Bohrer Lasertec GmbH (Austria) and Technische Univ. Wien (Austria); Bernhard Weinberger, Murad Jamalieh, Dr. Bohrer Lasertec GmbH (Austria)

Resonator design as well as the control of the beam shape are essential for successful application. A huge flat bed system (3,5 x 2,5 m) called 'Big Bertha' and a long optical bench (12 m) called 'Long Bertha' with flexible beam rails has been build as a basic research setup. Allmost all kinds of laser sources, optical components and measurement devices can be mounted and easily positioned with a special system called 'Beam Rail'. Additionally a twin hexapod operated beam expander with variable lenses can be used e.g. in order to optimize magnification factors for AOMs. Results of accurate M2 measurements of different laser sources are presented as well as the influence of various optical elements and examples for close to perfect beam paths are given.

10090-65, Session 13

The evolution of the optical vortices in optically induced 2D square photonic lattice

Yali Qin, Shengyi Mao, Yilei Li, Linlin Xue, Hongliang Ren, Zhejiang Univ. of Technology (China)

In nonlinear optics, people find that vortex beams can form vortex solitons which can propagate stably in photonic lattices, photonic lattice is a kind of optical periodic structures that can control the propagation of the beams, which have potentially important application in all-optical exchange, light switch and so on.

This paper has mainly studied the dynamics of a vortex beam in optically induced square lattice. It investigates the influence of the lattice and the conditions under which the vortex solitons could form. The nonlinear Schrödinger equations governs the vortex beams and the mechanism of photorefractive effect and can be numerical solved by optimized ADI-BPM. We investigate vortex beams propagation in square photonic lattice

with self-focusing nonlinearity and self-defocusing nonlinearity in the photorefractive substract respectively. For self-fousing nonlinearity, Vortices would decay into the fundamental solitons without the lattice. When there has the lattice, both on-site and off-site single-charged vortices can form the discrete vortex solitons that can propagate stably under appropriate conditions. Charge-flipping of double-charged vortices could be observed during the propagation and the vortex solitons are quasi-stable. When the intensity of the input beams is too low, energy coupling along the axial could be found in the single point of incidence. But after raising the intensity, there will form the vortex solitons. For self-defousing nonlinearity, On-site single-charged vortices could form the discrete vortex solitons whose four parts are focusing between the lattice points under appropriate conditions. Charge-flipping of double-charged vortices could also be observed during the propagation.

Conference 10091: Laser Applications in Microelectronic and Optoelectronic Manufacturing (LAMOM) XXII

Monday - Thursday 30–2 February 2017

Part of Proceedings of SPIE Vol. 10091 Laser Applications in Microelectronic and Optoelectronic Manufacturing (LAMOM) XXII

10091-1, Session 1

Laser processing of VO2 thin films for THz devices and metamaterials applications

(Invited Paper)

Nicholas A. Charipar, Heungsoo Kim, Scott A. Mathews, Kristin M. Charipar, Eric Breckenfeld, Raymond C. Y. Auyeung, Alberto Piqué, U.S. Naval Research Lab. (United States)

Vanadium dioxide (VO_2) undergoes a metal-insulator transition (MIT) at 68C, at which point its electrical conductivity changes by several orders of magnitude. This extremely fast (?t<100 fs) transition can be induced thermally, mechanically, electrically, or optically. The combination of fast switching times and response to a broad range of external stimuli make VO_2 an ideal material for a variety of novel devices and sensors. While the MIT in VO_2 has been exploited for a variety of microwave/terahertz applications (i.e. tunable filters and modulators), very few devices exploiting the fast switching time of VO_2 have been reported. The electrical properties of thin film VO_2 (conductivity, carrier concentration, switching speed, etc.) are highly dependent on growth and post-processing conditions. The optimization of these conditions is therefore critical to the design and fabrication of VO_2 devices. This talk will report the effects of various pulsed laser deposition (PLD) growth conditions on the metal-insulator transition in thin film VO_2. In particular, we report the effect of PLD growth conditions on the stress/strain state of the VO_2 layer, and the subsequent change in electrical properties. Finally, results from fabricated VO_2 devices (THz emitters and THz modulators) will be presented.

10091-2, Session 1

Selective structuring of molybdenum based multi-layered thin film by sub-picosecond pulsed laser source

Pinaki Das Gupta, Nazar Farid, Gerard M. O'Connor, National Univ. of Ireland, Galway (Ireland)

The molybdenum-based multi-layered thin film has a growing interest of research in touch panel industry. Selective structuring of Mo-Al-Mo multi-layered thin film (MAM) on 23nm thick ITO film on glass was performed using a pulsed Gaussian shaped (spatially and temporally) sub-picosecond laser source with wavelengths 1030nm, 515nm and 343nm each of pulse duration 500 femtoseconds. A beam scanning system was used to direct the focused laser beam (radius 15-25μm) over film surface. After laser beam irradiation, optical and electron microscopes were used to analyse the results. An energy dispersive x-ray and spectral imaging were performed for elemental analysis of crater profile and ejected elements, respectively.

The absorbed threshold fluence of laser processed MAM films was calculated by Liu's method at different wavelengths and four different fluence regime were identified. At very high fluence, a complete removal of MAM was recognised. Lowering the fluence results in a complete and partial removal of upper Mo and Al layers, respectively. Relatively higher expansion of Al than Mo builds up high pressure normally on Mo/Al interface resulted in a 'volcano-like' effect and Al flows out from fragmented top Mo layer. Below this fluence level, lower pressure on molybdenum layer by Al results 'nano-bump' on Mo surface. Initially, single pulsed threshold fluence was estimated using different laser wavelengths and primary results show threshold fluence changes with variation of the laser wavelength.

An analysis and demonstration of multi-layered MAM ablation by ultrashort sub-picosecond laser and the dependence of wavelength and absorbed laser fluence will be presented.

10091-3, Session 1

Tailoring of graphite oxide electrical properties using laser irradiation

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Graphene is an attractive material for electronics applications. Possessing of superior electronic and physical properties makes this material a good candidate for implementations of flexible electronic devices. Formation of graphene by graphite oxide (GO) reduction with laser irradiation was proven to be mass production suitable method. It offers localized modification of material, scaling flexibility, avoids using of hazardous chemical materials or complex heating systems like other reduction methods. Moreover, laser induced GO reduction allows to control reduction level by variating of laser treatment parameters. In such way electric material properties can be tuned.

In this work results of experiments on GO reduction with laser irradiation are presented. GO films on flexible polycarbonate substrate were produced by modified Hummers method. Pulse duration (nanosecond and picosecond), irradiation wavelength (1064 nm, 532 nm, 355 nm), pulse energy and beam scanning speed were varied during reduction experiments. Raman spectroscopy measurements and electrical resistance measurements were conducted on laser treated GO samples.

Experiments results showed that for certain range of laser microfabrication parameters, electrical properties of reduced GO, suitable for electronics applications can be achieved. Such laser modified GO films can be used as contacts for flexible supercapacitors.

10091-4, Session 1

Low temperature deposition of inorganic films by excimer laser assisted chemical vapor deposition

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In this study, silicon nitride film is deposited by laser assisted chemical vapor deposition technique based on the direct photolysis of SiH_4/NH_3 gas mixture using argon fluoride excimer laser of 193 nm wavelength at low substrate temperature around 100˚C. By illuminating laser beam in parallel to sample surface, sample damage or heating can be avoided allowing compatibility of temperature sensitive device architectures. Through examination of wide range of processing parameters for laser and reactant gas, optimal conditions for high deposition rate with high film quality are presented. The film characteristics obtained at different substrate temperatures are also compared in the range of room temperature to 300˚C through morphological, structural, optical, compositional and permeation characterization results.

10091-5, Session 1

Damage free Al doping of 4H-SiC with passivation films using XeF excimer laser irradiation in AlCl3 acid solution

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We propose an innovative method for aluminum doping of 4H-SiC with passivation films, induced by XeF excimer laser irradiation in AlCl3 acid solution (28.6 wt%). A 100-nm thick Si passivation film was deposited on an n-type 4H-SiC substrate by physical vapor deposition. Using a laser beam (200 µm ? 170 µm) with an irradiation fluence of 0.5–5.0 J/cm2, 1–300 shots were administered. After laser irradiation of 3.5 J/cm2 and 300 shots, an Al-Si-O compound film was formed on the SiC surface. The compound film was removed by chemical wet etching and plasma treatment. After the removal of the compound film, no irradiation damage was observed on the SiC surface. From the results of secondary ion mass spectrometry measurements, high concentration aluminum doping (about 1 ? 1020 / cm3 at the surface) was confirmed. The I-V characteristics of the junction between the n-type substrate and the irradiation area indicated clear rectification with a large on/off ratio of 9 decades in the range of ±10 V. When forward biased, electro luminescence phenomenon with a peak at 387 nm, corresponding to the electro luminescence of SiC's band gap, was confirmed. These results prove the achievement of Al doping of n-type SiC to p-type using laser irradiation without any damage to the SiC surface.

10091-6, Session 2

Crack suppression of SiO2 thin film formed by 157 nm F2 laser induced photochemical surface modification of hard silicone coating film on polycarbonate

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Light-weighting of vehicle is now strongly required for reducing gasoline consumption and CO2 emission. In this study, F2 laser was irradiated to the surface of hard silicone resin, coated by dip coating method onto the film of acrylic resin on a polycarbonate substrate. The surface part of the silicone resin was photo-chemically modified into SiO2. One of two types of aperture mask, 3?3 mm2 and 50?50 µm2, was set on the sample surface. The single pulse fluence was varied from 4 to 14 mJ/cm2, pulse repetition frequency was set to 10 Hz, and irradiation time was changed from 30 to 120 s. N2 gas was induced around the surface of the sample. After modification, SiO2 modified layer was etched by HF 1% diluted solution, and the etched depth was measured by a stylus-type surface profilometer.

As a result of experiments, stress in the SiO2 modified layer increased by increasing of F2 laser irradiation time. In case of using aperture mask of 3?3 mm2, cracks were generated only on the irradiated area for longer irradiation time than 60 s. It is considered that the tensile stress in the modified layer exceeded the tensile fracture strength of 48 MPa of typical SiO2. When a mesh mask of 50?50 µm2 aperture was used, no crack generated even for a long irradiation of 200 s. We found, the tensile stress in SiO2 modified film can be reduced remarkably with using smaller aperture size of mesh mask, and it is very effective to prevent cracking.

10091-7, Session 2

Laser processing for precise fabrication of the THz optics

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Zone plates with integrated band-pass filters and binary Fresnel lenses designed for the THz spectral range were fabricated by direct laser ablation in metal films and the silicon substrate. Results on the process performance and quality of the products are reviewed. The focusing performance was measured using the THz source that produces the 580 GHz radiation. The beam was directed to the centre of the fabricated optical elements. Zone plates with integrated band-pass filters have shown the dual performance of focusing and spectral selection. However, they possess limited transmission for electromagnetic radiation.

The dependence of ablation rate and surface roughness on the laser process parameters was thoroughly investigated in the silicon. The depth of the ablated grooves linearly depends on the number of laser scans number with a particular slope for each scanning speed. The process regime with the 125 mm/s scanning speed provided the most precise control over the ablation depth. The topography measurements of the laser fabricated multilevel phase zone plates (Fresnel lenses) with the 10 mm focal length showed good agreement with the calculated topography. The intensity distribution of the focus spots using the laser fabricated 2, 4 and 8 level binary Fresnel lenses showed better focusing performance when more depth levels were used in the lens production.

10091-8, Session 2

Fabrication of waveguides in Gorilla® Glass with fs-pulses and its nonlinear features

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Ultrafast waveguide fabrication has been an active research area since its demonstration, leading to numerous applications. Recently reported high quality waveguide in Gorilla Glass has promoted it as a good candidate for optical devices. In this study, 120-fs laser pulses centered at 520, 650 and 775 nm at a repetition rate of 1 kHz were applied to investigate the influence of the wavelength on micromachining. Grooves ablated onto Gorilla Glass surface with different pulse energies and scanning speeds presented similar features and threshold pulse energy, regardless the excitation wavelength. Fifteen millimeter long waveguides were produced 100 ?m below sample surface with pulse energy varying from 250 nJ up to 5 ?J (scanning speed of 200 ?m/s). Waveguides longitudinal and transversal profiles were analyzed via optical microscopy and its guiding properties characterized in an objective-lens based coupling system at 633 and 775 nm. Guide modes intensity distribution show that for waveguides fabricated with higher pulse energy light is guided further from the core, while for lower fabrication energy light is guided closer to the center in a more fundamental mode. Considering that light traveling through 15 mm of material in confined mode, we coupled 775 nm fs-pulses into fabricated waveguides. By monitoring the spectrum of the guided light as input pulse energy increased, spectral broadening assigned to self-phase modulation effects was observed followed by white-light generation starting at 450 nm. In conclusion, we found that micromachining on Gorilla Glass is wavelength independent and inscribed waveguides present desirable nonlinear features.

10091-9, Session 2

Microfabrication of through holes in polydimethylsiloxane (PDMS) sheets using a laser plasma EUV source

Tetsuya Makimura, Hikari Urai, Univ. of Tsukuba (Japan); Hiroyuki Niino, National Institute of Advanced Industrial Science and Technology (Japan)

Polydimethylsiloxane (PDMS) is a material used for cell culture substrates / bio-chips and micro total analysis systems / lab-on-chips due to its flexibility, chemical / thermo-dynamic stability, bio-compatibility, transparency and moldability. For further development, it is inevitable to develop a technique to fabricate precise three dimensional structures on micrometer-scale at high aspect ratio. In the previous works, we reported a technique for high-quality micromachining of PDMS without

chemical modification, by means of photo direct machining using laser plasma EUV sources. In the present work, we have investigated fabrication of through holes. The EUV radiations around 10 nm were generated by irradiation of Ta targets with Nd:YAG laser light (10 ns, 500 mJ/pulse). The generated EUV radiations were focused using an ellipsoidal mirror. It has a narrower incident angle than those in the previous works in order to form a EUV beam with higher directivity, so that higher aspect structures can be fabricated. The focused EUV beam was incident on PDMS sheets with a thickness of 15 micrometers, through holes in a contact mask placed on top of them. Using a contact

mask with holes with a diameter of three micrometers, complete through holes with a diameter of two micrometers are fabricated in the PDMS sheet. Using a contact mask with two micrometer holes, however, ablation holes almost reaches to the back side of the PDMS sheet. The fabricated structures can be explained in terms of geometrical optics. Thus, we have developed a technique for micromachining of PDMS sheets at high aspect ratios.

10091-10, Session 3

Laser-assisted manufacturing of super-insulation materials

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Nano-insulation materials have been accepted as the most promising superinsulation materials category utilizing fundamental merits for thermal insulation via nano-contact interfaces and intrinsically vacuum-like structures called Knudsen effect. However, the current manufacturing routes suffer from excessive production cost, energy consumption and environmental concerns. Low-density hollow glass microspheres mixed with polymeric binders, called syntactic foams have been fabricated towards composite level insulation materials yet with insufficient insulation performance.

In this work, new types of composite materials are fabricated in the form of optimally connected hollow glass spheres, via fluidic assembly process by using a few selected binders and nanomaterials in conjunction with selective laser treatment. The thermal and mechanical characterizations of the produced multiscale composites show the potential towards improved thermal insulation performance with reasonable mechanical strength.

10091-11, Session 3

High speed, mask-less, laser controlled deposition of microscale tungsten tracks using 405 nm wavelength diode laser

Jyi Sheuan Ten, Martin Sparkes, William O'Neill, Univ. of Cambridge (United Kingdom)

A rapid, mask-less deposition technique for the deposition of conductive tracks to nano- and micro-devices has been developed. The process uses a 405 nm wavelength diode laser for the direct deposition of tungsten tracks on silicon substrates via laser assisted chemical vapour deposition. Unlike lithographic processes this technique is single step and does not require chemical masks that may contaminate the substrate. To demonstrate the process, tungsten was deposited from tungsten hexacarbonyl precursors to produce conductive tracks with widths of 8-80 μm and heights of 0.01-16 μm at laser scan speeds up to 30 μm/s. The highest volumetric deposition rate achieved is 3900 μm^3/s, three orders of magnitude higher than that of focused ion beam deposition and on par with a 515 nm wavelength argon ion laser previously reported as the laser source. The microstructure and elemental composition of the deposits are comparable to that of large-area chemical vapour deposition methods using the same chemical precursor. The contact resistance and track resistance of the deposits has been measured using the transfer length method. The deposition temperature has been estimated from a laser heat transfer model accounting for temperature dependent optical and physical properties of the substrate. The peak temperatures achieved on silicon and other substrates are higher than the thermal dissociation temperature of numerous precursors, indicating that this technique can also be used to deposit other materials such as gold and platinum on various substrates.

10091-12, Session 3

Laser assisted hybrid additive manufacturing of thermoelectric modules

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Thermoelectric generators (TEGs) are an attractive means to produce electricity, particular from waste heat applications. TEGs can convert waste heat into useful electrical energy in many practical engineering applications including vehicle exhaust, power plants and industrial processes. To date, however, TEGs are almost exclusively manufactured as flat, rigid modules of limited size and shape, and therefore an appropriate mounting for intimate contact of TEGs modules onto arbitrary surfaces represents a significant challenge. In this study, we introduce laser assisted additive manufacturing method to produce multi-layered thermoelectric generator device directly on flat and non-flat surfaces for waste heat recovery. In order to fabricate thermoelectric legs of high aspect ratio, dispensing of thermoelectric materials inks are assisted by ultraviolet laser curing process via optimization of processing parameters such as dispensing speed, curing laser intensity and laser-to-nozzle distance. Selective laser sintering is also carried out to complete the manufacturing process by functionalizing thermoelectric materials. It is shown that the hybrid laser processing method is highly beneficial in directly fabricating thermoelectric modules on arbitrary engineering surfaces.

10091-13, Session 3

High-speed observation of ZnO microspherical crystals produced by laser ablation

Daisuke Nakamura, Ryohei Tasaki, Yuki Fujiwara, Fumiaki

Nagasaki, Mitsuhiro Higashihata, Hiroshi Ikenoue, Tatsuo Okada, Kyushu Univ. (Japan)

ZnO nano/microstructures have attracted much attention as building blocks for optoelectronic devices because of their high crystalline quality and unique structures. We have succeeded in synthesizing ZnO microspherical crystals by a simple atmospheric laser ablation method, and demonstrated ultraviolet whispering-gallery-mode lasing from the spheres. In the microsphere synthesis process, molten droplets formed into spherical shapes by surface tension, and crystalized during ejection from the ablation spot. In this study, we observed the generation of ZnO microspheres by high-speed camera. Now we are trying to control and manipulate the microspheres using a vortex beam.

10091-14, Session 3

Co-propagating FWM of axial symmetric laser pulse with femtosecond duration

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Four-wave mixing (FWM) of co-propagating femtosecond laser pulses is widely used in various practical applications for diagnostic of a medium, for example. Using the problem invariants (conservation laws for four wave pulses interaction) it is possible to develop an analytical solution of the problem under consideration in the frame-work of plane wave approximation and long pulse duration approximation (point approximation). This solution demonstrates an existence of various FWM modes under their co-propagation. Among them, there is a mode of wave propagation without unchanging intensities. In the case of pulse propagation with inhomogeneous beam profile, this mode results in occurrence of (or oscillating) spatial-temporal domain of unchangeable intensity during certain propagation distance, which depends on SOD and beam diffraction. Both these factors destroy this propagation mode. Nevertheless, a pulse with hyperbolic cosine shape exhibits We investigate an influence of a pulse shape as well as a beam profile.

10091-15, Session 4

Throughput scaling by spatial beam shaping and dynamic focusing *(Invited Paper)*

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Processing at constantly high processing speed allows throughput scaling via repetition rate, as long as effects at start and end of processing do not become disruptive. Examples suitable for scaling the repetition rate are machining on the surface of rotating cylinders or on flat substrates by applying polygon scanners.

Vector based beam movement is typically applied for processing along contours or for small coverage of area. Machining procedures robust with respect to acceleration are beneficial for achieving high precision at scaled throughput.

We report on vector based processing methods suitable for high precision at elevated average power by applying spatial beam shaping, combined with adapted temporal parameters and beam dynamics. Machining by nonlinear induced absorption inside of transparent materials exemplifies the benefit of process development supported by in situ diagnostics with high spatial and temporal resolution. Examples will be given for processing based on avoiding accumulation and on controlled accumulation.

10091-16, Session 4

Inline measurement for quality control from macro to micro laser applications *(Invited Paper)*

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The essential basis for a reliable and target-aimed process control is the understanding of the interaction between the laser beam and the treated material and this was gained by thorough research on the influence of the process input parameters on the interaction sub processes and on the treatment result. The main players con-ducting this research over the decades have been research facilities and institutes and this research is still in progress. Since the moment when it was possible to achieve the necessary power density to start the process of deep penetration welding, accompanied by a keyhole, there is hope - and need - to measure e.g. the depth of this vapor channel. In the decades in which the technology of deep penetration welding has been used, various approaches have been developed that allow a measurement of the depth of the keyhole. The aim of this contribution is to show a compact overview on the different approaches to monitor and/or control micro and macro laser welding processes and especially bring out those which successfully have been transferred from laboratory to serial production in the recent past and will be in the near future.

Laser materials processing in general offers several possibilities for process monitoring systems or process control but the complexity of the process itself, meaning the dependence of the processing result on several process input parameters, does not facilitate their use [1],[2]. As only continuous supervision of the manufacturing process can guarantee the high demands on the quality of the produced parts, process monitoring systems have become more and more standardized devices in laser applications. There is no doubt that the basis for reliable on-line process monitoring systems is the possibility to measure significant indicators, which demonstrates the instantaneous condition of the interaction zone and/or neighboring areas.

This contribution to the conference on the one hand will demonstrate an approach using chromatic coded line sensors for post-weld inspection, on the other hand will show a sensor, based on interferometric principle, which is capable to in-situ measure keyhole depth during deep penetration laser welding and further potential of this sensor approach..

10091-17, Session 4

New random trigger-feature for ultrashort-pulsed laser increases throughput, accuracy and quality in micromachining applications

Andreas E. H. Oehler, Hubert Ammann, Marco Benetti, Lumentum (Switzerland); Beat Jaeggi, Stefan Remund, Beat Neuenschwander, Bern Univ. of Applied Science (Switzerland); Dominique Wassermann, Lumentum (Switzerland)

For most micromachining applications, the laser focus has to be moved across the workpiece, either by steering the beam or by moving the workpiece. To maximize throughput, this movement should be as fast as possible. However, the required positioning accuracy often limits the obtainable speed. Especially the machining of small and complex features with high precision is constrained by the motion-systems maximum acceleration, limiting the obtainable moving spot velocity to very low values. In general, processing speed can vary widely within the same processing job. To obtain optimum quality at maximum throughput, ideally the pulse energy and the pulse-to-pulse pitch on the workpiece are kept constant.

This is only possible if laser-pulses can be randomly triggered, synchronized to the current spot velocity. For ultrafast lasers this is not easily possible, as by design they are usually operated at a fixed pulse repetition rate. The pulse frequency can only be changed by dividing down with integer numbers which leads to a rather coarse frequency grid, especially when applied close to the maximum used operating frequency.

This work reports on a new technique allowing random triggering of an ultrafast laser. The resulting timing uncertainty is less than ±25ns, which is negligible for real-world applications, energy stability is <2% rms.

The technique allows using acceleration-ramps of the implemented motion system instead of applying additional override moves or skywriting techniques. This can reduce the processing time by up to 40%.

Results of applying this technique to different processing geometries and strategies will be presented.

10091-18, Session 4

Influence of the pulse duration and the experimental approach onto the specific removal rate for ultra-short pulses

Beat Jaeggi, Beat Neuenschwander, Berner Fachhochschule (Switzerland); Stefan M. Remund, Thorsten Kramer, Berner Fachhochschule (Switzerland)

To be competitive in industrial applications the throughput is a key factor in laser micro machining using ultra-short pulsed laser systems. Both, ps and fs laser systems are suitable for industrial applications. Therefore one has to choose the right pulse duration for highest ablation efficiency. As shown in earlier publications the efficiency of the ablation process can be described by the specific removal rate which has a maximum value at an optimum fluence. But its value often bases on a calculation using the threshold fluence and energy penetration depth deduced by measuring the depth of ablated cavities machined with different fluences and number of pulses. But this calculated specific removal rate often differs from the one deduced from ablated squares as recently shown in literature. Further an unexpected drop of the specific removal rate was reported for stainless steel when the pulse duration was reduced from 900 fs to 400 fs. Thus the influence of the pulse duration in the fs and low ps regime onto the specific removal rate is investigated with different methods for industrial relevant materials to clearly distinguish between the influence of the pulse duration itself and the influence of the experimental approach.

10091-19, Session 5

FBG inscription in multimode microfibers via point-by-point damage with femtosecond laser

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This would be the first time, to author's knowledge, to report effective fiber Bragg grating (FBG) inscription on multimode microfiber fiber (MM-MF) with point-by-point method. Regular size multimode fibers (MMF) have core diameter larger than 50?m so that refractive index modulation by a one-dimensional array of micrometer size spots is not sufficient to reflect the light effectively to form a high quality FBG. In addition, large modal volume of regular MMF leads to nearly continuous FBG reflection spectrum with bandwidth over 10nm, resulting low sensing resolution and accuracy. In this paper, FBGs were successfully inscribed in a MM-MF with diameter of ~10?m. The reflection spectrum showed over 10dB signal-to-noise ratio (SNR) and less than 0.5nm bandwidth. A FBG was inscribed in the center of multimode fibers with 125?m diameter (105?m for core) and then the fiber was etched down to 10?m. The spectrum evolution was inline monitored during the etching process and agrees well with theoretical prediction based on modal analysis. The diameter reduction of fiber decreases its modal volume over one hundred times so that the remaining optical modes are separated by larger propagation constant difference, resulting distinguishable peaks on FBG reflection spectrum. Also, the lead-in MMF naturally provides uniform light illumination so that all the supported modes in MM-MF are excited. Additionally, a MM-MF with 10?m diameter is much better in mechanical strength compared to their single mode counterpart, which is normally under 1.5?m in diameter. Therefore, MM-MF based FBGs are more practical sensors for simultaneous multi-parameters with outstanding sensitivity and accuracy.

10091-20, Session 5

Femtosecond-pulse inscription of fiber Bragg gratings in multimode graded index fiber

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Femtosecond (fs) laser modification of refractive index (RI) in transparent materials enables the inscription of fiber Bragg gratings (FBGs) with new features and extended capabilities. The mechanism of RI change, which is based on the nonlinear fs pulses absorption, makes possible FBG creation in non-photosensitive materials, for example, in pure silica core fibers. Due to highly localized RI change, inscription of 3D FBGs in waveguides with complex geometry as well as multicore fibers can be carried out. Comparing with traditional UV technology, the FBG inscription with fs laser radiation is a perspective way for the development of new fiber lasers and components.

In this study, we present the results of FBG inscription in Corning 62.5/125 multimode graded index fiber with IR fs laser pulses. The specifics of point-by-point inscription including single and multiple FBGs inscription in limited fiber segment as well as different transverse modes excitation/suppression is discussed. Multimode FBGs inscribed with fs radiation are investigated for the first time directly in the Raman fiber laser (RFL) cavity. Using of the low-reflection FBG instead of the normally cleaved fiber end results in sufficient narrowing of the RFL output spectrum at 954 nm (from 0.7 to 0.2 nm at -3-dB level) without reduction of generated power.

10091-21, Session 6

Surface ablation of inorganic transparent materials using 70W femtosecond pulses at 1MHz

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Nowadays processing of transparent materials, such as glass, quartz, sapphire and others, is a subject of high interest for worldwide industry since these materials are widely used for mass markets such as consumer

electronics, flat display panels manufacturing, optoelectronics or watchmaking industry. The key issue is to combine high throughput, low residual stress and good processing quality in order to avoid chipping and any post-processing step such as grinding or polishing. Complimentary to non-ablative techniques used for zero-kerf glass cutting, surface ablation of such materials is interesting for engraving, grooving as well as full ablation cutting. Indeed this technique enables to process complex parts including via or blind, open or closed, straight or small radius of curvature patterns. We report on surface ablation experiments on transparent materials using a high average power (70W) and high repetition rate (1 MHz) femtosecond laser. These experiments have been done at 1030nm and 515nm on different inorganic transparent materials, such as regular and strengthened glass, borosilicate glass or sapphire, in order to underline their different ablation behavior. Despite the heat accumulation that occurs above 100 kHz we have reached a good compromise between throughput and processing quality. The effects of fluence, pulse-to-pulse overlap and number of passes are discussed in terms of etch rate, ablation efficiency, optimum fluence, maximum achievable depth, micro cracks formation and residual stresses. These experimental results will be also compared with numerical calculations obtained owing to a simple engineering model based on the two-temperature description of the ultrafast ablation.

10091-22, Session 6

Modification of glass using an axicon-generated non-symmetrical Bessel-Gaussian beam

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Conventional processing tools of glass cannot fulfil the permanently increasing industrial requirements for processing speed and quality. Direct laser ablation allows cutting complex contours in thin glasses. However, accumulation effects may significantly reduce the processing quality and throughput when the ablated crater becomes deeper. To some extent, this drawback can be suppressed by the rear-side processing approach, but it still lacks applicable processing speed. One of the most material-efficient and energy-efficient glass cutting technique is to weaken the material locally along the cutting path by generating cracks or material modifications and then separate sheets by applying thermal or mechanical load. Such approach provides a clean cut with almost zero kerf width without a need for post-processing.

In this work, the intra-volume modification of glass using picosecond Bessel-Gaussian beams has been investigated. The fundamental harmonic of the diode-pumped solid-state laser Atlantic HE (Ekspla), which operated at 1064 nm wavelength and delivered 300 ps pulses with the maximum energy of 2.5 mJ at 1 kHz repetition rate was applied. The Bessel-Gaussian beam was generated by focusing the Gaussian beam with a conical lens together with a demagnifying 4F optical system.

Deviation of the used conical lens shape from an ideal cone tip led to the nonsymmetrical intensity pattern modulated along the beam propagation axis. Such intensity distribution caused the significant elongation of laser-induced glass cracks along one direction. We demonstrated the application of extended cracks for fast cutting of glass with thickness up to 4 mm.

10091-23, Session 7

Observation of fs-laser spallative ablation by soft x-ray laser probe *(Invited Paper)*

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The dynamical processes of the femosecond laser-induced surface modifications come to attract much attention for the micro processing. However, it is difficult to observe the femtosecond laser ablation dynamics, because of non-repetitive, irreversible and rapidly changing phenomena in a small characteristic size. Thus, the details of femtosecond laser ablation process have not been understood well. The measurement technique with the sufficient temporal and spatial resolution is necessary for the better understanding of the femtosecond laser ablation. In this study, we have developed the pump and probe interferometer and reflective imaging technique of the metal surfaces during the femtosecond laser ablation by using the laser-driven soft x-ray laser at the wavelength of 13.9 nm. The depth and lateral resolutions of the interferometer were about 2 nm and 0.7 ?m, respectively. The pumping laser used for the ablation was a Ti: Sapphire laser pulse with the duration of 80 fs pulse at a central wavelength of 795 nm, and had a gaussian spatial profile. By using the x-ray imaging technique, the time resolved image of nano-scaled spallative ablation dynamics of the tungsten was obtained.

10091-24, Session 7

Modeling 2D and 3D periodic nanostructuring of materials with ultrafast laser pulses *(Invited Paper)*

Jean-Philippe Colombier, Anton Rudenko, Emile Bévillon, Hao Zhang, Tatiana E. Itina, Razvan Stoian, Lab. Hubert Curien (France)

Generation of periodic arrangements of matter on materials irradiated by laser fields of uniform and isotropic energy distribution is a key issue in controlling laser structuring processes below the diffractive limit. Using three-dimensional finite-difference time-domain methods, we evaluate energy deposition patterns below a material's rough surface [1] and in bulk dielectric materials containing randomly distributed nano-inhomogeneities [2]. We show that both surface and volume patterns can be attributed to spatially ordered electromagnetic solutions of linear and nonlinear Maxwell equations. In particular, simulations revealed that anisotropic energy deposition results from the coherent superposition of the incident and the inhomogeneity-scattered light waves. Transient electronic response is also analyzed by kinetic equations of free electron excitation/relaxation processes for dielectrics and by ab initio calculations for metals. They show that for nonplasmonic metals, ultrafast carrier excitation can drastically affect electronic structures, driving a transient surface plasmonic state with high consequences for optical resonances generation [3]. Comparing condition formations of 2D laser-induced periodic surface structures (LIPSS) and 3D self-organized nanogratings, we will discuss the role of collective scattering of nanoroughness and the feedback-driven growth of the nanostructures.

[1] H. Zhang, J.P. Colombier, C. Li, N. Faure, G. Cheng, and R. Stoian, Physical Review B 92, 174109 (2015).

[2] A. Rudenko, J.P. Colombier, and T.E. Itina, Physical Review B 93 (7), 075427 (2016).

[3] E. Bévillon, J.P. Colombier, V. Recoules, H. Zhang, C. Li and R. Stoian, Physical Review B 93 (16), 165416 (2016).

10091-25, Session 7

Electron-lattice energy relaxation in laser-excited nanoscale films studied by time-resolved electron diffraction

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Electron-phonon coupling processes determine electronic transport properties of materials and are responsible for the transfer of electronic excess energy to the lattice. With decreasing device dimensions an understanding of these processes in nanoscale materials is becoming increasingly important. Here we report the results of time-resolved MeV transmission electron diffraction experiments on nanoscale films of different materials to study their incoherent structural response after fs laser excitation. Experiments were carried out using the MeV Ultrafast Electron Diffraction (UED) facility recently established at the Accelerator Structure Test Area (ASTA) of SLAC National Accelerator Laboratory. UED@ASTA provides ultrashort (<300fs) electron pulses at relativistic energies (3-5 MeV), which we have used for precise measurements of the transient Debye-Waller-effect in the different samples over an extended range of excitation fluences to separate different contributions to the incoherent lattice response. Results will be presented for thin Bi-films of different thickness where phonon softening in the electronically excited state is responsible for an immediate increase of the r.m.s. atomic displacement within a few hundred fs, while "ordinary" electron-phonon coupling leads to subsequent heating of the material on a few ps time-scale. The data reveal a distinct dependence of the energy transfer dynamics on film thickness which becomes faster for stronger excitation and smaller film thickness, respectively. The latter effect is attributed to a cross-interfacial coupling of excited electrons to phonons in the substrate. We also report result on metal-insulator and metal-metal-heterostructures, highlighting the importance of interface and transport effects.

10091-26, Session 8

Ultrafast laser energy deposition in copper revealed by simulation and experimental determination of optical constants with pump-probe ellipsometry

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Ultrashort pulsed lasers offer a great potential in precise and efficient material processing. Experimental and theoretical studies on efficiency of laser material processing from metals have demonstrated a high degree of dependency on the laser pulse duration. Within these studies, the investigation of the transient energy deposition in material takes a great significance for the thermal material response after laser irradiation.

The scope of this study was to investigate the ultrafast energy deposition in a copper metal after the irradiation with a 680 fs ultrashort laser pulse at a 1056 nm wavelength. For this purpose, a numerical analysis of laser-matter interaction was performed by using the optical Drude critical point (DCP) model and thermal two temperature model (TTM). The DCP model was incorporated into the TTM to simulate the ultrafast laser energy deposition and thermal material response in copper. For comparison with experimental data a two-color pump probe ellipsometry setup was used. The pump-probe ellipsometry setup combines the high temporal resolution of pump-probe technique and ellipsometric measurements of optical constants.

It was found numerically that a dynamic change on reflectivity and absorption coefficient induced by a rapid temperature increase influences the behavior of the laser energy deposition during the irradiation. The time resolved simulation of optical constants (n, k) confirms the temporal experimental observation of refractive index and extinction coefficient within the first 10 ps from pump-probe ellipsometry setup.

10091-27, Session 8

Numerical study of the influence of picosecond laser spot size on laser ablation of metal for high laser fluence cases

Yiming Zhang, Beat Neuenschwander, Berner Fachhochschule Technik und Informatik (Switzerland); Valerio Romano, Berner Fachhochschule Technik und Informatik (Switzerland) and Univ. Bern (Switzerland)

Previously the influence of picosecond laser spot size on ablation depth and threshold fluence on copper has been experimentally investigated. In order to have a comprehensive understanding of the corresponding mechanisms for high laser fluence cases, an axisymmetric 2D model, combining modified Two Temperature Model (TTM) and hydrodynamics, was developed. Since the plasma shielding effect has a significant impact on the absorption of incident laser on the material surface, especially for the situation where the laser fluence is higher than threshold fluence, several assumptions were made. It was supposed that when the electron temperature reaches 0.9Tc (critical temperature of copper) an electron-plasma is formed above the surface of the material due to the thermionic emission increasing the electron number density to/above the threshold value. In addition, based on experimental data in literature, approximately 30% of the energy of the incident laser at the wavelength of 1064nm is assumed to be absorbed by the electron-plasma. Furthermore, as generally supposed in the literature, considerable energy loss caused by phase explosion was also taken into account once the surface temperature of the lattice increased to 0.9Tc, and the melted material is treated as compressible laminar flow with low Mach number. The numerical results indicate that the kinetic energy of the evaporated material increases when the laser spot size decreases, which could be a possible mechanism of the deeper ablation depth per pulse observed in the experiments with smaller laser spot sizes. For the occurrence of phase explosion, the surface temperature keeps constantly around 0.9Tc. Finally the calculated evaporated mass has the same order of magnitude as the corresponding experimental data.

10091-37, Session PTue

Periodic micro/nanostructuring of silicone rubber by 193 nm ArF excimer laser

Masayuki Okoshi, National Defense Academy (Japan) and Kanto Gakuin Univ. (Japan); Wisnu Setyo Pambudi, Hidetoshi Nojiri, National Defense Academy (Japan); Tsugito Yamashita, Kanto Gakuin Univ. (Japan)

Periodic micro/nanostructuring of silicone rubber surface was induced by the irradiation of 193 nm ArF excimer laser. The ArF laser was focused on the surface of silicone rubber by each microsphere made of silica glass of 2.5 micron diameter, which covered the entire surface of the silicone. The single-pulse fluence and irradiation time of the ArF laser were approximately 10 mJ/cm2 and 1 min, respectively. The pulse repetition rate was 1 Hz. The silicone rubber surface underneath each microsphere selectively swelled due to the photodissociation of Si-O bonds of silicone into the lower molecules during the ArF laser irradiation. From the observations by an optical microscope and atomic force microscope, the formed micro/nanostructures were also found to be periodical: they were formed at regular intervals of approximately 2.5 micron. Contact angle of water was measured to see hydrophobicity of the samples; it showed approximately 150 degrees on the micro/nanostructured silicone, indicating a clear super-hydrophobic property.

10091-38, Session PTue

Fabrication of nanostructures in hexagonal lattice by using six-beam interference pattern of femtosecond laser

Masataka Yoshida, Kazuhito Osawa, Yoshiki Nakata, Noriaki Miyanaga, Osaka Univ. (Japan)

Introduction

Nanoprocessing using femtosecond laser has been investigated actively. Among them, fabrication of metallic nano-sized structure in lattice by laser processing using interference pattern is drawing a lot of attention. In addition, it has been known by simulation that a variety of plasmonic devices such as SRR(Split-Ring Resonator) can be fabricated by using interference pattern of six beams with amplitude and phase variation between the beams.

In this study, metal thin film processing by using six-beam interference pattern was experimented. The change of nano-sized structure as functions of film thickness and fluence was investigated.

Experimental setup

A femtosecond laser at 785 [nm] centre wavelength, with pulse width of approximately 190 [fs] and maximum shot energy is approximately 550 [uJ] was used (Cyber laser, IFRIT). A beam was split by a diffractive optical element, generating one zeroth- and six equal first-order diffracted beams. The zeroth-order beam was dumped, and the residual first-order beams interfered on a target through a demagnification system. The target was 20- to 60-nm-thick gold thin film deposited on a silica glass substrate.

Result

Nanostructures in a hexagonal lattice with lattice constant of 2.25 [um] were fabricated in a single shot. The unit nanostructures were nanodrop and MHA(Metallic Hole Array), which had been fabricated by interference pattern of four beams. The results enable us to fabricate a variety of plasmonic devices such as metamaterial, which are different from those fabricated by using interference pattern of four beams.

10091-39, Session PTue

Formation of periodic micro/nanostructure onto aluminum thin film by vacuum UV laser

Ryota Matsunaga, Masayuki Okoshi, National Defense Academy (Japan)

Periodic micro/nanostructure of approximately 20 nm thick aluminum thin film surface which was vacuum-evaporated on silicone rubber substrate was induced by the irradiation of 193 nm ArF excimer laser. The ArF laser was focused on the surface of aluminum thin film by each microsphere made of silica glass of 2.5 micron diameter, which aligned into single layer on the entire surface of the aluminum thin film. The single-pulse fluence and irradiation time of the ArF laser were approximately 10 mJ/cm2 and from 15 to 60 min, respectively. The pulse repetition rate was 1 Hz. From the observations by SEM after removing microspheres, the pillar-shaped micro/nanostructures 1 micron in diameter and 3 to 5 micron in height were successfully formed on the aluminum thin film surface underneath each microsphere during the ArF laser irradiation. Also, the formed micro/nanostructures were also found to be periodical: they were formed at regular intervals of approximately 2.5 micron. The samples also showed a hydrophobic property owing to the micro/nanostructuring by the ArF laser irradiation.

10091-40, Session PTue

Polycarbonate resin drilling by longitudinally excited CO2 laser

Kazuyuki Uno, Masaya Kato, Tetsuya Akitsu, Univ. of Yamanashi (Japan); Takahisa Jitsuno, Osaka Univ. (Japan)

A CO2 laser (9.2 – 11.4 ?m) has large absorption by polymeric materials and can excavate them efficiently. However, a short pulse CO2 laser is important for processing without heat effect (carbonization). We developed a short-pulse CO2 laser pumped by a longitudinally excitation scheme with a very simple and compact device. The laser consisted of a 45-cm-long ceramic pipe with two electrodes, two mirrors, a high-voltage power supply and a storage capacitance. The laser pulse waveform had a spike pulse with a pulse width of about 100 ns and an energy of several mJ, and a pulse tail with a controllable energy (about 0 – 50 mJ). The spike pulse gives ablation process and the pulse tail gives heat process. Therefore, in this work, we investigated polycarbonate resin drilling characteristics depended on the pulse-tail energy, the fluence, the number of shots and the repetition rate. The short pulse with the spike pulse width of 203 ns and the pulse tail length of 100 ?s produced a hole with the ablation depth of 1000 ?m and carbonization at the fluence of 3.6 J/cm2, the repetition rate of 200 Hz and the 2000 shot irradiation. The tail-free short pulse with the pulse width of 170 ns produced a hole with the ablation depth of 300 ?m without carbonization at the fluence of 1.4 J/cm2, the repetition rate of 200 Hz and the 2000 shot irradiation. A tail-free short pulse with a higher fluence will produce a deeper hole without carbonization.

10091-41, Session PTue

Permeability influences on the performance of porous aerostatic bearing with micro-holes array restrictive layer

Yu ting Lu, Kuo Yu Chien, Metal Industries Research & Development Ctr. (Taiwan)

Porous type aerostatic bearing with high loading efficiency, good stiffness and excellent self-stable property is often applied in high precision equipment. The properties of porous materials are usually not very stable among each manufacturing batch process, resulting in variation of the characteristics including pore size, pore distribution, and permeability. In order to solve the performance inconsistency, MIRDC has developed a new mechanism of porous type aerostatic bearing with a micro-hole array restrictive layer on the bearing surface. This new mechanism successfully overcomes the problem of inhomogeneity of the porous materials and also improves bearing loading capacity, efficiency, stiffness and stability effectively compared to traditional porous air bearing. By controlling the numbers and geometric design of micro-hole to limit flow rate, bearings have stable dynamic property and high loading capacity performance. Verification the load capacity and stiffness of bearing could be enhanced by the new mechanism of micro-hole array restrictive layer. The results also confirmed the basic design principle for the new type porous aerostatic bearing. Higher loading capacity could be obtained by choosing high permeability porous material, dynamic stability and stiffness could be obtained by adjusting the geometry parameters of micro-hole array to control permeability.

In this research, the main studies focus on manufacture micro-hole array by picosecond laser. The experiment results show micro holes diameter less 100?m and bearing flatness<1?m. By laser processing parameters include laser energy, holes pitch, and pulse number main effect factors to control the exit holes size and uniformity of hole. The holes size range about 30~80?m between on planar porous aerostatic bearing with dual restrictive layer can be achieved.

10091-42, Session PTue

Scattering of phase-change dots

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The applications of phase-change material have attracted much attention, because of its obvious optical and electrical contrast between the amorphous and crystalline phase state. It has been applied to versatile areas such as high-density optical data storage, phase change memory, nanolithography, and phase-change device. In this paper, the femto-second laser-induced forward transfer is used to deposit the pattern of phase-change material. Laser-induced forward transfer (LIFT) method is a low cost and powerful fabrication process, which is adaptable for variety material and substrate. With the help of LIFT, the fabrication of these nano-scale phase-change material patterns could be easily achieved. The features of the $Ge_2Sb_2Te_5$ dot pattern can be effectively controlled by adjusting incident laser fluence. For different dot sizes, the patterns show different optical properties. The scattering spectra and the surface images of $Ge_2Sb_2Te_5$ patterns are measured by dark-field spectroscopy and atomic force microscopy individually. The simulation results of optical scattering are in agreement with the experiment results. This study provides the fundamental electromagnetic properties on phase-change material and the application of switchable device in nano-scale.

10091-43, Session PTue

Maskless, high-resolution patterning of Ni electrodes by laser reductive sintering of NiO nanoparticle ink under ambient conditions

Vu Binh Nam, Gachon Univ. (Korea, Republic of); Dongwoo Paeng, Yoonsoo Rho, Costas P. Grigoropoulos, Univ. of California, Berkeley (United States); Daeho Lee, Gachon Univ. (Korea, Republic of)

Patterning by laser direct writing (LDW) process is one of the promising routes to achieve photolithography-free electrode fabrication exploiting the several advantages of the laser process. On the other hand, non-vacuum solution-processible thin film deposition methods utilizing nanoparticle (NP) inks enable low temperature treatment by taking advantage of the significant depression of the NP melting point with reduced size. Consequently, the combination of NP ink deposition and LDW can effectively perform high-resolution, direct patterning of electrodes on various types of substrates without inflicting thermal damage. However, most of the materials used for this fabrication method were limited to noble metals such as silver and gold. Employing inexpensive materials is indispensable for the process to be applied in mainstream manufacturing.

In this presentation, we will introduce a method for direct patterning of Ni electrodes through reductive sintering of NiO NP ink by LDW process. Since synthesized NiO ink contains ultra-small precrystallized NPs, high-resolution patterning with very sharp edges and smooth surface morphology can be achieved. Also, a two-laser system to investigate the kinetics of reductive sintering of NiO to Ni and related results will be presented.

10091-44, Session PTue

Temperature control of CO2 laser glass melting for fiber processing technology

Mohamed Amine Jebali, AFL (United States)

Large diameter fiber processing technology had gained significant interest due to the increasing demand for multi-kilowatt fiber lasers. This technology is used for the fabrication of fiber-based components such as end-pump and side pump combiners, large diameter endcaps, ball lenses for collimators and focusers... Due to the very high fused silica absorption at 10.6um, CO_2 lasers were remarkably efficient in achieving controlled heating and melting of large diameter glass rods. This technology is very attractive in industrial production due to its low maintenance requirements. It is widely used in the research and development field due to its flexibility in achieving large, adjustable and uniform heating area when compared to conventional heating technologies like arc discharge and filament. However, commercially available CO_2 lasers can experience power, polarization and mode instability, which becomes important at higher output powers. To overcome this limitation, we present a novel feedback control technique for stabilizing the glass temperature. The proposed feedback control loop consist of direct measurement of glass temperature rather that sampling the output power of the CO_2 fiber laser.

10091-45, Session PTue

Selective laser reduction of metalic nanomaterials

Seung Hwan Ko, Jaeho Shin, Phillip Won, Hyunmin Cho, Dongkwan Kim, Seoul National Univ. (Korea, Republic of)

Laser was used as a local heat source for photo-thermo-chemial reduction of oxidized metal oxide nanomaterials.

Various metal oxide nanomaterials was applied to reduction to develop selective laser induced reduction for electronics applications on flexible substrate.

10091-46, Session PTue

Laser surface modification of ZnO for solar converters

Dmitrii Redka, Valentin Afanasjev, Nikolai Mukhin, Saint Petersburg Electrotechnical Univ. "LETI" (Russian Federation); Evgeniy Terukov, Ioffe Institute (Russian Federation); Alexsandr S. Grishkanich, ITMO Univ. (Russian Federation); Sören Hirsch, Fachhochschule Brandenburg (Germany)

The aim of this work was to investigate the surface modification of zinc oxide, its optical and electrophysical properties by plasma and laser treatment. The ZnO films were prepared by chemical vapor deposition using the organometallic compounds at a low pressure. $(C_2H_5)_2Zn$ and deionized water were applied as precursors. Their concentration ratio was $[H_2O]:[DEZ] = 5:6$. The ZnO films were doped by boron using a gas mixture of 2% B_2H_6 in hydrogen. Plasma treatment of Boron-doped ZnO aimed at surface modification of the films has been performed in RF magnetron sputtering systems at ambient temperature and typical pressure of about 60 mTorr. For the treatment the samples were placed on a target holder directly above the magnet as the sputtered target. This position of the samples provides strong magnetic field in the vicinity of the treated sample which increases the efficiency of ionization of argon (Ar) atoms by electron impacts and, therefore, increases the density of plasma and flux of Ar ions toward treated surface. As a result one can expect decrease of the treatment time without increasing the RF power density. For our experiments we have used a magnetron system. The treatment times ranged from 5 to 17 minutes for the power density with typical value of 1.3W/cm2. Laser treatment of zinc oxide films made at the wavelength 355 nm with various levels of radiation power density (6...24 GW / cm2). At high levels of radiation power density, the increase in surface resistance caused by a violation of the uniformity of the film caused by its partial destruction. The results can be used to create thin-film solar modules of a large size.

10091-47, Session PTue

Beam shaping by spatial light modulator and 4f system to square and top-flat for interference laser processing

Kazuhito Osawa, Masataka Yoshida, Yoshiki Nakata, Noriaki Miyanaga, Osaka Univ. (Japan); Aiko Narazaki, National Institute of Advanced Industrial Science and Technology (Japan); Tatsuya Shoji, Yasuyuki Tsuboi, Osaka City Univ. (Japan)

Nanostructures in lattice can be produced by laser processing using interference pattern of multi beams. In the case of Gaussian beam, shape of nanostructures distribute according to fluence distribution of the original beam. In addition, non-processed region can not be avoided in wide area processing using multi-shot because of its circular beam shape. To solve these problems, top-flat and square beam profile is required. To shape beam profile, apodizing filter having gradient neutral density has been used. In this case, the top-flat shape is fixed, and is not adjustable to change of beam profile. In this study, we demonstrated beam shaping to top-flat and square by Spatial Light Modulator (SLM) and spatial frequency filtering.

A femtosecond laser system (Cyber laser, IFRIT) operated at 785 [nm] with typical pulse width of 190 fs was used as a source beam. Spatial phase distribution of the beam was modulated periodically by SLM inserted to the beam path. By filtering the higher spatial frequency component at Fourier plane in 4f system, the spatial amplitude distribution of the zero-order beam was shaped. The optimized diameter of the spatial frequency filter was D=2.0 [mm] with the 150 [mm] focal length of the 4f system. In the condition, the beam profile was shaped to top-flat with 66.1% of the peak fluence of the original beam within the intensity variation of 3.7 [rms]. This result enables us to fabricate large area devices using multi-shot processing.

10091-48, Session PTue

Pseudo-Bessel beam for laser machining applications

Yu-Chieh Lin, Chien-Chung Fu, Yen-Yin Lin, National Tsing Hua Univ. (Taiwan)

Tunable liquid lens is an effective way to move the focus point of a laser beam back and forth in the axial direction to generate a pseudo-Bessel beam from a Gaussian laser beam, so these devices have been adopted to extend depth of field in optical imaging systems. Therefore, these devices can also relief the focus region requirements in laser machining applications. The required averaged laser power level in laser machining applications is much higher than optical imaging systems, the slight absorption of liquid lens becomes an acute consideration in laser machining applications. In this work, we will measure the changes of a pseudo-Bessel beam which was generated by a tunable liquid lens, such as, tunable acoustic gradient index of refraction (TAG) lens, when a 50 W 1064 nm laser incident into the tunable liquid lens. The temperature is continually increasing during high power laser operation, so the optical charactertics of tunable liquid lens will changes. In order to stabilize the optical performance of tunable liquid lens to achieve consistent machining results, a temperature stabilized system was integrated into the tunable liquid lens. At the same time, we will compare the feature of engraved metal samples with and without tunable liquid lens. Our work significantly improve the stability of a tunable liquid lens inserted laser machining system.

10091-49, Session PTue

Ultrafast laser scribing of transparent conductive oxides in Cu(In,Ga)Se2 solar cells via laser lift-off process: The control of laser-induced damage

Aiko Narazaki, Tadatake Sato, Hiroyuki Niino, Hideyuki Takada, Kenji Torizuka, Jiro Nishinaga, Yukiko Kamikawa-Shimizu, Shogo Ishizuka, Hajime Shibata, Shigeru Niki, National Institute of Advanced Industrial Science and Technology (Japan)

Ultrafast laser scribing of a top electrode, transparent conductive oxide (TCO) of Cu(In,Ga)Se2 (CIGS) solar cells has been investigated using a lift-off process with 300 fs pulse. Laser ablation of CIGS light-absorbing layer caused blow-off of the top TCO, dependent on both laser parameters such as laser spot area and TCO film thickness. The larger spot and thinner film lead to a lower laser threshold, which is favorable to diminish laser-induced damages. Using this process as P3 scribe, a submodule with an active area of 4 cm2 was fabricated by all laser scribing exhibited the conversion efficiency of 15.0 % after post-annealing, which is comparable to mechanically-scribed one. Thus, the ultrafast laser scribing of TCO via laser lift-off process is effective for manufacturing high-efficiency solar cell modules.

10091-28, Session 9

Nanograting formation in air through plasmonic near-field ablation induced by femtosecond laser pulses *(Invited Paper)*

Godai Miyaji, Tokyo Univ. of Agriculture and Technology (Japan); Kenzo Miyazaki, Kyoto Univ. (Japan)

Superimposed multiple shots of low-fluence femtosecond (fs) laser pulses form a periodic nanostructure on solid surfaces through ablation. We have demonstrated that the self-organization process of nanostructuring can be regulated to fabricate a homogeneous nanograting on the target surface in air. A simple two-step ablation process was developed to control plasmonic near-fields generated by fs pulses. The results have shown the nature of a single spatial standing wave mode of surface plasmon polaritons of which periodically enhanced near-fields ablate the target surface, to form the nanograting with 200-nm or 50-nm period on GaN, using 800-nm or 266-nm fs pulses, respectively.

10091-29, Session 9

Nanolithography by optothermal manipulation of plasmonic nanoparticles *(Invited Paper)*

Theobald Lohmueller, Ludwig-Maximilians-Univ. München (Germany)

Plasmonic nanoparticles feature intriguing optical properties that can be used to manipulate them by means of light. Light that is absorbed by gold nanoparticles, for example, is very efficiently converted into heat and a single particle can thus be used as fine tool to apply heat to a nanoscopic area. At the same time, gold nanoparticles are subject to optical forces when they are irradiated with a focused laser beam, which renders it possible to optically push or trap them in two- and three dimensions.

Here, I going to show how the combination of plasmonic heating and optical force can be used to control chemical reactions and particle transformations on a single particle level. Furthermore, I will demonstrate how this approach

can be applied for nanofabrication and the direct writing of nanostructures with sub-diffraction limited resolution.

10091-30, Session 9

Formation of periodic gold surface structure by femtosecond laser irradiation to thin film

Akihiro Takami, Yasutaka Nakajima, Mitsuhiro Terakawa, Keio Univ. (Japan)

Gold micro- and nanostructures are attractive for applications in novel electrical and optical devices because of the unique absorption properties; however, formation of regular laser-induced periodic surface structure (LIPSS) on a gold surface has been challenging due to the weak electron-phonon coupling parameter of gold as well as the significant thermal effects. In our previous study, we demonstrated fabrication of platinum nanowire gratings by femtosecond laser irradiation to platinum thin films on substrates. In this study, we applied the fabrication method to a gold thin film. Gold thin films were deposited onto fused silica substrates with different film thicknesses, which were followed by scanning irradiation of linearly polarized femtosecond laser pulses (central wavelength 800 nm, pulse duration 180 fs, repetition rate 1 kHz and scanning speed 10 ?m/s). Periodic gold structures were formed on the substrate perpendicularly to the laser polarization. The periodicities were comparable to or longer than the laser wavelength. The periodicities of the formed structures depend on the film thicknesses. Electric filed intensity distribution in ultra-thin metal films might affect the periodicities of the structures. Gold micro- and nanostructures fabricated by this method have potential to be applied to novel photonic/plasmonic devices or two dimensional metamaterials.

10091-31, Session 10

Direct printing of micro/nanostructures by femtosecond laser excitation of nanocrystals

Heng Pan, Wan Shou, Missouri Univ. of Science and Technology (United States)

Direct writing using single or multiple energized beams (e.g. laser, ion or electron beams) provides high feature resolution (<1μm) compared with other solution-based printing methods (e.g. inkjet printing). There have been extensive research on micro/nano additive manufacturing methods employing laser (or optical) and ion/electron beams. Many of these processes utilize specially designed photosensitive materials consisting of additives and effective components. Due to the presence of additive (such as polymer and binders), the effective components are relatively low resulting in high threshold for device operation. In order to direct print functional devices at low cost, there has been extensive research on laser processing of pre-synthesized nanomaterials for non-polymer functional device manufacturing. Pre-synthesized nanocrystals can have better control in the stoichiometry and crystallinity. In addition, pre-synthesis process enjoys the flexibility in material choice since a variety of materials can be synthesized. Femtosecond laser assembly and deposition of nanomaterials can be a feasible 3D micro/nano additive manufacturing approach, although mechanisms leading to assembly and deposition have not been fully understood. It is suggested that laser trapping force could be one mechanism leading to assembly. In this paper, we propose a mechanism for 2D and 3D deposition of nanocrystals by laser excitation with moderate peak intensities(10e11-10e12 W/cm2). The method does not rely on laser trapping. It is postulated that laser induced charging is responsible for the deposition. The scheme paves the way for laser selective electrophoretic deposition as a micro/nanoscale additive manufacturing approach.

10091-32, Session 12

Ultraviolet laser processing of ceramics for microelectronics manufacturing: Volume ablation rates and processing techniques for scribing, cutting, and drilling

Robert S. Sposili, James M. Bovatsek, Raj Patel, Spectra-Physics (United States)

Ceramic materials are used extensively in the microelectronics, semiconductor, and lighting industries because of their electrically insulating and thermally conductive properties, as well as for their high-temperature-service capabilities. However, they also tend to be brittle, which presents significant challenges for conventional machining processes—especially as smaller and more intricate features are increasingly required for advanced applications. In this paper we report on a series of experiments which demonstrate and characterize the efficacy of the Talon® UV laser platform in machining ceramics commonly used in microelectronics manufacturing, such as aluminum oxide (alumina) and aluminum nitride. With a series of laser pocket milling experiments, fundamental volume ablation rate and ablation efficiency data were generated. In addition, techniques for various industrial machining processes such as deep scribing and low-/no- taper hole-drilling were developed and demonstrated. Addressing a diverse application space, the Talon family of product offerings covers a wide spectrum of operating conditions, including higher pulse energies (to 500 μJ) at modest pulse repetition frequencies (PRFs) as well as somewhat lower pulse energies with much higher PRFs and therefore higher average power levels (30 W). Generally, lasers with higher average powers offer higher processing rates but we demonstrate that for some processes, a lower average power but higher pulse energy source can match—or even outperform—the capability of a higher average power laser.

10091-33, Session 12

Industrial femtosecond lasers for machining of heat-sensitive materials

Frank Hendricks, Benjamin Bernard, Victor V. Matylitsky, Spectra-Physics Rankweil (Austria)

Heat-sensitive materials, such as polymers, are used increasingly in various industrial sectors such as medical device manufacturing and organic electronics. Medical applications include implantable devices like stents, catheters and wires, which need to be structured and cut with minimum heat damage. Also the flat panel display market moves from LCD displays to organic LED (OLED) solutions, which utilize heat-sensitive polymer substrates. In both areas, the substrates often consist of multilayer stacks with different types of materials, such as metals, dielectric layers and polymers with different physical characteristic. The different thermal behavior and laser absorption properties of the materials used makes these stacks difficult to machine using conventional laser sources.

Femtosecond lasers are an enabling technology for micromachining of these materials since it is possible to machine ultrafine structures with minimum thermal impact and very precise control over material removed. An industrial femtosecond Spirit® HE laser system from Spectra-Physics® with pulse duration <400 fs, pulse energies of >120 μJ and average output powers of >16 W is an ideal tool for industrial micromachining of a wide range of materials with highest quality and efficiency. The laser offers process flexibility with programmable pulse energy, repetition rate, and pulse width. In this paper, we provide an overview of machining heat-sensitive materials using Spirit® HE laser. In particular, we show how the laser parameters (e.g. laser wavelength, pulse duration, applied energy and repetition rate) and the processing strategy (gas assisted single pass cut vs. multi-scan process) influence the efficiency and quality of laser processing.

10091-34, Session 12

Ultrashort-pulsed laser material processing with high repetition rate burst pulses

Roland M. Mayerhofer, Rofin-Baasel Lasertechnik GmbH & Co. KG (Germany)

Thanks to the past years' development efforts towards higher average power levels, higher repetition rates and, of course, improved robustness, ultra-short pulsed lasers have been able to enter more and more industrial 24/7-production areas. Despite some exceptions, where ultrashort-pulsed lasers with very high repetition rates are used to weld glass and other sensitive materials, the majority of industrial applications are related to material removal or the use of non-linear effects in transparent materials.

An interesting feature of ultra-short pulsed lasers in MOPA-configuration is the so-called "burst" mode. It provides pulse-packages at nanosecond separation using programmable power slopes. Thus, the energy distribution of the pulses within a burst can be adjusted to the specific application task. Using burst pulses, laser-material-interaction is brought into a different regime, as subsequent pulses precondition the material and plasma effects can be used effectively.

Burst pulses can help optimizing surface quality and ablation rates of engraved structures simultaneously. For laser filamentation of transparent and brittle materials, burst pulses provide filaments lengths of several millimeters.

The paper will describe suitable laser concepts and industrial applications of ultra-short pulsed lasers with burst mode. The influence of pulse bursts on removal rates and surface quality on various materials will be discussed.

10091-35, Session 12

Studies on nanosecond 532nm & 355nm and ultrafast 532nm & 515nm laser cutting super-hard materials

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Super-hard materials have been widely used in cutting tools as a cutting tool insert (CTI). Traditionally, EDM (electron-discharge machine) is used for processing these materials. However, EDM system has disadvantages of valid only for electric conductor, slow removal rate, excessive tool wear, potential fire hazard etc. Instead, laser has been considered to be a better option to replace EDM due to effective and efficient process. It has been proved better cutting quality and higher speed achieved with lasers. The cutting solution has been accepted by cutting tool industry. The current processing focus is on how to increase cutting speed (>20mm/min) and achieving good cutting edge quality enough for ready-to-use. Selection of right laser source and processing method becomes necessary.

In this paper, micro-processing of three key super-hard materials of poly-crystal diamond (PCD)/tungsten-carbide (WC), CVD-diamond and cubic boron nitride (CNB) have been systematically studied using nanosecond laser (532nm & 355nm), and ultrafast laser (532nm & 515nm). Our purpose is to investigate a full laser micro-cutting solution to achieve a ready-use CTI. The results show a clean cut with little burns and recasting at edge. The cutting speed of ~2-10mm/min depending thickness was obtained. The laser ablation process was also studied by varying laser parameters (wavelength, pulse width, pulse energy, repetition rate) and tool path to improve cutting speed. Also studies on material removal efficiency (MRE) of PCD/WC with 355nm-ns and 515nm-fs laser as function of laser fluence show that 355nm-ns laser is able to achieve higher max. MRE for PCD and WC. Thus, ultrafast laser is not necessarily used for super-hard material cutting. Instead, post-polishing with ultrafast laser can be used to clean cutting surface and improve smoothness.

It has been found that the obtained ma. MRE of 0.12-0.14mm3/(W. min.) with 355nm-ns laser is ~2 times higher than that of <0.06mm3/(W.min.) with ns 1064nm fiber laser. This indicates a wavelength dependence.

10091-36, Session 12

Achievement of consistent high reliability fiber splicing by CO2 laser heating

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CO2 laser splicing of optical fibers became commercially available only in recent years. CO2 laser heating is different from other heating methods in that the power from the CO2 laser beam is efficiently absorbed by the outer layer of the glass, which in turn conducts the energy inwards. In this case, there is no consumable heating element such as electrodes or resistive filaments that may leave contaminants or deposits on the glass surface. The CO2 absorptive heating can also be very well controlled, with minimal vaporization and re-deposition of the glass itself.

The relatively gentle CO2 laser heating and lack of heating element contaminants results in a smooth spliced-fiber glass surface, and enables remarkable spliced-fiber strength results. As previously reported, some strength results are within the range of pristine fiber breaking strength. However, consistent achievement of high strength has been limited due to legacy fiber preparation processes and other constraints. In fact, while using such processes, the minimum breaking strength results with CO2 laser splicing are similar to those that may be achieved with conventional arc fusion splicing, even though the maximum achievable splice strength is greatly superior.

To better exploit the high strength potential of CO2 laser splicing, recent work has focused on improvements relative to legacy fiber preparation (stripping and cleaning) used for high strength splicing, as well as other process improvements. By application of new methods and controls, spliced fiber strength results typically greater than 400kpsi and seldom less than 350kpsi have been achieved.

Conference 10092: Laser-based Micro- and Nanoprocessing XI

Tuesday - Thursday 31–2 February 2017

Part of Proceedings of SPIE Vol. 10092 Laser-based Micro- and Nanoprocessing XI

10092-1, Session 1

Metamaterial absorber for molecular detection and identification *(Invited Paper)*

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Metamaterial absorber was used for a background-suppressed surface-enhanced molecular detection technique. By utilizing the resonant coupling between plasmonic modes of a metamaterial absorber and infrared (IR) vibrational modes of a self-assembled monolayer (SAM), attomole level molecular sensitivity was experimentally demonstrated. IR absorption spectroscopy of molecular vibrations is of importance in chemical, material, medical science and so on, since it provides essential information of the molecular structure, composition, and orientation. In the vibrational spectroscopic techniques, in addition to the weak signals from the molecules, strong background degrades the signal-to-noise ratio, and suppression of the background is crucial for the further improvement of the sensitivity. Here, we demonstrate low-background resonant Surface enhanced IR absorption (SEIRA) by using the metamaterial IR absorber that offers significant background suppression as well as plasmonic enhancement. By using mask-less laser lithography technique, metamaterial absorber which consisted of 1D array of Au micro-ribbons on a thick Au film separated by a transparent gap layer made of MgF_2 was fabricated. This metamaterial structure was designed to exhibit an anomalous IR absorption at ~ 3000 cm-1, which spectrally overlapped with C-H stretching vibrational modes. 16-Mercaptohexadecanoic acid (16-MHDA) was used as a test molecule, which formed a 2-nm thick SAM with their thiol head-group chemisorbed on the Au surface. In the FTIR measurements, the symmetric and asymmetric C-H stretching modes were clearly observed as reflection peaks within a broad plasmonic absorption of the metamaterial, and 1.8 attomole molecular sensitivity was experimentally demonstrated.

10092-2, Session 1

Tailored femtosecond Bessel beams for fabrication of high-aspect-ratio through Si vias *(Invited Paper)*

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The steady pursuit of high-performance, low-power-consumption, and small-footprint microelectronic devices has made three-dimensional integrated circuits (3D ICs) an attractive replacement for conventional 2D ICs. One of the major challenges is the fabrication of high-aspect-ratio through-silicon vias (TSVs), which is a key technology for the 3D assembly of Si ICs. Here, we present high-quality and high-aspect-ratio TSVs fast fabricated using femtosecond (fs) 1.5-um Bessel beams. By performing laser ablation in air using conventional Bessel beams generated by an axicon lens, nearly taper-free TSVs with diameters of ~5 um in 50-um-thick Si substrates, which corresponds to aspect ratios of ~10, can be produced. To suppress the severe damage caused by the sidelobes of the conventional Bessel beam to the TSVs, a fs Bessel beam is tailored by using specially designed binary phase plates (BPPs) for the first time. We theoretically and experimentally demonstrate that this method can create a fs laser beam with a ~6-um lateral spot size and ~400-um focal depth, while reducing the sidelobe ratio (SLR, the ratio of the peak intensity of the maximum sidelobe to that of the central lobe) to ~0.6%, which is much smaller than the ~16% SLR for a conventional Bessel beam. The developed technique successfully creates a 2D array of TSVs in 100-um thick Si substrates without any sidelobe damage and with aspect ratios of ~ 15. Our technique is potentially applicable for 3D assembly in the manufacturing of 3D Si ICs.

10092-3, Session 1

Ultrafast lasers for precise and corrosion free marking on chirurgical steels

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We report on the development and investigation on industrial NIR laser marking of stainless steel by comparing ns-ps-fs pulse durations. The Application we aim for are industrial marking of medical equipment mostly surgical instruments with an optimal behavior for long term visibility and traceability under clinical conditions mainly cleaning and sterilization.

Nowadays many parts and products are marked for the purpose of identification and traceability. One kind of laser marking is the well known annealing of stainless steel by ns marking lasers. When annealing, a colored oxide layer grows due to the local heating of the material surface. Compared to the raw material, the annealed marking shows increased corrosion sensitivity. Regarding the traceability, the poor durability of the ns marking resulting in contrast reduction and the corrosion susceptibility are a huge problem. Within the scope of our investigation, the laser annealing of stainless steel (1.4021 and 1.4301) is optimized in terms of corrosion resistance and durability. Therefore three different laser sources with ns-ps-fs pulse duration were observed. The focus rests on the realization of parameter studies (various lasers) and their effect on the corrosion and passivation behavior. In addition readability and machine readability by camera systems in case of Data matrix codes has been checked. Furthermore analysis of the oxide layers by use of EDX and XRD was performed to obtain further information on the composition and structure of the markings.

10092-4, Session 1

Ultrashort pulse laser micro-machining of high-aspect ratio structure in transparent materials using back-side ablation

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Cutting and drilling of optically transparent materials using ultrashort pulse laser systems is no longer considered a scientific application. Precise machining and increased reliability of the laser sources now satisfies the needs of industrial mass production. Compared with conventional methods, like diamond cutting and water jet drilling, laser processing reduces the crack formation and allows manufacturing of higher aspect ratio features. The scope of application ranges from sapphire dicing, hardened glass or diamond processing, to flat panel display cutting.

An ablation process by using a Gaussian laser beam and several parallel overlapping lines leads to a V-shaped structured groove. This limits the structuring depth for a given kerf width. The unique possibility of initiating the ablation process from the backside in transparent material is a possible strategy to increase the aspect ratio of the machined structure. In this work we investigate the influence of the pulse duration on the ablation process and compare the achievable groove depth depending on the kerf width for front-side and back-side ablation. Additionally the optimum relation between the kerf width and number of over scans is presented. The investigations were carried out using Spirit® HE laser from Spectra-Physics®, which can provide adjustable pulse duration from <400 fs to 14 ps, the repetition rate of up to 1MHz and average output power of >16 W (1040nm).

10092-5, Session 1

Surface processing of stainless steel with high-energy picosecond laser pulses with an elliptical focus

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A combination of a cylindrical and spherical lens was used to create an elliptical beam to ablate rectilinear grooves on stainless steel samples. Near-infrared with the pulse duration of 8 ps laser pulses with energies in the range of 250?μJ – 2.3?mJ were applied at a repetition rate of 300?kHz. The ablation rates obtained with elliptical beams of different focoused length were compared to the ones obtained with conventional circular beams for different feed rates. The maximum ablation rates achieved with the round and the elliptical beam were 0.01 mm?/min/W and 0.37 mm?/min/W, respectively. At the maximum ablation rate the ellipticity was 0.9955 and the peak fluence was about 50 J/cm? for both, the round and the elliptical beam. In contrast to conventional circular beam that shows the low ablated volume rates around 0.01 mm?/min/W in high pulse energies, the elliptical focous exhibits high ablated volume rate and high throughput.

10092-6, Session 2

Micro and nano- biomimetic structures for cell migration study fabricated by hybrid subtractive and additive 3D femtosecond laser processing *(Invited Paper)*

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Lab-on-a-chip devices have been intensively developed during the last decade when emerging technologies offered possibilities to manufacture reliable devices with increased spatial resolution. These biochips allowed testing chemical reactions in nanoliter volumes with enhanced sensitivity and lower consumption of reagents. There is space to further consolidate biochip assembling processing since the new technologies attempt direct fabrication in view of reducing costs and time by increasing efficiency and functionalities.

Rapid prototyping by ultrafast lasers which induces local modifications inside transparent materials of both glass and polymers with high precision at micro- and nanoscale is a promising tool for fabrication of such biochips. We have developed a new technology by combining subtractive ultrafast laser assisted chemical etching of glasses and additive two-photon polymerization to integrate 3D glass and polymer microstructures in a single biochip. The innovative hybrid "ship-in-a-bottle" approach is not only an instrument that can tailor 3D environments but a tool to fabricate biomimetic in vivo structures inside a glass microfluidic chip. It was possible to create appropriate environment for cell culturing and to offer robustness and transparency for optical interrogation. Cancer cells were cultivated inside biochips and monitored over short and long periods. With the view of understanding cancer cells specific behavior such as migration or invasiveness inside human body, different geometrical configurations and chemical conditions were proposed. The cells were found responsive to a gradient of nutrient concentration through 2 μm diameter channels of a 3D polymeric scaffold integrated inside glass biochip.

10092-7, Session 2

Influence of the initial surface texture on the resulting surface roughness and waviness for micro-machining with ultra-short laser pulses

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The resulting surface roughness and waviness after processing with ultra-short pulsed laser radiation depend on the laser parameters as well as on the machining strategy and the scanning system. However the results depend on the material and its initial surface quality and finishing as well. The improvement of surface finishing represents effort and produces additional costs. For industrial applications it is important to reduce the preparation of a workpiece for laser micro-machining to optimize quality and reduce costs.

The effects of the ablation process and the influence of the machining strategy and scanning system onto the surface roughness and waviness can be differenced due to their separate manner. By using the optimal laser parameters on an initially perfect surface, the ablation process mainly increases the roughness to a certain value for most metallic materials. However, imperfections in the scanning system causing a slight variation in the scanning speed lead to a raise of the waviness on the sample surface.

For a basic understanding of the influence of grinding marks, the sample surfaces were initially furnished with regular grooves of different depths and spatial frequencies to gain a homogenous and well-defined original surface. On these surfaces the effect of different beam waists and machining strategy are investigated and the results are compared with a simulation of the process. Furthermore the behaviors of common surface finishes used in industrial applications for laser micro-machining are studied and the relation onto the resulting surface roughness and waviness is presented.

10092-8, Session 2

Femtosecond laser writing of new type of waveguides in silver containing zinc phosphate glass

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Femtosecond laser writing in glasses is a growing field of research and development in photonics, since it provides a versatile, robust and efficient approach to directly address 3D material structuring. Laser-glass interaction process has been studied for many years, especially the local changes of the refractive index that have been classified by three distinct types (types I, II and III, respectively). These refractive index modifications are widely used for the creation of photonics devices such as waveguides [1], couplers,

photonic crystals to fabricate integrated optical functions in glasses for photonic applications as optical circuits or integrated sensors.

Femtosecond laser writing in a home-developed silver containing zinc phosphate glasses induces the creation of fluorescent silver clusters distributed around the laser-glass interaction voxel [2]. In this paper, we introduce a new type of refractive index modification in glasses. It is based on the creation of these photo-induced silver clusters allowing a local change in the refractive index $\Delta n = 5x10-3$, which is sufficient for the creation of waveguides and photonics devices. The wave guiding process in our glasses along these structures with original geometry is demonstrated for wavelengths from visible to NIR [3], giving a promising access to integrated optical circuits in these silver containing glasses. Moreover, the characterization of the waveguides is presented, including their original geometry, the refractive index change, the mode profile, the estimation of propagation losses and a comparison with simulation results.

1. K. M. Davis, K. Miura, N. Sugimoto, and K. Hirao, Opt. Lett. 21, 1729-1731 (1996).

2. M. Bellec, A. Royon, K. Bourhis, J. Choi, B. Bousquet, M. Treguer, T. Cardinal, J.-J. Videau, M. Richardson, and L. Canioni, The Journal of Physical Chemistry C 114, 15584-15588 (2010).

3. S. Danto, F. Désévédavy, Y. Petit, J.-C. Desmoulin, A. Abou Khalil, C. Strutynski, M. Dussauze, F. Smektala, T. Cardinal, and L. Canioni, Advanced Optical Materials 4, 162-168 (2016).

10092-9, Session 2

Tunable hydrophobicity assisted by light-responsive surface micro-structures

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Nowadays, several processing technologies are available for fabricating complex polymeric architectures which are mostly static in nature and they cannot be morphologically modified once fabricated. The use of light-responsive materials, such as azobenzene polymeric compounds, can open the opportunity to engineer surface structures and trigger peculiar properties such as complex optical functionalities or anisotropic hydrophobic behavior by laser-assisted processing.

We consider azopolymers, in which the rapid and reversible photoisomerization reaction of azobenzene molecules can actuate mass transport phenomena typically parallel to the light polarization [1]. The azopolymeric film is patterned by soft-imprinting technique as an array of cylindrical micro-pillars. Upon a linearly polarized illumination (wavelength of 490 nm, laser beam intensity of 50 W/cm2), we observe an elongation of the pillars along the polarization direction, in such a way that the pillars assume an ellipsoidal cross-section. A rotation of the polarization by 90° triggers a reorientation of the ellipsoidal pillars whose major axis rotates parallel to the driving electric field.

By taking advantage of the laser-induced deformation we demonstrate the possibility to modify the surface hydrophobicity along specific directions. A further rotation by 90° induces a retraction of the elongated pillars, reconfiguring them as cylinders with circular base, therefore restoring the pristine configuration and the initial surface properties in terms of wettability.

The findings are promising in applications exploiting tunable smart architectures including optical metasurfaces and dynamically tuned surfaces wettability.

[1] Priimagi, A.; and Shevchenko, A. J. Polym. Sci., Part B: Polym. Phys. 52(3), 163-182 (2014).

10092-10, Session 3

Femtosecond laser nano/microfabrication via three-dimensional focal field engineering *(Invited Paper)*

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In the conventional femtosecond laser direct writing with a Gaussian beam, the focus is an ellipsoid with the long axis along the beam propagation direction, resulting in the ellipsoidal fabricated dot. Due to the simple shape of the dot, complex 3D nano/microstructures should be written dot by dot by the focus scanning, which is usually time-consuming. Therefore, a rapid nano/microfabrication technique is becoming highly desired to achieve arbitrary 3D nano/microstructures.

By 2D phase modulation of the Gaussian beam, multi-focuses were generated for the direct writing of several same nano/microstructures simultaneously to save fabrication time, and donut and other 2D intensity distributions were produced for the single exposure fabrication of 2D microstructures. Here, we demonstrate the single-exposure femtosecond laser nano/microfabrication of a 3D microstructure via the 3D focus engineering by using the 2D phase-only spatial light modulation. With a single exposure, a whole 3D microstructure like a double-helix is polymerized simultaneously by two-photon absorption, whose configuration is controlled by the designed 3D focal intensity distribution. In the same time, a longitudinal circular intensity distribution is generated for the multi-photon inscription of a depressed cladding waveguide inside glass, where the transverse scanning is adopted.

10092-11, Session 3

Transformation of Gaussian beams into M-beams for advanced microvia drilling

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Typical laser systems produce Gaussian laser beams that may not be suitable for high precision materials processing. This study considers laser microvia drilling of multilayer polymeric substrates for high density interconnects in microelectronic devices. Closely spaced microvias reduce the interconnect distance between the processors to meet the ever increasing demand for transferring large volumes of data at high rates. 9.3 ?m wavelength CO2 lasers are commonly used for drilling microvias in current polymeric substrates because of their higher absorption coefficient than 10.6 ?m wavelength conventional CO2 lasers. High absorption coefficient provides a volumetric heating mechanism of shallow depth to enable surface-controlled vaporization of the polymeric materials. Gaussian or top-hat laser beams generally leave carbonized polymeric residue at the bottom corner and on the side wall of the microvias, and this residue hinders the subsequent microsoldering of electronic devices to the interconnects. This problem can be eliminated using M-beams for microvia drilling. A thermal model is developed in this study to determine the intensity distribution of the M-beam for reducing the formation of the residue. To achieve this M-beam from a Gaussian beam, a lens is designed using the Fresnel diffraction model. Drilling experiments are conducted using an M-beam and the shape and size of the microvia are found to closely match the theoretical predictions.

10092-12, Session 3

Structural modification of gallium lanthanum sulfide glass induced by ultrafast laser inscription

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Ultrafast laser inscription (ULI) is a very fast and promising procedure for manufacturing of three-dimensional (3D) waveguide structures in very different substrates. 3D photonics enabled by ULI has found so far applications in stellar interferometry, fundamentals of linear/nonlinear optics and quantum optics experiments.

While ULI is rapidly progressing towards being a mature and flexible technological platform for integrated optics, the complex physics of the laser matter interaction and the successive thermo-mechanical processes leading to structural modifications in the glasses is not yet well understood, except than for a few materials. A better understanding of these processes would certainly enhance the quality and reliability of the ULI platform.

Here we present the results of an experimental chemical-physical study aiming at the characterization of the structural effects of femtosecond laser irradiation in Gallium Lanthanum Sulfide (GLS) glasses. GLS is a chalcogenide glass suitable for ULI and with a transparency window extending down to 10 micron wavelength, thus making it an excellent candidate for the development of mid-infrared photonic components. For the first time to our knowledge, we report clear signatures of structural changes occurring in micro-Raman spectra of the irradiated regions, which are probably associated to a local depletion of Gallium Sulfide structures. Additionally we characterized quantitatively the strain birefringence induced by ULI, indicating a circular symmetry of the optical axis orientation around the laser irradiated region and a birefringence of a few ten ppm. Implications of the results to the improvement of ULI in chalcogenide materials will be discussed.

10092-13, Session 3

Fabrication and assembling of a microfluidic optical stretcher polymeric chip combining femtosecond laser and micro injection molding technologies

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Microfluidic optical stretchers are valuable optofluidic devices for studying single cell mechanical properties. These usually consist of a single microfluidic channel where cells, with dimensions ranging from 5 to 20 ?m are trapped and manipulated through optical forces induced by two counter-propagating laser beams. Recently, monolithic optical stretchers have been directly fabricated in fused silica by femtosecond laser micromachining (FLM). Such a technology allows writing in a single step in the substrate volume both the microfluidic channel and the optical waveguides with a high degree of precision and flexibility. However, this method is very slow and cannot be applied to cheaper materials like polymers. Therefore, novel technological platforms are needed to boost the production of such devices on a mass scale.

In this work, we propose integration of FLM with microinjection moulding (?IM) as a novel route towards the cost-effective and flexible manufacturing of polymeric Lab-on-Chip (LoC) devices. In particular, we have fabricated and assembled a PMMA microfluidic optical stretcher by exploiting firstly FLM to manufacture a metallic mould prototype with reconfigurable inserts. Afterwards, such mould was employed for the production, through ?IM, of the two PMMA thin plates composing the device. The microchannel with reservoirs and lodgings for the optical fibers delivering the laser radiation for cell trapping were reproduced on one plate, while the other included access holes to the channel. The device was assembled by direct fs-laser welding, ensuring sealing of the channel and avoiding thermal deformation and/or contamination. Finally, it was validated with red blood cells.

10092-14, Session 3

Optical vortex illumination structures twisted polymeric microfiber

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Optical vortex carries orbital angular momentum associated with a helical wavefront arising from phase singularity, enabling us to twist and rotate materials on nano or micro scale. It has been widely investigated in many fields, such as optical manipulations and materials processing.

In this paper, we present the first demonstration, to the best of our knowledge, of twisted polymeric microfiber fabricated by optical vortex illumination on an ultraviolet (UV) curing resin.

A continuous-wave laser with a wavelength of 405nm was used, and its output was converted to the optical vortex with a topological charge of 1-4 by using a spiral phase plate. The optical vortex was focused to be a few micrometer annular spot onto the 100-110?m thick curing resin (NOA63) sandwiched by two slide glasses.

The resin was polymerized within an irradiation time of 0.1 second, and substantially, the polymerized resin revolved axially to produce twisted offshoots, in which a number of offshoots was directly determined by the topological charge of the optical vortex. A twisted fiber with a length of ~100 ?m and a core diameter of few micrometer was also established within 1 second. Also, the twisted direction of the fiber was controlled merely by inverting the topological charge of the optical vortex.

These results evidence that the orbital angular momentum of the optical vortex can be transferred to the curing resin to structure twisted fiber. Such twisted fiber will be potentially applied to a novel laser device with a chirality.

10092-15, Session 4

Quasi-periodical surface microstructures for photovoltaic cells and battery materials

(Invited Paper)

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Surface microstructures influence the functionality of a treated surface in different applications. Ultra-short pulsed lasers are potent tools for

micromachining of a lot of materials. At certain laser parameters periodical and/or quasi-periodical μm-size surface structures evolve during processing on various materials. The μm-sized cone-like surface features with their extraordinary shape and distribution can be processed at various conditions. Therefore, the laser micro-processing parameters can be refined for distinct applications and requirements. In consequence, the performance of the final product can be increased with the proper surface structure and as a result of the right set of laser processing parameters. With respect to the laser ablation and material parameters, such as fluence, permittivity and phase change enthalpy, the difference in structuring of the materials is explained.

In the case of photovoltaic cells, silicon has been treated using different combinations of process parameters. The size and distribution of the surface features is changed to decrease and to modify the spectral reflectance for silicon solar cells. The solar cell efficiency is increased by the lower spectral reflectance. In addition the semiconductors germanium, gallium-arsenide and zinc-oxide have been evaluated to verify the prediction of the laser ablation adapted plasmonics theory for laser micro-structuring.

In the case of battery materials laser-induced quasi-periodic surface structures have been investigated on the materials LiCoO2 (LCO) and LiNi1/3Mn1/3Co1/3O2 (NMC). The active area of the electrodes has been increased and in consequence the electrochemical performance of Li-ion batteries.

10092-16, Session 4

Patterning of organic photovoltaic on R2R processed thin film barriers using IR laser sources *(Invited Paper)*

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The current state of the art in encapsulating flexible organic photovoltaic (OPV) devices is by sandwiching the OPV cells between two ultra-barrier foils. The motivation of the work is to simplify the process of encapsulation of the devices enabling it to reduce the number of production steps and materials and to improve the life time of these devices. This can be achieved by developing direct laser structuring on top of flexible barrier foils in combination with direct encapsulation. As an outcome, more functionality will be integrated into less material. On a research and development level, direct laser structuring on these flexible barrier films is under investigation. Direct laser structuring of such integrated front sheet with a bottom electrode or TC layer (so-called P1 process), as well as structuring of the organic stack (P2 process) and top electrode (P3 process) is very challenging since a complete electrical isolation for P1 is required, and none of the processes should influence the barrier performance underneath the laser scribes.

In this paper we present the development of laser processes for flexible OPV on roll-to-roll (R2R) produced thin film barrier (single SIN barrier layer, WVTR < 10-6 g/m2.day) with indium tin oxide (ITO) as bottom electrode. For this purpose femto-, pico- and nanosecond IR lasers are tested. To verify that the laser scribing does not result in barrier damage underneath, often optical inspection is not sufficient to confirm this. A new test method based on the optical Ca-test was developed that shows a clear improvement in damage analysis underneath laser scribes. This way well defined process windows can be obtained for IR TC patterning.

10092-17, Session 4

Roll-to-roll suitable short-pulsed laser scribing of organic photovoltaics and close-to-process characterization

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The proper and long term operation of organic electronic devices like organic photovoltaics OPV strongly depends on their resistance to environmental influences such as permeation of water vapor or oxygen. Thus, major efforts are spent to encapsulate OPV in barrier materials. State of the art is sandwich-like encapsulation between two ultra-barrier foils. The advantage of encapsulation is faced by two major disadvantages: high costs (~1/3 of total manufacturing costs) and parasitic intrinsic water due to sponge effects of the OPV substrate foil.

To fight these drawbacks, a promising approach is to use the OPV substrate itself as barrier by enhancing its functionality through integration of an ultra-barrier coating, followed by alternating deposition and structuring of OPV functional layers. In effect, more functionality will be integrated into less material and production steps are reduced in number. No benefit without challenge: since the ultra-barrier now is integrated as 1st functional layer, no violation of the barrier functionality by the following process steps is allowed, while all electrical functionalities must be maintained.

As most reasonable and – in state of the art manufacturing – well-studied structuring tool, short and ultrashort pulsed lasers are used. Regarding the OPV, laser machining applies to three layers: bottom electrode made of transparent conductive materials (so-called P1 process), organic photovoltaic operative stack (P2 process) and (metal-based) top electrode (P3 process) (fig.1).

In this paper, results and investigations on laser processing of organic stack (P2) and top electrode (P3) with short and ultrashort pulsed laser systems with UV, GR and IR wavelengths are presented. Since main focus besides functional structuring is on damage prevention regarding the ultra-barrier, proper methods of characterization needed to be qualified. Optical inspection as a 1st step is giving a hint, but no trustful result. Therefore, a variety of characterization methods (like optical and confocal microscopy, SEM, electrical testing…) and their correlation are presented with respect to their significance regarding the declaration “barrier damage / no barrier damage”. As “gold standard”, the optical Ca-test as laboratory method is presented, to which all other methods are compared. Criterion along with the reliable classification with respect for future production applicability was the potential R2R integrability and close-to-process usability. Therefore, a new contact-free and fast characterization method, called Hyperspectral imaging (HSI), was investigated. The technique brings a significant improvement in P2 and P3 laser processing and damage analysis. Using both, material selective (ultra-)short pulsed laser processing in combination with quasi – in-situ monitoring, leads to a reliable P2 and P3 process window and, therefore, to a potential R2R production of enhanced OPV cells.

10092-18, Session 4

Tailoring material properties of organic semiconductors by ultrafast laser pulses and its applications

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Electronic devices made from organic semiconductors are attractive in terms of the variety of materials, high tunability of material properties,

and cost-efficient manufacturing process. Moreover, their thin, light and flexible forms are advantageous in developing wearable devices for ICT, energy, and healthcare applications such as OPVs, OLED displays, lightings, and stretchable sensors. However, the low quantum efficiency of organic electronic devices has been a serious issue toward industrial realization. Although heat or mechanical treatments have been used to control the molecular rearrangement leading to improvement of the electron mobility and other properties, these methods are applied with limitation as they are not selective and localized processes. We recently reported that ultrafast lasers can selectively adjust the material properties of thin organic semiconducting film. In particular, ultrafast laser irradiation can induce photo-expansion of conducting polymers such as P3HT:PCBM and PEDOT:PSS systems, which are widely used in organic photovoltaics and thin film transistors. Phase separation and rearrangement of polymer chains were observed in photo-expanded region. Those phenomena were characterized by micro-RAMAN, GIWAXS (Grazing Incidence Wide Angle X-ray Scattering), and NEXAFS (Near Edge X-ray Absorption Fine Structure). Laser polarization and pulse width are dominant parameters in controlling photo-induced phase separation and the direction of the polymer chain rearrangement. In addition, ultrafast laser induced surface ripples were applied to organic semiconducting devices to enhance electron mobility of the system. We will present the details of photo-induced improvement of the properties of organic semiconducting polymers and discuss their future applications.

10092-19, Session 4

Fabrication and characterization of silicon-based 3D Electrodes for high-energy lithium-ion batteries

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For next generation of high power lithium-ion batteries, silicon as anode material is of great interest due to its higher specific capacity (3579 mAh/g). However, the volume change during de-/intercalation of lithium-ions can reach values up to 400 % causing particle pulverization, loss of electrical contact and even delimitation of the composite electrode from the current collector. In order to overcome these drawbacks for silicon anodes we are developing new 3D electrode architectures. Laser nano-structuring of the current collectors is developed for improving the electrode adhesion and laser micro-structuring of thick film composite electrodes is applied for generating of free standing structures. Recent studies showed a tremendous improvement of film adhesion on laser modified metallic current collectors. Furthermore, free standing structures could be attributed to sustain high volume changes during electrochemical cycling and to increase the lithium-ion diffusion kinetics. Thick film composite Si/C-anode materials with different silicon content were deposited on laser modified current collectors. Film adhesion and its dependence regarding active material and type of surface topography of current collectors such as nano-ripples and hierarchical surface structures were investigated. 3D architectures were generated in silicon-based electrodes by using ultrafast laser ablation. Electrochemical properties of cells with structured and unstructured electrodes were characterized. Laser-induced breakdown spectroscopy was utilized to measure the lithium distribution at different state of health in order to study the degradation mechanisms of structured and unstructured electrodes. The contribution of 3D architectures of electrodes for cycle stability, capacity retention and cell life-time will be discussed in detail.

10092-20, Session 4

Laser processing of high energy lithium nickel manganese cobalt oxide electrodes for lithium-ion batteries

Jan-Hendric Rakebrandt, Peter Smyrek, Yijing Zheng, Karlsruhe Institute of Technology (Germany) and Karlsruhe Nano Micro Facility (Germany); Hans Jürgen Seifert, Karlsruhe Institute of Technology (Germany); Wilhelm Pfleging, Karlsruhe Institute of Technology (Germany) and Karlsruhe Nano Micro Facility (Germany)

Lithium-ion batteries became the most promising types of energy storage devices due to their high gravimetric and volumetric capacity, high cycle life-time, and low self-discharge. Nowadays, the cathode material lithium nickel manganese cobalt oxide ($Li(Ni_{1/3}Mn_{1/3}Co_{1/3})O_2$, NMC-111) has been one of the most successful cathodes and is widely used in commercial lithium-ion batteries due to many advantages such as high energy density (<150 Wh/kg, cell level), high power density, high specific capacity (163 mAh/g), high rate capability and good thermal stability in the fully charged state. However, to meet the requirements for the increasing demand for rechargeable high energy batteries, nickel-rich composite cathodes with specific capacities up to 210 mAh/g are needed in order to reach the aimed energy density of 250 Wh/kg on cell level in 2020. In our research we develop laser based technologies in order to provide high energy lithium-ion batteries. For this purpose, we produced nickel-rich lithium nickel manganese cobalt oxide cathodes via tape cast method containing 80-90wt% of active material with a film thickness of 100-200μm. We investigated the specific capacities using galvanostatic measurements for different types on NMC compositions of nickel, manganese and cobalt at different charging currents ("C-rates"). Therefore, the cathodes were cycled using a metallic lithium anode and a standard liquid electrolyte. An improved lithium-ion diffusion kinetic and an increased active surface area can be achieved by laser-assisted generating of three dimensional (3D) architectures which leads to higher power densities. Unstructured and structured cathodes were compared using laser ablation at 350fs. Our current research has shown that laser structuring of electrode materials lead to a significant improvement in electrochemical performance, even at high charging and discharging C-rates. After electrochemical cycling the lithium distribution and possible degradation processes will be investigated using Laser-induced Breakdown Spectroscopy (LIBS). The up-scaling of the laser process for high energy batteries will be discussed.

10092-53, Session PTue

Laser drilling of silica assisted by supercritical fluid

Keisuke Yoshiki, Univ. of Hyogo (Japan)

We propose a novel high aspect laser drilling technique for silica substrate assisted by supercritical CO_2 instead of water. Supercritical CO_2 has excellent solubility and fluidity, which facilitates efficient removal of ablated debris to the outside of the drilled hole. Thus, laser drilling using supercritical CO_2 results in deeper, thinner holes than those drilled using air and water. In experiments conducted, silica slab was placed in an enclosure filled with CO_2 around the critical point. Subsequently, a sub-picosecond pulsed laser focused and scanned on the sample created deeper and thinner holes with aspect ratios greater than 100.

The use of supercritical CO_2, resulted in an increase in the aspect ratio of laser ablation drilling from 10.7 obtained in water to more than 100, and the fluctuation of hole diameter was 2 times less than the water equivalent. This method was feasible even for 3D channels, even those with right-angle corners. We propose that supercritical CO_2 should become the new standard assist liquid. Hence, future investigations should proceed with estimating the capabilities of machining using supercritical CO_2.

To estimate the ability of removability of debris, the observation of ablated materials and shock waves generated by pulsed laser ablation was carried out. We estimated the behavior of explosion and convection process after pulse irradiation, and conclude the free convection in the hole is the dominant process to remove the debris.

10092-54, Session PTue

Laser irradiation of WE54 surface through simulated body fluid layer

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Mg alloys are superior to other metallic biomaterials for temporary implant application, owing to their biodegradability and biocompatibility features. However, the high reactivity and the rapid corrosion rate of Mg alloys are major barriers for their usage in bioapplication. WE54 Mg alloy is a potential new biomaterial, containing a rare earth element, which plays a vital role in enhancing corrosion resistance. In this paper, laser surface modification method is used to improve the surface properties of WE54. A 500 W nanosecond pulse Nd: YAG laser beam is focused on the specimen through a 2mm layer of simulated body fluid (SBF). Optimized laser parameters are used to obtain a calcium and phosphate layer/ion on the surface of WE54. As a result, a new microstructure as well as a Ca/P layer are obtained in a single process, which is conductive for the cell attachment and growth.

Scanning electron microscope and X-ray diffraction are used for examination of the modified surface microstructure and phases, respectively. Variable wavy surface morphologies are obtained for laser power varying from 150 W to 300 W. Higher Ca/P deposit is obtained in for a 0.5 mm defocused laser beam and 250 W power conditions. Layer by layer surface microstructure is studied to understand the change in the element distribution as well as laser irradiated depth. The laser modified WE54 alloy is used for the cell culture to examine the improvement in cell attachment. The cell adhesion in WE54 alloy is observed after laser irradiation through SBF.

10092-55, Session PTue

Third order optical nonlinearities and defect generation in diamond with ultrashort pulses

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Diamond´s wide transmission window, low absorption loss and high index of refraction, has prompted the interest on its use as a platform for nonlinear and quantum optics. In this direction, frequency generation was demonstrated in diamonds, while its optically active defects are proposed as a good option for single photon emitters. Although diamond photonics has driven an interesting area of fundamental and applied sciences, studies on the third-order optical nonlinearities of diamond are still scarce.

In this work, femtosecond laser pulses were used to study third-order optical nonlinearities in type II diamond, in the range from 300 up to 1500 nm. To the best of our knowledge, this is the first time such nonlinear spectrum is reported in this range. The experimental results are compared with theoretical predictions for nonlinear refraction in solids. Such data, as well as optical Kerr gate results also obtained, are of foremost relevance to understand ultrafast optical processes in diamond. We have also investigated femtosecond laser micromachining in diamond, aiming at producing nitrogen-vacancy (NV) centers to be used as single-photon sources for quantum optics. We observed a threshold energy for diamond modification of ~15 nJ (120-fs and NA = 1.25). After annealing at 680ºC for 1 hour, the micromachined areas became fluorescent, which suggests the formation of optically active defects. The properties of such defects for quantum optics are currently under investigation.

10092-56, Session PTue

Stealth dicing of transparent materials using Bessel beams and novel beam shapes

Rémi Meyer, Ludovic Rapp, Jassem Safioui, John M. Dudley, François Courvoisier, FEMTO-ST (France)

Ultrafast Bessel beams have been shown to be excellent tools to control laser energy deposition in transparent materials and control stealth dicing, ie material separation after single pass laser illumination. Here we demonstrate that the transverse intensity profile of the beam can be further engineered to provide better fracture efficiency and reduce the amount of defects generated in the processed glass. To quantitatively compare different beam profiles, we use a 3-points bending test to measure the deflection required to fracture laser-processed samples. Weibull statistical fits allow for comparing the distributions. We report severe differences between beams with multiple hot spots. We specifically show a strong enhancement of the ability to cleave in comparison with Bessel beams as well as a strong improvement of the final robustness of the separated glass. We demonstrate cleaving with precision better than 1 μm over the whole 20 mm sample length with writing speed as high as 25 mm/s. The research leading to these results, has received funding from the European Union Seventh Framework Programme [ICT-2013.3.2- Photonics] under grant agreement n°619177, project TiSa-TD.

10092-57, Session PTue

Laser-assisted reduction of copper oxide thin films coated on paper based substrates

Magnus Engholm, Enkeleda Balliu, Thomas Ohlund, Henrik Andersson, Håkan Olin, Mid Sweden Univ. (Sweden)

Printed electronics is becoming more popular for fabrication of applications on flexible substrates. Substrates used is to a large extent plastics but paper is becoming more widespread due to lower cost and recyclability. Consider also the possibility of using the very large area manufacturing techniques (roll-to-roll) today used in the paper making industry for production of electronic applications. Manufacturing of conductive tracks at low cost is of special importance for large area printed electronics, where frequently used materials are metal nano-particles, carbon powder or conductive polymers in the form of inks. However, using paper as a substrate require processing methods that gives a low resistivity and at the same time leaves the paper substrate without damage. Copper oxide (CuO) has shown to be an interesting and very cost effective alternative for fabrication of printed electronics. In this work we have investigated the use of an aqueous, CuO-based ink (16 wt%) to create well-defined and uniform conductive tracks on different paper based substrates under ambient conditions. Laser-assisted reduction was evaluated by using a 532 nm laser source (pulsed and CW) in combination with a high-speed laser scanning mirror system. By careful optimization of the processing parameters, the laser processed inkjet printed CuO-patterns could be fully reduced to Cu-rich micro structures with thin film resistivity in the ~7-10 uOhm cm range corresponding to ~ 4 times

the copper bulk resistivity. The obtained results are promising showing no delamination, thin film cracks or observable damage to the paper substrate.

10092-58, Session PTue

Nanostructuring of sapphire using time-modulated nanosecond laser pulses

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The nanostructuring of dielectric surfaces using laser radiation is still a challenge. The IPSM-LIFE (laser-induced front side etching using in-situ prestructured metal layer) method allows the easy, large area and fast laser nanostructuring of dielectrics. At the IPSM-LIFE a metal covered dielectric is irradiated where the structuring is assisted by a self-organised molten metal layer deformation process. The IPSM-LIFE can be divided into a low and high fluence step: At low laser fluence the irradiation of thin metal layers on dielectric surfaces results in a melting and nanostructuring process of the metal layer and partially of the dielectric surface. Furthermore, a subsequent high laser fluence treatment of the metal nanostructures result in a structuring of the dielectric surface. At this study a sapphire substrate Al_2O_3(1-102) was magnetron covered with a 10 nm thin molybdenum layer and irradiated by an infrared laser with an adjustable time-dependent pulse form with a time resolution of 1 ns (wavelength 1064 nm, pulse duration 1 – 600 ns, Gaussian beam profile). The laser treatment allows the fabrication of different modifications into the sapphire surface like deep holes with a surface diameter into the sub-µm range due to a nanodrilling process and surface structures with a lateral size down to 10 nm due to a pattern transfer process. The resultant structures were investigated by atomic force (AFM) and scanning electron microscopy (SEM). The process was simulated and the simulation results were compared with experimental ones.

10092-59, Session PTue

Direct writing of zero taper high aspect ratio features on elastomer micromoulds with femtosecond laser

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Production of disposable medical microcomponents pose a challenge for the medical device industry, due to the need to keep the cost low while coping with the very high quality and functional standards typical of the industry. This involves long development and certification processes when the manufacturing process is adopted if compared with the prototyping technology used for the initial tests.

In particular, piezoceramic transducers for medical image are being miniaturized to be introduced in the body to assist fine surgery, as support for navigation of surgical needles and vascular catheterism. The traditional production route for these sensors is mechanical (dicing of the piezoceramic block), being limited in the feasible feature size. The features consist in densely packaged columns of high aspect ratio (typically 1:5 or larger) and lateral dimension of several tens of microns. The fill factor and lateral dimensions of the column largely determine the image quality and characteristics, as they dominate the resonant frequency of the device. Conventional sensors are produced through saw cutting of a piezoceramic block and encapsulating in an epoxy filling, a route known as "Dice and Fill", which provide high performance at frequencies of 3-10 MHz thanks to their high sensitivity and low acoustic impedance.

Within the frame of the collaborative project FABIMED (http://www.fabimed.eu), laser based direct write methods are being explored to produce the mould directly on the elastomer, without the need of a master. This method can be used for development and for production, allowing mass customization and reducing the time to market.

Micromachining of PDMS within the required specifications poses very challenging problems. In this paper, the use of an alternative elastomer material is proposed, in combination with a visible ultrafast laser beam, to enable the production of elastomeric moulds with the required geometrical features and quality.

Ultrasound transducers for medical imaging demand increasing performance/cost ratio, pushing the limits of current piezoceramic machining manufacturing methods. We are developing a method based on direct laser machining of elastomeric moulds for replication of the transducer microstructure, consisting in a dense arrangement of micropillars.

The work studies the benefits of using platinum catalyst loaded elastomers for producing the moulds, and the laser-material interaction in the femtosecond regime. Previous work show high aspect ration (1:5 to 1:7) drilling and machining of transparent PDMS through nonlinear absorption and filamentation.

Processing catalyst enhanced siloxane improves the geometrical and surface quality of the machined features, and allow for better than 1:15 aspect ratios. Cylindrical columns of 1000 microns depth and under 60 microns diameter, with zero taper, are shown to be produced with 400 fs laser, 15 microJ pulses at 1 MHz and 515 nm.

10092-60, Session PTue

Process and parameter optimisation for micro structuring of 3D freeform metallic surfaces - a comparative study of short-pulse (nanosecond) and ultrafast (picosecond, femtosecond) laser ablation

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Layer-based laser ablation of three dimensional micro structured freeform surfaces has become of significant importance for technical applications such as biomimetic surfaces in recent years. In order to identify the optimum set of process parameters for a complex laser ablation operation, a design of experiments (DoE) study has been carried out with laser sources covering pulse durations regime of femtosecond (fs), picosecond (ps) and nanosecond (ns). The aim was to identify the optimum parameter set for achieving best surface roughness and, as a second criteria, for the optimisation machining time to be reduced to a minimum. In a first step, rectangular pockets have been machined and a DoE based parameter variation was performed. In particular, the parameters wavelength (1030 nm, 515 nm, 343 nm), machining speed, laser power, and laser pulse duration (fs, ps, ns) have been modified. Surface roughness was measured and an optimum set of parameters was calculated. Finally, with this parameter set a shark skin like micro structured test structure covering a macroscopic freeform surface was ablated in a layer based manner utilising a full CAD/CAM approach. The results show that the ultrafast laser radiation has the best performance to achieve lowest surface roughness and best ablation efficiency. While scanning speed and pulse duration have a linear influence on achievable roughness, laser power has a quadratic influence in relation to the global maximum on the surface roughness result.

10092-61, Session PTue

Extension of incubation models to moving surfaces irradiated by ultra-short pulse lasers

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In pulsed-laser micromachining, incubation refers to the chemical and structural change of a surface due to irradiation from a single pulse, and the effect of this change on the absorption of the subsequent pulse. Ability to account for change in absorption properties of a surface allows for prediction of the damage that will occur with irradiation and provides a pathway to uncover the complicated processes that govern incubation. However, the model as it currently stands only accounts for laser pulses irradiating a single spot on a surface. We have developed, as a first step towards implementing incubation models for fabrication of surfaces with real-world applications, a mathematical description of the manner in which fluence accumulates during irradiation of surfaces moving with constant velocity relative to a beam. Within this description, we define the criteria for the profile of total deposited energy to be both fully-developed and constant along the scanning direction center line and show that, under these conditions, incubation models can be extended to moving surfaces. We demonstrate the necessity of such a framework with proof-of-concept experiments on three surfaces with distinct incubation behavior: glass, Titanium, and Polyethylene terephthalate (PET). Additionally, when the conditions described above are relaxed, the manner in which energy accumulates and the total energy deposited become functions of the scanning direction coordinate. Comparison of damage incurred on surfaces lased in this manner with their energy profiles can provide a new tool to further our understanding of the processes governing incubation.

10092-62, Session PTue

Laser ablation on polyimide film for nano-pattern transfer

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Deep ultraviolet laser ablation of polyimide film has received extensive attention on its ablation mechanism in the past thirty years. However, by far investigation on reducing the feature size of polyimide patterns has not been widely reported. In this report, periodic nano-dot patterns are produced by imaging a binary hole-array mask onto a polyimide film with a 193 nm ArF laser. To prepare a 100 nm thick polyimide film, polyimide precursors are diluted with NMP-based solvent, spined on silicon wafer and cured in nitrogen atmosphere. A 36x Schwarzschild reflective objective with N.A= 0.5 is employed to de-magnify the hole array patterns and achieve a sub-micro size on the substrate. Ablation rate of polyimide film at different fluence is investigated first to understand its ablation threshold and the minimum fluence required for total film ablation by averaging the total ablation depth of five pulses. For nano-pattern ablation, single pulse is used to avoid channelling effect of laser ablation on the sidewalls of the structures. SEM imaging indicates that pattern profile evolves from nano-pit to nano-dot by increasing the energy density. Heat diffusion leads to material reflows where no ablation occurs at a high fluence, producing the nano-dot array. Due to the strong thermal and chemical stability of polyimide film, such nano-arrays may be useful for nano-pattern transfer onto metal films.

10092-63, Session PTue

Fresnel calculation of holograms for micrometer-scale material structuring on substrates with complex surface topography

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In this work the numerical realization of the Fresnel approximation for the calculation of diffraction effects is presented. Based on the diffraction effect the calculation of holograms was realized. The holographical projection of light-patterns for the structuring of materials creates opportunities to structure arbitrary shaped target surfaces. The direct use of Fresnel-Integral for this kind of calculation was used for the realization of compensation of the initial beam deviation. The limits of compensation were analyzed and discussed. The problem of big data calculation was analyzed, summarized and partially solved through parallelization. The concept of the segmentation of calculation-sets in the subtasks was formalized implemented and evaluated. For the numerical description of the Fresnel approximation a datatype structure was prepared. The realization of datatypes was implemented under the consideration of optimization for the parallelization concept. The key calculation based on the task-segmentation concept was implemented using Python-CUDA. The direct calculation of holographical masks makes a free organization of the projection-setup possible. The limitation of the geometry and orientation of the reconstruction beam by using of the Fraunhofer-approximation (classical version of the digital holography) are removed for the directly implementation of the Fresnel calculations. The practical aspects of the realization of the holographical masks are discussed. The application of the hologram calculation for the opaque masks and the degradation of the image quality were analyzed. The diffraction efficiency of the opaque masks is discussed and summarized.

10092-64, Session PTue

Evaluation of Bessel beam machining for scalable fabrication of conductive channels through diamond

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Scalable methods must be developed for fabricating high-density arrays of conductive microchannels through ~0.5 mm-thick synthetic diamonds in order to form radiation-hard 3D particle tracking detectors for use in future high-energy particle physics experiments, such as those beyond the scheduled 2022 high-luminosity upgrade of the Large Hadron Collider. Prototype detectors with small-area arrays of graphitic columns, each written by slowly translating a femtosecond laser beam focus through the diamond, have established proof of concept, but much faster procedures are needed to manufacture large arrays of electrodes with <100 micron spacing over diameters of ~10 cm. We have used a Bessel beam, formed using a 10 degree axicon and 0.68 NA aspheric lens, to very quickly write micron-diameter columns through ~0.5 mm-thick electronic grade CVD diamonds without axially translating the diamond with respect to the beam. We employ an optical microscope to visualize columns, Raman spectroscopy to ascertain the degree of graphitization, and cat-whisker probes to test

overall conductivity. Bessel focusing enables formation of a complete column with just a few femtosecond laser pulses, and so provides a scalable manufacturing method. However, reduction in the electrode resistivity is desired. To this end, expulsion of material from the column is probably needed, as carbon plasma will otherwise condense back into diamond, due to the disparate densities of graphite and diamond. We describe the use of several different femtosecond laser systems to evaluate a range of pulse parameters with the goal of increasing the level of graphitization and improving the conductivity of the electrodes.

10092-65, Session PTue

Revealing the mechanism of femtosecond laser ablation using multivariate analysis and beam shaping

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Femtosecond laser ablation is a promising and increasingly useful tool for precision materials processing. Its non-thermal process and ability to ablate almost any material are attractive for multiple applications. Despite extensive research, the factors affecting the ablation threshold (minimum fluence required to cause material removal), and the incubation effect (reduction in the ablation threshold for higher numbers of pulses) are not yet completely understood. Here, we present a meta-analysis of ablation threshold and incubation data gathered from over 100 previously published studies. This database also contains common material properties (optical, electrical, thermal, mechanical, etc), and irradiation conditions. Multivariate analysis was used to determine the most important factors affecting the femtosecond ablation threshold and incubation parameter, revealing new insights into the mechanism of this process. We also explore the effects of spatially shaped beams (Bessel, vortex, Gaussian). To quantify the ablation threshold for non-Gaussian beams, a novel ablation threshold measurement technique based on the diagonal scan (D-scan) method was developed and demonstrated on undoped silicon and quartz, using 800 nm, 110 fs pulses at 1 kHz. The most efficient shape was found to be the zero order Bessel beam. This beam generated a 5- to 15-fold improvement in laser micromachining efficiency over that of a Gaussian beam. Significant variations in efficiency were found for different numbers of pulses, attributed to laser-induced defect generation and accumulation. The new knowledge from these approaches provides a path to optimising laser micromachining performance for a wide variety of materials.

10092-66, Session PTue

Laser cutting and drilling with zero conicity

Robert Braunschweig, LASEA (United States); Paul-Etienne Martin, Lasea (France); Axel Kupisiewicz, Lasea (Belgium); Sébastien Estival, Pierre Laygue, Mathieu Dijoux, Lasea (France)

Laser drilling and cutting processes have been well established and controlled in the industry for many years. Ultrashort pulsed lasers have allowed to extend cutting and drilling towards “micro” applications for all type of materials thanks to excellent quality results. This allowed for new markets to open to these laser cutting and drilling, whereas only wire cutting (electro erosion) was giving satisfying results.

However, a main issue always remained with these laser processes: the formation of a conical trench (or a conical hole in case of drilling), meaning the opening width on the input is larger than the one in the output.

The solution in order to compensate for this conicity, also known as clearance angle, is to create an angle between the part and the laser beam throughout the process, which compensates for the natural conicity creation. This movement applied to the laser beam is also called a precession movement.

LASEA will be presenting its brand new patented precession technology, which is applicable either for drilling as well as for cutting. The module presented allows for an increase of cutting speed in order to take advantage of even more laser average power, in the excess of 100W in femtosecond regime, while obtaining drilling or cutting with zero or even negative taper. This is made possible thanks to the unique coupling with a standard scanner module.

We will be presenting the main technology concept of our unique precession module as well as processing samples performed.

10092-67, Session PTue

Reducing graphene-metal contact resistance via laser nano-welding

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Performance of the graphene-based devices is usually limited by the large electrical contact resistance at the graphene-metal junctions. In this work, a laser nano-welding method has been investigated to reduce the graphene-metal contact resistances by improving the carrier injection at the junctions. Laser-induced breakdown of C-C bonds was performed at the edges of graphene-metal contact areas, to facilitate the bonding between the metallic atoms and graphene after the annealing process and, therefore, maximize the carrier transport. It is experimentally proved that the structural defects and open-ended C atoms are formed as a result of the laser irradiation performed at ?=514 nm and moderate power levels of 3 mW. The edge-contacted junctions were then realized by an annealing step that followed the laser nano-welding step. After the laser nano-welding/annealing treatments, a graphene-gold contact resistivity of 4 Ω.μm2 has been achieved, which was only 6% of its pristine value, close to the required values projected by the 2015 International Technology Roadmap for Semiconductors (ITRS 2015). Moreover, the site-selective nature of the proposed laser nano-welding method prevents degradation of the superior electrical properties of the graphene channel which is considered a common limitation in most of approaches proposed for achieving a reproducible low graphene-metal contact resistance.

10092-68, Session PTue

Direct femtosecond laser irradiation of polymeric substrates for high resolution ink-jet printing of conductive lines

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Inkjet printing of conductive inks for flexible electronics is a key technology currently used for applications such as flexible batteries, wearable devices, lighting displays, etc. Its main advantage is the ability to operate in a drop-on-demand mode, thus reducing the cost of inks and enhancing the flexibility of the patterning process. However, this technique still suffers from two major challenges: high-resolution and precision printing. An approach to solve these issues consists on the creation of surface wettability patterns that confine the spreading of ink droplets on a hydrophilic region surrounded by hydrophobic regions. In this field, direct femtosecond laser processing can provide an adequate approach for selective polymer modification.

In this work, polyethylene terephthalate (PET) and polyimide (PI) films of 125 um, two polymers commonly used for ink-jet printing, have been processed with a Ti:Sapphire laser system which generates 130 fs pulses at a central wavelength of 800 nm, with a 1 kHz repetition rate. A study of the formation of surface micro/nanostructures was performed by scanning the selected areas at a constant speed for different laser parameters. These structures have notably increased the surface water and Ag ink wettability. The fabricated polymer surfaces were subsequently used as substrates for ink-jet printing of Ag conductive lines for improving and controlling the ink jet flow in a highly efficient way, giving rise to Ag lines with a resolution five times better than the one for non-treated polymers.

10092-69, Session PTue

Volume modification of sapphire wafers by using bursts of picosecond laser pulses

Mindaugas Gedvilas, Gediminas Ra?iukaitis, Ctr. for Physical Sciences and Technology (Lithuania)

Synthetic sapphire (Al2O3) is the second hardest material just after diamond. It is often used in diverse technical applications and consumer products. The main market for sapphire in the electronic industry today is light emitting diodes (LED) based on GaN epitaxial grown on the sapphire substrate. Sapphire is entering market of mobile phones and is used in manufacturing components with complex geometry by utilizing laser-assisted fabrication.

In this work, volume modification of wafer was performed by irradiation of successions of picosecond laser pulses (bursts). The laser beam with the transverse Gaussian intensity profile was tightly focused inside the volume of sapphire. Laser irradiation source generated bursts of pulses. The number of pulses in the burst was experimentally controlled. The total energy of pulses in the bursts slightly exceeded the energy of the single pulse. The temporal distance between pulses in the burst was of a few tens of nanoseconds. The laser irradiation initiated internal modifications and cracks in the volume of sapphire. The largest transverse and longitudinal modification sizes were achieved by using bursts of 4-7 successive pulses. During such short time span, an electronic system was not able to relax to an equilibrium state. In this way, the e?ect of laser radiation on the material was enhanced, and heat accumulation in the highly localized material area was used for efficient fabrication. The laser fabrication method by using bursts of pulses allows more efficient use of laser energy.

10092-70, Session PTue

In situ observation of ultrafast laser induced micro nano structures using structured light illumination

Alberto Aguilar, Jean-Philippe Colombier, Razvan Stoian, Lab. Hubert Curien (France); Cyril Mauclair, Lab. Hubert Curien (France) and GIE Manutech-USD (France)

The interest of laser-induced micro-nano structurating for surface functionalization is at the core of numerous recent developments in various fields. Ultrafast laser pulses can be used to achieve structuring of surfaces at the micro nano scale. Under certain irradiation conditions, the formation of Laser Induced Periodic Surface Structures (LIPSS or 'ripples') is observed. The LIPSS dimensions range from 100 nm to 2-3 micrometers. The topological characterization is generally conducted ex-situ, after the laser irradiation by systems such as SEM and/or AFM with a resolution beyond the diffraction limit. These measurements require dedicated sample environments that are not easily compatible with other surface modification or characterization set ups - such as laser irradiation for nano-structures generation. Optical techniques have the advantage of non-contact measurements in any environments and are readily applicable for characterization in situ. However, the spatial resolution of regular optical microscopy (~1μm) surpasses the typical size of the most commonly observed laser-induced nano-structures (a few 100nm). In this paper, we use a super resolution microscopy technique based on structured illumination for in-situ observation of the irradiated surface. The achieved resolution is experimentally measured to be 100 nm using USAF targets. The LIPSS formation on stainless steel and Si surfaces is observed IN-SITU in the case of multi-pulse irradiation. In particular, the pulse-to-pulse ripples pattern evolution is investigated for various irradiation conditions, showing different behaviors leading to the permanent LIPSS pattern.

10092-72, Session PTue

Laser shock wave assisted patterning on NiTi shape memory alloy surfaces

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Shape memory alloys (SMAs) are a unique class of smart materials that have become of recent interest in engineering, biomedical and aerospace technologies. Here, we report an advanced direct imprinting method with low cost, quick, and low environmental impact to create thermally controllable surface pattern using laser pulses. Patterned micro indents were generated on NiTi (50-50 %) SMAs using an Nd:YAG laser operating at 1064 nm combined with suitable transparent overlay, a sacrificial layer of graphite, and copper grid. Laser pulses at different energy densities generating pressure pulses up to 10 GPa on the surface was focused through the confinement medium, ablating the copper grid to create plasma and transferring the grid pattern onto the NiTi surface. AFM, SEM and optical microscope images of square pattern with different sizes were obtained. One dimensional profile analysis show that depth of the pattern initially increased linearly until the optical breakdown of the transparent overlay occurs and dense ionized plasma absorbs and reflects the laser beam.

Experimental data is in good agreement with theoretical simulation of laser induced shock wave propagation inside material. Stress wave closely followed the rise time of the laser pulse to its peak values and initial decay. Rapid attenuation and dispersion of stress wave was observed. Ongoing experiments on different wavelength and confinement medium conditions and recovery ratio (ratio of depth of cold indent to the depth of the initial indent) will also be presented.

10092-21, Session 5

Applications of laser-induced periodic surface structures (LIPSS) *(Invited Paper)*

Jörn Bonse, Sabrina V. Kirner, Bundesanstalt für Materialforschung und -prüfung (Germany); Sandra Höhm, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany); Nadja Epperlein, Dirk Spaltmann, Bundesanstalt für Materialforschung und -prüfung (Germany); Arkadi Rosenfeld, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie

(Germany); Jörg Krüger, Bundesanstalt für Materialforschung und -prüfung (Germany)

Laser-induced periodic surface structures (LIPSS, ripples) are a universal phenomenon that can be observed on almost any material after the irradiation by linearly polarized laser beams, particularly when using ultrashort laser pulses with durations in the picosecond to femtosecond range. During the past few years significantly increasing research activities have been reported in the field of LIPSS, since their generation in a single-step process provides a simple way of nanostructuring and surface functionalization towards the control of optical, mechanical or chemical properties. In this contribution current applications of LIPSS are reviewed, including the colorization of technical surfaces, the control of surface wetting, the mimicry of the natural texture of animal integuments, the tailoring of surface colonization by bacterial biofilms, and the improvement of the tribological performance of nanostructured metal surfaces.

10092-22, Session 5

Temporal Airy pulses for controlled high aspect ratio nanomachining of dielectrics: Experiments and simulations *(Invited Paper)*

Thomas Winkler, Nadine Götte, Bastian Zielinski, Cristian Sarpe-Tudoran, Arne Senftleben, Thomas Baumert, Univ. Kassel (Germany)

Understanding the interplay between optical pulse parameters and ultrafast material response is critical in achieving efficient and controlled laser nanomachining. In general, the key to initiate material processing is the deposition of a sufficient energy density within the electronic system. In dielectrics this critical energy density corresponds typically to a plasma frequency in the near infra red spectral region. Creating this density instantaneously with ultrashort laser pulses of few tens of femtoseconds pulse duration in the same spectral region, the penetration depth into the material will strongly decrease with increasing electron density. Consequently, staying below this critical density will allow deep penetration depths. This calls for delayed ionization processes to deposit the energy for processing, thus, introducing the temporal structure of the laser pulses as a control parameter. In this contribution we demonstrate this concept experimentally [1] and substantiate the physical picture by further experiments and numerical calculations [2]. Besides machining of nanophotonic devices in dielectrics, the technique has the potential to enhance laser-based nano-cell surgery and cell poration techniques [3].

1. Götte, N. et al. Temporal Airy pulses for controlled high aspect ratio nanomachining of dielectrics. Optica 3, 389 (2016).

2. Winkler, T. et al. Probing spatial properties of electronic excitation in water after interaction with temporally shaped femtosecond laser pulses. Experiments and simulations. Appl. Surf. Sci. 374, 235–242 (2016).

3. Courvoisier, S. et al. Temporal Airy pulses control cell poration. APL Photonics 1, 46102 (2016).

10092-23, Session 5

Laser direct writing of carbon/Au composite electrodes for high-performance micro-supercapacitors

Jinguang Cai, Tohoku Univ. (Japan) and China Academy of Engineering Physics (China); Akira Watanabe, Tohoku Univ. (Japan); Chao Lv, Institute of Materials, China Academy of Engineering Physics (China) and Tohoku Univ. (Japan)

Recently, the rapid development of miniaturized portable flexible electronic devices has attracted worldwide attention on the micro-energy storage units with high energy and power densities. Micro-supercapacitors (MSCs) are recognized as the potential power supply units for on-chip micro-devices, because of their apparent advantages including high power density, robust cycle performance, maintenance-free features, small size, and flexibility, as well as the simplified packaging processes and compatibility to the integrated circuits. However, the materials and fabrication methods should be cost-effective, scalable, and compatible to current electronic industry. Carbon materials have adaptive properties such as high conductivity, specific surface area, electrochemical stability as well as high mechanical tolerance, making them good candidates for flexible high-performance MSCs. Laser direct writing is a non-contact fast single-step fabrication technique with no requirements for masks, post-processing, and complex clean environments, and can be easily integrated with a current electronic product line for commercial use. In our previous work, high-performance all-solid-state flexible carbon MSCs have been demonstrated by laser direct writing on polyimide film using a low-cost 405nm blue-violet semiconductor laser. However, the carbon electrodes have relatively low conductivity. In this work, in-situ two-step laser direct writing method was employed to fabricate carbon/Au composite electrodes with improved conductivity for high-rate micro-supercapacitors. The resultant typical composite electrodes exhibited a specific capacitance of 1.2 mF/cm2 at a high scan rate of 10,000 mV/s, which is comparable to the MSCs fabricated by pulsed CO2 laser and most of MSCs based on carbon materials even carbon nanotubes and graphene.

10092-24, Session 5

Short pulse fiber laser surface texturing on Ti6Al4V for tribological applications

Harish Vox, L. Vijayaraghavan, Soundarapandian Santhanakrishnan, Indian Institute of Technology Madras (India)

Titanium and its alloys are unique and still remain to be the apex choice for aerospace, marine engineering and medical applications due to their high strength to weight ratio, superior corrosion resistance and enhanced biocompatibility. However, they are often characterized by poor wear resistance and high reactivity towards oxygen which restrict their purpose especially for non-tribological applications. Surface engineering techniques have proven to be the most promising and efficient way to combating the wear of titanium alloys. Laser surface texturing is a state of the art surface modification technique usually deployed to produce tailored micro and nanostructures to enhance their biological (cellular viability), wetting and tribological performances. The aim of this paper is focused at understanding the laser-material interactions with titanium and the effect of geometric patterns on the tribological behavior. Periodic texture patterns of circles, squares and triangles were generated on the sample surface at a pulse width of 25 nano-seconds using a fiber laser (1064 nm). The generated features were characterized by laser confocal microscope and were found to have maximum conformance with original dimensions without losing the geometrical integrity. It was observed that the suitability and flexibility of the fiber laser system with optimal parameters could create patterns more effectively. The wear performance of titanium alloy will be assessed based on the arrangement and distribution of the pattern geometries in different lubrication environments.

10092-25, Session 6

Photonic nano manufacturing of high performance energy device on flexible substrate *(Invited Paper)*

Shutong Wang, The Univ. of Tennessee Knoxville (United States) and Sichuan Univ. (China); Yongchao Yu, Ruozhou Li, The Univ. of Tennessee Knoxville (United States); Chong

Zheng, The Univ. of Tennesee Knoxsville (United States); Delong Ma, The Univ. of Tennessee Knoxsville (United States); Guoying Feng, Sichuan Univ. (China); Anming Hu, The Univ. of Tennessee Knoxville (United States) and Beijing Univ. of Technology (China)

With the developing of wearable electronics and information society, integrated energy storage devices on flexible substrates are urgently demanded. We successfully demonstrated using direct laser-reduction of the hydrated GO and chloroauric acid (HAuCl4) nanocomposite to fabricate in-plane micro-super-capacitors (MSCs) with fast ion diffusion on paper. The electrode conductivities of these flexible MSCs reach up to 1.1 x 106 S m-1, which provide superior rate capability, and large specific capacitances of 0.77 mF cm-2 (17.2 F cm-3 for volumetric capacitance) at 1 V s-1, and 0.46 mF cm-2 (10.2 F cm-3) at 100 V s-1. We also have demonstrated that pulsed laser irradiation rapidly converts the polyimide (PI) sheets into an electrically conductive porous carbon structure in ambient conditions. The specific capacitance of single layer surface super-capacitors can reach 20.4 mF/cm2 at 0.1 mA/cm2 discharge current density. The next, we successfully fabricate the multi-layer super-capacitor with the PI substrate using femtosecond laser the multi-photon effect, and the specific capacitances of double layers and three layers super-capacitors are 37.5 mF/cm2 and 42.8 mF/cm2 , respectively. The current experiment unveiled that this specific capacitance value now sets the upper limit for electrochemical double layers capacitance for all carbon-based super-capacitors. We add some pseudocapacitor electrode material, for example manganese dioxide (MnO2) and sodium vanadium phosphate (NVP), to the polyamic acid (PAA) to synthesis the composite PI sheets. Replacing porous carbon by those pseudocapacitor electrode material, the hybrid supercapacitor fabricated by laser written induces a significant enhancement of performance. This flexible hybrid-capacitor is promising to power portable and wearable electronic devices.

10092-26, Session 6

Investigation of micro-structured Li(Ni1/3Mn1/3Co1/3)O2 cathodes by laser-induced breakdown spectroscopy

Peter Smyrek, Karlsruhe Institute of Technology (Germany) and Karlsruhe Nano Micro Facility (Germany); Yijing Zheng, Jan-Hendric Rakebrandt, Hans Jürgen Seifert, Karlsruhe Institute of Technology (Germany); Wilhelm Pfleging, Karlsruhe Institute of Technology (Germany) and Karlsruhe Nano Micro Facility (Germany)

Lithium-ion batteries are under intense investigation regarding an improvement in cell life-time, cycle stability and high rate capability by simultaneously providing reasonable costs. In industry and application-oriented research, composite thick film cathodes with lithium nickel manganese cobalt oxide Li(NixMnyCoz)O2 (NMC) as active material are currently of main interest. It is commonly recognized that the development of new NMC electrode architectures and the use of innovative manufacturing strategies will provide advanced battery performances. Based on preliminary investigations, three-dimensional (3D) micro-structures such as free standing micro-pillars and micro-capillary structures were generated in Li(Ni1/3Mn1/3Co1/3)O2 cathodes by removing the active material down to the substrate. This rather new technical laser-based approach leads to a significant improvement related to lithium-ion diffusion kinetic and a homogenous and rapid electrolyte wetting. Nevertheless, direct chemical analysis is quite important in order to correlate electrochemical properties with 3D architectures. For this purpose, laser-induced breakdown spectroscopy (LIBS) was used in order to investigate post-mortem the lithium distribution of unstructured and fs laser-structured NMC electrodes at different State-of-Health. LIBS calibration was performed based on NMC electrodes with defined lithium amount. Those samples were produced by titration technique in a voltage window of 3.0 V - 5.0 V. Element mapping and element depth-profiling with a lateral resolution of 100 ?m were applied in order to characterize the whole electrode surface with a foot-print area of 5 cm x 5 cm (pouch cell design). The main goal is to develop an optimized 3D cell design with improved electrochemical properties which can be correlated to a characteristic lithium distribution along 3D micro-structures at different State-of-Health. Results achieved from post-mortem studies of pouch cells with laser-structured and unstructured NMC electrodes will be presented.

10092-27, Session 6

Direct laser interference patterning of metallic sleeves for roll-to-roll hot embossing

Valentin Lang, TU Dresden (Germany) and Fraunhofer IWS Dresden (Germany); Andreas Rank, TU Dresden (Germany); Andrés-Fabián Lasagni, TU Dresden (Germany) and Fraunhofer IWS Dresden (Germany)

Periodic patterns in the micrometer- and sub-micrometer-range on materials surfaces have a significant impact on the matter interactions with its environment. Technological implementation of such patterns proved to enable optimization of mechanical, chemical and biological characteristics of the surfaces. Direct laser interference patterning (DLIP) shows notable eligibility for fabrication of such small-scale periodic surface-patterns, because it unites the feasibility of fabricating features with dimension even below one micrometer with a considerable potential in processing speeds. In recent years optimization of the fabrication speed of DLIP led to values up to 1 m?/min. Further increase of the fabrication speed can be enabled by adding an additional step into the process chain by treating the surface of a tool instead of treating the substrate directly. In detail this strategy can be realized for instance by the combination of DLIP with hot embossing. In this study, we introduce an attempt of structuring nickel sleeves, which are installed in a roll-to-roll hot embossing unit afterwards in order to pattern polymer foils with speeds up to 15 m2/min. The work focuses mainly on the laser interference patterning of the sleeves. The investigations yield insight into the effects of process parameters on pattern characteristics like aspect ratio and homogeneity. Line-like surface architectures are shown with spatial periods between 1.5 μm and 6 μm. For the first time, via DLIP-treatment of a nickel sleeve a seamless roll-to-roll hot embossing process can be realized enabling seamless roll-to-roll processing of polymer foils.

10092-28, Session 7

Producing nanoscale laser spot for heat assisted magnetic recording *(Invited Paper)*

Xianfan Xu, Purdue Univ. (United States)

Heat-assisted magnetic recording (HAMR) has the potential to keep increasing the areal density in next generation hard disc drives (HDDs) by producing a nanoscale laser spot using optical antenna, called near field transducer (NFT) to locally and temporally heat a sub-diffraction-limited region in the recording medium. The NFTs made of plasmonic nanoscale optical antenna provide the capability of sub-wavelength light manipulation at optical frequencies. These antennas are designed using both plasmonic resonance and localized plasmons to produce an enhance field in an area far below the diffraction limit. To reduce the self-heating effect in the NFT, which could cause materials failure that lead to degradation of the overall hard drive performance, the NFT must deliver sufficient power to the recording medium with as small as possible incident laser power. In this talk, the design and characterization of these plasmonic antennas and the effect of optical properties on field localization, absorption and coupling efficiency will be discussed. Computations of heat dissipation and the induced temperature rise in NFT are carried out to study their dependence on materials' properties. With the recent significant interests in searching

for alternative low-loss plasmonic materials in the visible and near infrared range, the possibility of using alternative plasmonic materials for delivering higher power and simultaneously reducing heating in NFT are investigated. NFT characterization using scanning near-field scanning optical microscopy (s-NSOM) will also be discussed.

10092-29, Session 7

Optimized laser marking and cutting using high-speed variable focus scanning *(Invited Paper)*

Craig B. Arnold, Princeton Univ. (United States)

Laser micromachining to mark or dice hard materials such as silicon for photovoltaics or glass for displays requires high accuracy and throughput to meet the stringent manufacturing demands of such high volume applications. In this talk we discuss methods to improve cutting and marking efficiency through the use of high speed variable focal elements. Although x-y scanning of a focused laser beam can be accomplished using a variety of fast methods, control of the z-position of the focal spot has been traditionally limited to slower mechanism. However by employing fast scan methods in z, it is possible to engineer an effective line-focus from a single point source, and in contrast to static beam shaping, such approaches do not redistribute energy to outer regions of the beam profile enabling higher optical throughput and more efficient material removal. We demonstrate this effect using a tunable acoustic gradient index of refraction (TAG Lens) to accomplish high speed z-scanning at rates of greater than 100kHz. We then apply this to hard materials including glass, semiconductors and metals and will discuss the advantages and limitations of such material processing for laser manufacturing.

10092-30, Session 7

Mask-free patterning of high-conductivity gold nanowire in open air by spatially modulated femtosecond laser pulses

Andong Wang, Beijing Institute of Technology (China) and Univ. of Nebraska-Lincoln (United States); Xiaowei Li, Lianti Qu, Beijing Institute of Technology (China); Yongfeng Lu, Univ. of Nebraska-Lincoln (United States); Lan Jiang, Beijing Institute of Technology (China)

Metal nanowire fabrication has drawn tremendous attention in recent years due to its wide application in electronics, optoelectronics, and plasmonics. However, conventional laser fabrication technologies are limited by diffraction limit thus the fabrication resolution cannot meet the increasingly high demand of modern devices. Herein we report on a novel method for high-resolution high-quality metal nanowire fabrication by using Hermite-Gaussian beam to ablate metal thin film. The nanowire is formed due to the intensity valley in the center of the laser beam while the surrounding film is ablated. Arbitrary nanowire can be generated on the substrate by dynamically adjusting the orientation of the intensity valley. This method shows obvious advantages compared to conventional methods. First, the minimum nanowire has a width of ~60 nm (≈1/13 of the laser wavelength), which is much smaller than the diffraction limit. The high resolution is achieved by combining the ultrashort nature of the femtosecond laser and the low thermal conductivity of the thin film. In addition, the fabricated nanowires have good inside qualities. No inner nanopores and particle intervals are generated inside the nanowire, thus endowing the nanowire with good electronic characteristics: the conductivity of the nanowires is as high as 1.2?10^7 S/m (≈1/4 of buck material), and the maximum current density is up to 1.66?10^8 A/m2. Last, the nanowire has a good adhesion to the substrates, which can withstand ultrasonic bath for a long time. These advantages make our method a good approach for high-resolution high-quality nanowire fabrication as a complementary method to conventional lithography methods.

10092-31, Session 7

Formation of porous networks on polymeric surfaces by femtosecond laser micromachining

Youssef Assaf, Anne-Marie Kietzig, McGill Univ. (Canada)

In this study, porous network structures were successfully created on various polymer surfaces by femtosecond laser micromachining. Six different polymers (poly(tetrafluoroethylene) (PTFE), poly(methyl methacrylate) (PMMA), high density poly(ethylene) (HDPE), poly(lactic acid) (PLA), poly(carbonate) (PC), and poly(ethylene terephthalate) (PET)) were machined at different fluences and pulse numbers and the resulting structures were identified and quantitatively compared by lacunarity analysis. At low fluence and pulse numbers, porous networks were confirmed to form on PTFE, HDPE, PET, and PC. However, significant network bundling and deterioration was observed when machining at high fluence and pulse numbers. Operation slightly above threshold fluence and at low pulse numbers is therefore recommended for porous network formation. On the other hand, machining conditions had no effect on microstructure topology for PMMA and PLA. Finally, the thickness over which the microstructures formed was measured and compared to two intrinsic material dependent parameters which were determined by line ablation experiments: the single pulse threshold fluence and the incubation coefficient. Results indicated that a lower threshold fluence at operating conditions favors material removal over structure formation and is thus detrimental to porous network formation. Favorable machining conditions and material dependent parameters for the formation of porous networks on polymer surfaces have thus been identified. Therefore, the ability of femtosecond laser micromachining to induce porosity, enhanced surface area, and dual-scale roughness on polymeric surfaces in a single step process has been established. All of these properties are favorable for cell attachment and growth which makes such surfaces ideal candidates for novel biomaterials.

10092-32, Session 7

Parametric study of laser-induced periodic surface structures on copper

Stella Maragkaki, Andreas Ostendorf, Evgeny L. Gurevich, Ruhr-Univ. Bochum (Germany)

Laser-induced periodic surface structures, or ripples, are periodic modulation of the surface profile upon laser ablation. The formation of LIPSS has gained remarkable attraction due to the fact that it is a single-step process of creating nanostructures on metals, semiconductor or dielectrics. Furthermore, the periodic patterns can be used to provide new enhanced properties and surface functionalities.

Ultrashort laser pulses, at normal incident, can produce periodic surface structures with amplitudes and periodicity in the sub-micrometer regime. However, the physical origin of LIPSS is still under debate. Here, we present the formation of periodic surface structures on a polished copper surface. Nanostructures have been defined by means of LIPSS with periods comparable to the laser wavelength. We study the laser fluence and wavelength dependence to address the dynamics and physical mechanism of LIPSS formation on metals. The influence of both parameters was examined on both the pico-and femtosecond time regime. The surface morphologies obtained are presented by means of scanning electron microspopy. The advantage of ultrashort laser technology together with the parametric investigation of different laser wavelengths enable the determination of the optimum conditions for the better understanding of the underlying mechanisms.

10092-33, Session 7

Selective metallization based on laser direct writing and additive metallization process

Akira Watanabe, Tohoku Univ. (Japan); Jinguang Cai, China Academy of Engineering Physics (China)

A smart city is a concept to integrate multiple information and communication based on Internet of Things technology (IoT). Flexible and wearable devices are key elements in the IoT products. The development of an on-demand production based on printed process is an important issue to reduce the developing period and the cost. In this study, we report the selective metallization on a flexible polymer film based on laser direct writing and the following additive metallization process. Various shaped Cu grid structures were successfully fabricated on a transparent flexible polymer substrate by laser direct writing using a Cu nanoparticle ink, where a CW blue-violet laser was employed as a laser source. A Cu micro-grid on a flexible polymer film attached on a human hand showed the resistance changes responding to the motion, which showed the possibility of the sensing of a human motion. One of the challenging issues in the application of laser written metal micropatterns to interconnection is the insufficient thickness. Cu micro-patterning with 4 micrometer line width and 2 micrometer thickness was achieved by combination of the laser direct writing of a seed micropattern and the following electroplating. The on-demand fabrication of a wireless charging antenna was achieved by laser direct writing of a seed antenna pattern on a polyimide film coated with palladium acetylacetonate-dispersed ethyl cellulose and the following electroless Ni plating. The wireless charging of an in-plane type micro-super capacitor using a commercial Qi wireless charger was demonstrated

10092-34, Session 8

Nonlinear laser lithography: From basic science to applications *(Invited Paper)*

Fatih Ömer Ilday, Bilkent Univ. (Turkey)

Nonlinear Laser Lithography (NLL) allows femtosecond laser-driven, self-organized structuring of materials (Ilday, et al., Nature Photon., 2013). NLL judiciously exploits positive nonlocal feedback between the material and the laser beam to initiate, and negative local feedback to regulate formation of nanostructures with unprecedented uniformity, at high speed, low cost on non-planar or flexible surfaces. Fundamental reason for its long-range order (with subnanometre uniformity in periodicity) is the nonlocal nature of the feedback.

Upon its introduction, several applications of NLL have been demonstrated, e.g., control of tribological, wettability properties of surfaces or structuring of silicon for improved light trapping. Furthermore, NLL is a great model system for a broad class of self-organizing systems, whereby we have shown that geometries of self-organized patterns can be controlled with “structured noise”.

We can now answer an open question of laser-induced periodic structures of why and when nanostructures are generated in parallel or perpendicular to the laser field, both of which have been observed. We explain the physical origins and demonstrate real-time switching between these two modes.

Recently, we have extended NLL to the third dimension by demonstrating self-organized functional 3D superstructures deep inside silicon chips, demonstrating the first in-chip phase-holograms for arbitrary wavefront control, lenses and gratings for beam steering, multilevel, erasable information storage, embedded microfluidic channels for cooling of microchips, through-Si vias for interconnects, microstructures for MEMS applications, slicing of a wafer into microns-thick plates for low-cost Si photovoltaics, and even arbitrary 3D sculpturing of the entire chip.

10092-35, Session 8

Direct laser interference patterning, 20 years of development: From the basics to industrial applications

Andrés-Fabián Lasagni, TU Dresden (Germany) and Fraunhofer IWS Dresden (Germany); Carsten Gachot, Kim E Trinh, Michael Hans, Institute for Functional Materials, Universität des Saarlandes (Germany); Teja Roch, Technische Universität Dresden (Germany) and Fraunhofer-Institut für Werkstoff- und Strahltechnik IWS (Germany); Sebastian Eckhardt, Fraunhofer-Institut für Werkstoff- und Strahltechnik IWS (Germany) and Technische Universität Dresden (Germany); Tim Kunze, Matthias Bieda, Fraunhofer-Institut für Werkstoff- und Strahltechnik IWS (Germany); Denise Günther, Valentin Lang, Technische Universität Dresden (Germany) and Fraunhofer-Institut für Werkstoff- und Strahltechnik IWS (Germany); Frank Mücklich, Institut fuer Neue Materialien, Univ. des Saarlandes (Germany) and Materials Engineering Ctr. Saarland (MECS), Univ. des Saarlandes (Germany)

Starting from a simple concept, transferring the shape of an interference pattern directly to the surface of a material by selective local ablation or modification of the material at the interference maxima positions, the method of Direct Laser Interference Patterning (DLIP) has been continuously developed in the last 20 years.

Starting in the 90s with lamp-pumped solid-state lasers (e.g. Nd:YAG), high power diode-pumped lasers allow today to obtain impressive processing speed even close to 1 m?/min. The objective: to improve the performance of surfaces through the use periodically ordered micro- and nanostructures. This talk describes 20 years of evolution of the DLIP method. From the processing of thin metallic films to hard coatings using nanosecond, picosecond and even femtosecond laser systems, going through different optical setups and industrial systems recently developed. Furthermore, several technological applications are discussed, where the DLIP method has not only shown to provide the required surface properties but also outstanding economical advantages compared to traditional methods. Finally, the first application of this technology in astronautics is introduced: reducing the number of pathogen bacteria at the International Space Station (ISS).

10092-36, Session 8

Line-shaped femtosecond laser pulses for large-area machining *(Invited Paper)*

Satoshi Hasegawa, Yoshio Hayasaki, Utsunomiya Univ. (Japan)

Femtosecond laser pulses formed in a desired spatial pattern by a computer-generated hologram (CGH) displayed on a spatial light modulator (SLM) can perform material laser processing with high throughput and high light-use efficiency. This holographic femtosecond laser processing technique has been applied to two-photon polymerization, optical device fabrications in transparent glass and polymers, cell transfection, and laser cleaning. In addition to the spatial shaping of laser pulses, spatial control of polarization has been applied to surface nanostructuring for control of tribological properties, wettability, reflectance, and retardance.

For wide-area fabrication in realistic applications, a linear beam offers considerably higher processing throughput than an ordinary Gaussian beam, because the total length of the beam scanning is reduced, and consequently the throughput is not restricted by mechanical limits. In addition to these quantitative advantages, line-beam processing has qualitative advantages,

including the absence of artifacts derived from the scanning of a focused beam, as well as less debris, because the direction of the flying debris is parallel to the scanning direction of the beam, and part of the debris is removed by the laser beam itself.

In this presentation, we present the method of designing a computer-generated hologram for producing a line-shaped beam, and the experimental setup. We demonstrated single-shot fabrication of a line structure on a glass surface, a fabrication of retardation property inside a glass, peeling of a thin film, laser grooving of stainless steel, and laser sweeping of debris.

10092-37, Session 8

Ultrashort pulse laser-induced texturing of large area metal surfaces by full exploitation of process parameters: Challenges and perspectives

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Ultrashort pulse (USP) lasers have been extensively utilized as an effective and reliable tool for fabrication of so-called laser-induced periodic surface structures, ripples and micro spikes enabling a tailoring of some key surface properties like wettability, tribology and colour.

Nevertheless, a way to control the structure shape and size and enhance the versatility of the features that can be created on the surface is crucial in order to successfully implement the desired properties.

Here we present a systematic study of the influence of four key parameters on stainless steel surface, carried out using a high power, high repetition rate, industrial femtosecond laser source. In our experiment we vary fluence (0.1 J/cm2 – 1.5 J/cm2), pulse overlap (2-1000 pulses per spot), successive scans (1-1000), and repetition rate (100 kHz – 1MHz) to explore the nanostructure formation under high repetition rate laser irradiation. The results are compared for two wavelengths (1030 nm and 515 nm).

A complete SEM characterization of the treated surface has been carried out to analyse the impact of each of the parameters on the resulting nanostructure. Our data show that the nanostructures' size strongly depends on the wavelength, and that for high repetition rate case the induced nanostructure's final morphology doesn't depend only on the total irradiation dose, but also on the number of scans that it is delivered. Finally, we demonstrate that increasing the number of successive scans leads to a saturation behaviour beyond which the nanostructure morphology doesn't change any more.

We believe that these results represent a significant step ahead for USP lasers in large-scale surface texturing.

10092-38, Session 8

Development of a scanner-based Direct Laser Interference Patterning optical head – new surface structuring opportunities

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Periodic surfaces structures with micrometer or submicrometer resolution produced on the surface of different technological parts can be used to improve their mechanical, biological or optical characteristics. In the last years, important efforts have been made to develop new technologies in order to fabricate tailored surface structures. One of the most promising technologies is direct laser interference patterning (DLIP), a versatile tool for the functionalization of surfaces. In DLIP, a laser beam is split into two or more coherent beams which are guided to interfere on the workpiece surface. The obtained interference pattern introduces modulated laser intensities over the component's surface, enabling the direct fabrication of periodic patterns based on selective laser ablation or melting. Depending on the angle between the laser beams and laser wavelength, the pattern's spatial period can be perfectly controlled.

Nowadays, DLIP high speed concepts already permit structuring speeds of up to 0.9 m?/min (e.g. for bio applications and electrical contacts) under constant process parameters. However, the fabrication of individualized surface structures fabricated "on-the-fly" (e.g. for product counterfeit protection) requires the utilization of flexible machining concepts capable of allowing both, a high flexibility and high performance. In this study, a scanner-based DLIP optical head is presented which combines the flexibility of the DLIP technology with a high-performance galvanometer scanner system. An evaluation of the structuring results and speeds as well as various application examples such as diffraction-based security features will be presented.

10092-39, Session 8

Power and pulse energy scaling for high-volume UV-laser microprocessing

Ralph F. Delmdahl, Oliver Haupt, Igor Bragin, Hans-Stephan Albrecht, Coherent LaserSystems GmbH & Co. KG (Germany)

In industrial laser microprocessing, throughput is as important as is process quality. Treating large areas in minimum time is pivotal in achieving reduced unit costs in high-volume production. Excimer lasers meet the requirements for clean and precise structuring and enable the smallest structures in an efficient way. The latest technical developments in high power excimer lasers is bound to take cost-efficient UV-laser microprocessing to the next level and bridges the gap between achievable precision and achievable throughput. New excimer laser developments and beam concepts together with latest performance data for upscaling both UV power and UV pulse energy will be discussed in this paper against the background of upcoming market trends and high volume applications.

10092-40, Session 9

Surface structuring by single pulse laser interference: Principles and applications *(Invited Paper)*

Johannes Boneberg, Univ. Konstanz (Germany)

A nanosecond laser pulse is split into several beams. These beams are then overlapped on the sample surface. The resulting interference pattern induces surface modifications. It is shown how this interference pattern can be used for the parallel modification of surfaces, e.g. SAMs, catalytic layers, metallic and magnetic thin films. The different mechanisms of the pattering process are discussed.

10092-41, Session 9

High-speed micro-scale laser shock peening using a fiber laser

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Laser shock peening using low-energy nanosecond (ns) fiber lasers was investigated in this study to realize high-speed micro-scale laser shock peening on selected positions without causing surface damage. Due to the employment of a fiber laser with high-frequency and prominent environmental adaptability, the laser peening system is able to work with a much higher speed compared to traditional peening systems using Nd:YAG lasers and is promising for in-situ applications in harsh environments. Detailed surface morphology investigations both on sacrificial coatings and Al alloy surfaces after the fiber laser peening revealed the effects of focal position, pulse duration, peak power density, and impact times. Micro-dent arrays were also obtained with different spot-to-spot distances. Obvious micro-hardness improvement was observed inside the laser-peening-induced microdents after the fiber laser shock peening.

10092-42, Session 9

Femtosecond laser 3D microstructuring of plasmonic nanoparticle doped hybrid polymer

Linas Jonu?auskas, Vilnius Univ. (Lithuania); Marcus Lau, Univ. Duisburg-Essen (Germany); Simonas Varapnickas, Vilnius Univ. (Lithuania); Peter Gruber, Technische Univ. Wien (Austria); Bilal Gökce, Stephan Barcikowski, Univ. Duisburg-Essen (Germany); Aleksandr Ovsianikov, Technische Univ. Wien (Austria); Mangirdas Malinauskas, Vilnius Univ. (Lithuania)

The improvement of materials suitable for rapid processing by applying femtosecond lasers is currently of huge interest in science and technology. In this context, we report on three dimensional laser lithography (3DLL) of a negative silicon/zirconium hybrid photopolymer SZ2080 enhanced by doping with gold nanoparticles (AuNP). 3DLL is performed by a 515 nm, 200 kHz and 300 fs amplified laser system while the Au NP with sizes around ~7 nm are generated by a 1064 nm, 100 kHz and 10 ps laser via pulsed laser ablation in liquids (PLAL). The effect of doping is investigated: by varying the nanoparticle concentration from 4.8e-6 wt% to 9.8e-3 wt% it is found that the fabricated line widths are both, enlarged and diminished. An increase in feature size up to 14.8% is observed when the photopolymer is doped with 3.9e-3 wt% AuNP compared to the structures achieved in pure SZ2080. Explanation for such phenomena is suggested and is based on an interplay of AuNP causing extinction, plasmonic near field enhancement and laser induced nonlinear light-matter interaction. While implicating both, positive and negative effects on the photosensitivity, the doping has no adverse impact on the mechanical quality of intricate 3D microstructures produced from the nanocompound. Additionally, we found that SZ2080 increases the long term (~months) colloidal stability of AuNP in isopropanol. These results promise a simple way of controlling photosensitivity of laser processable materials with low (~e-3 wt%) dopant concentrations which is particularly interesting in the field of ultrafast laser material processing.

10092-43, Session 9

Direct laser interference patterning of transparent and colored polymer substrates: ablation, swelling, and the development of a simulation model

Sabri Alamri, Fraunhofer IWS Dresden (Germany) and TU Dresden (Germany); Andrés Fabián Lasagni, TU Dresden (Germany) and Fraunhofer IWS Dresden (Germany)

It is well known that micro and sub-micrometer periodical structures play a significant role on the properties of a surface. Ranging from friction reduction to the bacterial adhesion control, the modification of the material surface is the key for improving the performance of a device or even creating a completely new function. Among different laser processing techniques, Direct Laser Interference Patterning (DLIP) is one of the most efficient routes for texturing materials up to the nanometer scale with high throughput. It relies on the local surface modification process induced when two or more beams interfere and thus produce periodic surface structures with controllable pitch and geometry. Nevertheless, identical experimental conditions applied to different polymers can result on totally different topologies. The aim of this study is to investigate the general mechanism of DLIP on polymers, taking into account different phenomena involved in the structuring process. In this frame, a new model has been developed taking into consideration experimental observations from pigmented and non-pigmented polycarbonate treated with ultraviolet (263nm) and infrared (1053nm) laser radiation. The polycarbonate material was selected since it exhibits stable and well-defined structures. Depending on the laser processing conditions (e.g. laser wavelength and energy density), the type of material used as well as the spatial period of the produced surface patterns, three different structuring mechanisms were identified. The treated surfaces were investigated using scanning electron microscopy and white light interferometry.

10092-44, Session 10

Pilot-scale synthesis of catalysis-relevant nanoparticles by high-power ultrafast laser ablation in liquids *(Invited Paper)*

Bilal Gökce, René Streubel, Stephan Barcikowski, Univ. Duisburg-Essen (Germany)

Pilot-Scale Synthesis of catalysis-relevant nanoparticles by high-power ultrafast laser ablation in liquids

Pulsed Laser Ablation in Liquids is an innovative method, which is used to obtain colloidal solutions of nanoparticles that show unique properties and are not achievable by conventional synthesis methods. However, this method lacks of key parameters and scaling factors as well as a correlation between these factors and the occurring operating costs.

During the laser driven synthesis cavitation bubbles filled with nanoparticles are formed. These cavitation bubbles along with already dispersed nanoparticles in the solution are the two major factors that limit the energy that can be coupled into the target material by shielding subsequent laser pulses. While the latter shielding effect can be avoided by suitable fluid handling avoiding the former is more difficult due to the lifetime (~100µs) and the size (~100µm) of cavitation bubbles which depend on the laser energy and pulse duration.

In this work we present a strategy to scale up the process by enhancing the productivity of the synthesis. This approach utilizes a MHz-repetition rate laser system consisting of a 500W ps-laser source and a laser scanner that reaches a scanning speed of up to 500m/s. This unique system enables spatial bypassing the cavitation bubble and thereby applying most of the laser energy to the target. By using this system productivities of up to 5 gram per hour are demonstrated in a continuous process.

10092-45, Session 10

High-speed ultrafast laser machining with tertiary beam positioning

Chuan Yang, Haibin Zhang, Electro Scientific Industries, Inc. (United States)

For an industrial laser application, high process throughput and low average cost of ownership are critical to commercial success. Benefiting from high peak power, nonlinear absorption and small-achievable spot size, ultrafast lasers offer advantages of minimal heat affected zone, great taper and sidewall quality, and small via capability that exceeds the limits of their predecessors in via drilling for electronic packaging. In the past decade, ultrafast lasers have both grown in power and reduced in cost. For example, recently, disk and fiber technology have both shown stable operation in the 50W to 200W range, mostly at high repetition rate (beyond 500 kHz) that helps avoid detrimental nonlinear effects.

However, to effectively and efficiently scale the throughput with the fast-growing power capability of the ultrafast lasers while keeping the beneficial laser-material interactions is very challenging, mainly because of the bottleneck imposed by the inertia-related acceleration limit and servo gain bandwidth when only stages and galvanometers are being used. On the other side, inertia-free scanning solutions like acoustic optics and electronic optical deflectors have small scan field, and therefore not suitable for large-panel processing.

Our recent system developments combine stages, galvanometers, and AODs into a coordinated tertiary architecture for high bandwidth and meanwhile large field beam positioning. Synchronized three-level movements allow extremely fast local speed and continuous motion over the whole stage travel range. We present the via drilling results from such ultrafast system with up to 3MHz pulse to pulse random access, enabling high quality low cost ultrafast machining with emerging high average power laser sources.

10092-46, Session 10

Ultra-short pulse laser micro patterning with highest throughput by utilization of a novel multi-beam processing head

Oliver Homburg, Manfred Jarczynski, Thomas Mitra, LIMO Lissotschenko Mikrooptik GmbH (Germany); Stephan Brüning, Schepers GmbH & Co., KG (Germany)

In the last decade much improvement has been achieved for ultra-short pulse lasers with high repetition rates. This laser technology has vastly matured so that it entered a manifold of industrial applications recently compared to mainly scientific use in the past. Compared to ns-pulse ablation ultra-short pulses in the ps- or even fs regime lead to still colder ablation and further reduced heat-affected zones. This is crucial for micro patterning when structure sizes are getting smaller and requirements are getting stronger at the same time. An additional advantage of ultra-fast processing is its applicability to a large variety of materials, e.g. metals and several high bandgap materials like glass and ceramics.

One challenge for ultra-fast micro machining is throughput. The operational capacity of these processes can be maximized by increasing the scan rate or the number of beams – subject parallelism. This contribution focuses on process parallelism of ultra-short pulsed lasers with high repetition rate and individually addressable acousto-optical beam modulation. The core of the multi-beam generation is a smooth diffractive beam splitter component with high uniform spots and negligible loss, and a prismatic array compressor to match beam size and pitch. The optical design and the practical realization of an 8 beam processing head in combination with a high average power single mode ultra-short pulsed laser source are presented as well as the currently on-going and promising laboratory research and micro machining results. Finally, an outlook of scaling the processing head to several tens of beams is given.

10092-47, Session 10

Influence of solvent mixture on the ablation rate of iron using femtosecond laser pulses

Alexander Kanitz, Jan S. Hoppius, Evgeny L. Gurevich, Andreas Ostendorf, Ruhr-Univ. Bochum (Germany)

Ultrashort pulse laser ablation has become a very important industrial method for highly precise material processing with applications ranging from sensitive thin film processing to drilling and cutting of metals. By adding a solvent like water to the process, the quality of cutting edges and the efficiency of the process can be improved. For example, the heat-affected zone width and the re-deposition of debris can be reduced. Additionally, ligand-free nanoparticles with enhanced chemistry can be produced by the re-condensation of nanoparticles into the liquid solvent after the ablation process. Especially the composition of the nanoparticles can be controlled by the use of different solvents. In previous studies it was shown that the used solvent significantly alters the ablation efficiency and quality due to the complex physico-chemical interaction at the substrate-liquid interface. It is assumed that not only the chemical and physical properties as a macroscopic entity play an important role but also microscopic properties, e.g., the molecular structure of the used solvent. In this study, we demonstrate the controllability of the ablation efficiency and quality of iron by using different solvent mixtures of water-ethanol and water-acetone as liquid environment. The ablation efficiency and quality are investigated by means of white-light interferometry, EDX and SEM. We discuss the role of the different molecules as well physical and chemical properties of the solvents and their influence during the process.

10092-48, Session 10

High-speed surface functionalization by direct laser interference patterning

Tobias Dyck, 4JET microtech GmbH und Co. KG (Germany); Andrés-Fabián Lasagni, TU Dresden (Germany) and Fraunhofer IWS (Germany)

The material processing by two or more interfering laser beams, is referred to as Direct Laser Interference Patterning (DLIP). The periodic intensity pattern of the overlapping laser beams is used to ablate or modify the material so a functionalization of the surface is achieved. By adjusting the number, direction, intensity and polarization of the interfering beams, the detailed geometry of the intensity pattern can be shaped and the realizable feature sizes can be continuously adjusted within the micro- and submicrometer range. Consequently, the surface texture can be engineered and tailored to perfectly suit the needs of a given application.

Typical applications of DLIP range from in- and out coupling of light in solar cells or organic LEDs over improvement of tribological properties in engine parts to security markings and decoration applications due to the shimmering effect of the periodic textures. On laboratory scale, an improvement over unprocessed surfaces has been demonstrated in all of these mentioned applications. However, so far the feed rates have not sufficed to allow an industrial application of the technology.

Now, in a joint project of laser manufacturer, optics designer and engineering company, a machine platform has been developed which allows high surface processing speeds in an industrial environment. Feed rates in the range of square meters per minute (corresponding to about one billion features per second) can be achieved. With the help of this platform, DLIP can finally be lifted to industrial application.

10092-49, Session 11

Laser surface preparation for adhesive improvement of Ti6Al4V

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Titanium alloys are generally noticed for their high specific strength and their good corrosion resistance. They are widely used in light-weight structures especially in the aerospace industry. Surface preparation of Ti6Al4V for bonding improvement is conventionally performed by chemical, electrochemical pre-treatments (chromic acid anodisation, phosphate-fluoride, sol-gel,...) and/or sandblasting in order to modify the morphology and the chemistry of the surface. However, these processes produce a large volume of hazardous chemical or abrasive waste. They require high technical efforts and are therefore economically and environmentally inefficient. Laser processes could lead to a good alternative solution in terms of eco-compatibility, repeatability and ease of manufacturing.

In this paper, we report on the latest developments of the collaboration between ALPhANOV and I2M institute on the laser surface preparation for adhesive bonding improvement of Ti-6Al-4V. We focus our investigations on the effect of pulsed laser irradiation (fluence, scan speed and lateral overlap) with a visible (515nm) nanosecond "rod-type fiber" laser on the surface morphology and its bonding behaviour (cohesive or adhesive failure). The penetration of the adhesive in the roughness induced by laser irradiation was characterized. We also assessed the impact of such laser treatments on the mechanical strength of the irradiated substrates.

The surfaces were inspected by different means as optical microscopy, 3D profilometer and scanning electron microscopy (SEM). The adhesion performance of the laser treated surface was evaluated by means of DCB tests.

10092-50, Session 11

High throughput laser texturing of antibacterial surfaces on steel

Laura Gemini, Marc Faucon, ALPhANOV (France); Luca Romoli, Univ. degli Studi di Parma (Italy); Rainer Kling, ALPhANOV (France)

Super-hydrophobic surfaces are of primary interest in applications where self-cleaning and antibacterial behaviors of components and tools are essential. Several physico-chemical techniques already exist to produce such surfaces, as deposition of specific coatings and photolithography. Nevertheless, these multi-step techniques carry intrinsic process limits on geometry and size of the processed surface, as well as long processing takt time. In this context, laser surface texturing has widely demonstrated to be an easy one-step method to produce super-hydrophobic surfaces on several materials. As a consequence of the ultra-fast laser interaction, the surface is textured with nano and micro features (ripples, grooves, bumps and spikes) which in turn define its hydrophobic behavior. In this work, a high average-power (up to 100W), high repetition-rate (up to 4MHz), ultra-short pulse (<1ps) infrared (1030nm) laser is employed to produce super-hydrophobic surfaces on 316L steel. The main goal is to retrieve the set of process and laser parameters for which the super-hydrophobic behavior, together with the process takt time, is optimized. The morphology and composition of the textured surfaces is firstly analyzed by SEM, AFM and EDS analyses. The elemental composition of the surface and the contact angle are measured over time in order to investigate the effect of air environment on the hydrophobic properties. Finally, antibacterial analyses are carried to evaluate the rate of bacterial growth in relation to the super-hydrophobic surface properties.

10092-51, Session 11

Study of TLIPSS formation on different metals and alloys and their selective etching

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Laser micromachining of materials is intensively developed in the last decade in order to change or to provide new features for their surface. From practical point of view, cost-effective technologies of the surface modification with the large area are required. The formation of laser-induced periodic surface structures (LIPSS) appear to be useful for that, since it is based on the self-ordering mechanism when laser radiation is focused in the spot size that is much larger than period of the structures. The formation of new type of LIPSS – thermochemical one (TLIPSS), arising not from ablation, but from metal oxidation process was recently demonstrated. In this case, the surface relief grows up without formation of debris formed by redeposition of ablation products. The aim of the present work is to check a possibility and to define processing parameters (beam size - up to 20 ?m, pulse energy – up to 200 nJ, number of pulses per spot – up to 5*10^5, angle of incident – up to 45°) for high-ordered TLIPSS formation on surfaces of Ti, Cr, Ni, NiCr thin films under fs irradiation (IR and higher harmonics). It was proposed that the TLIPSS formation depends significantly on oxygen diffusion through metal oxide that is the reason of absence of TLIPSS formation on Ni and NiCr with low Cr concentration. Besides TLIPSS formation with period close to the laser wavelength, ablative LIPSS formation with period of ≈?/3 was found. The results of high aspect ratio structures formation under selective etching of TLIPSS are also presented

10092-52, Session 11

Functionalised polyurethane for efficient laser micromachining

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Pulsed laser ablation is a valuable micromachining approach that can offer significant advantages over conventional lithographic techniques. Although significant research has been undertaken on commercially available polymers, many challenges still remain, including contamination by debris on the surface, a rough etched appearance and high ablation thresholds.

Functionalizing polymers with a photosensitive group is a novel way and effective way to improve the efficiency of laser micromachining. In this study, several polyurethane films grafted with different concentrations of the chromophore anthracene have been synthesized that are specifically designed for 248 nm KrF excimer laser ablation. A series of micromachined trenches were created in each polyurethane film with a varied number of pulses and fluences. The resultant ablation features were examined through optical interference tomography and scanning electron microscopy.

The anthracene grafted polyurethanes exhibited a significantly improved edge quality and reduced surface debris compared with the unmodified polyurethane. Under the same laser fluence and number of pulses the spots etched in the anthracene-doped polyurethane show sharp depth profiles and smooth surfaces, whereas the spots etched in the polyurethane without anthracene group grafted present rough cavities with debris according to the SEM images. The addition of a small amount of anthracene (1.47%) shows a reduction in ablation threshold from unmodified polyurethane showing that the desired effect can be achieved with very little modification to the polymer.

10092-71, Session 11

Recoverable stress induced two-way shape memory effect on NiTi surface using laser-produced shock wave

Byron Grant, Selahaddin Gumus, Dovletgeldi Seyitliyev, Orhan Alal, Zachary Thomas, Western Kentucky Univ. (United States)

Shape memory alloys (SMAs) are a unique class of smart materials with the ability to modify their shapes with temperature and stress. SMAs are playing a growing role in supplying key actuation forces and sealing functions in oil and gas, automotive, aerospace and biomedical industries. Their ability to remain elastic under large deformation makes SMAs potential candidates for super-elastic devices in civil structures, and their super elasticity, remarkable corrosion resistance, biological and magnetic resonance compatibility and high bending resistance have already resulted in their implementation in biomedical devices. In this experiment, the surfaces of NiTi (50-50 %) SMAs were patterned by laser shock-assisted direct imprinting. This approach is more simplistic and efficient than traditional indentation techniques, and has also shown to be an effective method in patterning these materials. Different laser energy densities ranging from 5 mJ/pulse to 56 mJ/pulse were used to observe recovery on SMA surface. The temperature dependent heat profiles of the NiTi surfaces after laser scribing at 56mJ/pulse show the partially-recovered indents, which indicate a “two-way shape memory effect (TWSME).” Experimental data is in good agreement with theoretical simulation of laser induced shock wave propagation inside NiTi SMAs. Stress wave closely followed the rise time of the laser pulse to its peak values and initial decay. Further investigations are underway to improve the TWSME such that the indents are recovered to a greater extent.

Monday - Wednesday 30–1 February 2017

Part of Proceedings of SPIE Vol. 10093 Synthesis and Photonics of Nanoscale Materials XIV

10093-1, Session 1

Defect engineering in single layer transition metal dichalcogenides *(Invited Paper)*

Nestor Perea-Lopez, Mauricio Terrones, The Pennsylvania State Univ. (United States)

Single-Layer transition metal dichalcogenides (SL-TMDs) are an emerging family of layered materials that are progressively proving to be an exceptional framework for fundamental science and also have the possibilities for high technological impact applications. Far from idealizations, all SL-TMDs have structural defects in their crystalline lattices, regardless of their synthetic origin. The presence of defects in TMD crystals can have a detrimental or favorable effects on their physico-chemical properties, such effect is evaluated depending on the target application. In this talk we do a comprehensive review defects in SL-TMDs starting with the dimensionality and atomic structure of defects, the synthetic routes leading to defects of each kind and lastly the modification of physico-chemical properties arising from such defects. We believe that a deep understanding of structural defect in SL-TMDs is essential to move forward the field of Defect Engineering because it would enable the control of density, type and distribution of defects. A summary of the progress and the perspectives of this emerging field will be discussed.

10093-2, Session 1

New approaches for synthesis and processing of two-dimensional materials

Masoud Mahjouri-Samani, Christopher M. Rouleau, Alexander A. Puretzky, Gyula Eres, Kai Xiao, Oak Ridge National Lab. (United States); Gerd Duscher, The Univ. of Tennessee Knoxville (United States); Mina Yoon, David B. Geohegan, Oak Ridge National Lab. (United States)

Atomically-thin two-dimensional (2D) metal chalcogenides have emerged as an exciting class of materials which have the potential to enable numerous new applications that range from electronics to photonics. Developing new methods for controlled synthesis and manipulation of these layered materials is crucial for emerging applications in functional devices. Here, we demonstrate non-equilibrium laser-based approaches to form and deliver atoms, cluster or stoichiometric nanoparticles with tunable kinetic energies for the synthesis and processing of 2D layered semiconductors. Utilizing the stoichiometric nanoparticles as feedstocks, we demonstrate the formation of either small domain nanosheet networks (~ 20 nm) or large crystalline domains (~100 μm). On the other hand, atomic precursors with tunable kinetic energies are used in doping, alloying and conversion of 2D monolayers. Patterned arrays of lateral heterojunctions between 2D layered semiconductors, MoSe2/MoS2, are formed by e-beam lithography and selective conversion processes. Moreover, we explore the nonequilibrium, bottom-up synthesis of single crystalline monolayers of MoSe2-x with controllable levels of Se vacancies far beyond intrinsic levels (up to 20 %) exhibiting unique optical and electrical properties. These non-equilibrium laser-based approaches provide unique synthesis and processing opportunities that are not easily accessible through conventional methods.

10093-3, Session 1

Heterostructures of two-dimensional materials and interlayer coupling *(Invited Paper)*

Xi Ling, Boston Univ. (United States)

Large scale integration of atomically thin metals (e.g. graphene), semiconductors (e.g. transition metal dichalcogenides (TMDs)), and insulators (e.g. hexagonal boron nitride) is critical for constructing the building blocks for future nanoelectronics and nanophotonics. Here, we developed a general synthesis methodology to achieve both vertical and in-plane "parallel stitched" heterostructures between a two-dimensional (2D) and TMD materials, which enables both multifunctional electronic/optoelectronic devices and their large scale integration. This is achieved via selective "sowing" of aromatic molecule seeds during the chemical vapor deposition growth. MoS2 is used as a model system to form heterostructures with diverse other 2D materials. Direct and controllable synthesis of large-scale parallel stitched graphene-MoS2 heterostructures was further investigated. Unique nanometer overlapped junctions were obtained at the parallel stitched interface, which are highly desirable both as metal-semiconductor contact and functional devices/systems. Furthermore, optical characterization tools (such as photoluminescence, Raman and absorption spectroscopy) are used to investigate the interlayer coupling in the heterostructures, which offers important guidance for the exploration of the tunability of the functionality of the materials.

10093-4, Session 1

Correlating the optical properties of WS2 monolayers grown by chemical vapor deposition with isoelectronic Mo doping Level

Kai Wang, Oak Ridge National Lab. (United States); Nick Cross, The Univ. of Tennessee Knoxville (United States); Abdelaziz Boulesbaa, Oak Ridge National Lab. (United States); Pushpa R. Pudasaini, Mengkun Tian, The Univ. of Tennessee Knoxville (United States); Masoud Mahjouri-Samani, Mark P. Oxley, Christopher M. Rouleau, Alexander A. Puretzky, Oak Ridge National Lab. (United States); Philip D. Rack, Oak Ridge National Lab. (United States) and The Univ. of Tennessee Knoxville (United States); Kai Xiao, Mina Yoon, Gyula Eres, Gerd Duscher, David B. Geohegan, Oak Ridge National Lab. (United States)

Incorporating dopants in monolayer transition metal dichalcogenides (TMD) can enable manipulations of their electrical and optical properties. Previous attempts in amphoteric doping in monolayer TMDs have proven to be challenging. Here we report the incorporation of molybdenum (Mo) atoms in monolayer WS2 during growth by chemical vapor deposition, and correlate the distribution of Mo atoms with the optical properties including photoluminescence and ultrafast transient absorption dynamics. Dark field scanning transmission electron microscopy imaging quantified the isoelectronic doping of Mo in WS2 and revealed its gradual distribution along a triangular WS2 monolayer crystal, increasing from 0% at the edge to 2% in the center of the triangular WS2 triangular crystals. This agrees well with the Raman spectra data that showed two obvious modes between 360 cm-1 and 400 cm-1 that corresponded to MoS2 in the center. This in-plane gradual distribution of Mo in WS2 was found to account for the spatial variations in photoluminescence intensity and emission energy. Transition absorption spectroscopy further indicated that the incorporation of Mo in

WS2 regulate the amplitude ratio of XA and XB of WS2. The effect of Mo incorporation on the electronic structure of WS2 was further elucidated by density functional theory. Finally, we compared the electrical properties of Mo incorporated and pristine WS2 monolayers by fabricating field-effect transistors. The isoelectronic doping of Mo in WS2 provides an alternative approach to engineer the bandgap and also enriches our understanding the influence of the doping on the excitonic dynamics.

10093-5, Session 2

Extreme manipulation of light-matter interactions in 2D TMDC materials *(Invited Paper)*

Linyou Cao, North Carolina State Univ. (United States)

Two-dimensional (2D) transition metal dichalcogenide (TMDC) materials have the potential to open up a new age of atomic-scale photonics. However, much fundamental of the light-matter interaction of these materials has generally remained to be elusive. The optical response of the materials is very weak due to the atomically thin dimension, which stands as a huge challenge for the device development. Here we present our recent results on engineering the light-matter interaction of 2D TMDC, including absorption, reflection, and emission. We demonstrate that excitonic effects dominate the light-matter interaction of the TMDC materials with layer number less than 5-7. The light absorption of atomically thin TMDC materials (< 4 layers) can be dramatically improved up to >75% for narrowband or broadband incidence like solar radiation. We also demonstrate a giant tunability (> 60%) in the refractive index of 2D TMDC materials by electrical gating. Additionally, we show the light emission efficiency of 2D TMDC materials can be manipulated by substrate effects and intercalated ions.

10093-6, Session 2

Optical signatures of defects in low temperature Raman and photoluminescence spectra of 2D crystals

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Currently, two-dimensional (2D) layered materials are rapidly emerging as a new platform for many potential applications in nanoscale optoelectronics, optics, flexible electronics, energy, etc. Monolayers of 2D crystals [e.g., transition metals dichalcogenides (TMDs)] are basically surface and therefore, their optoelectronic properties are very sensitive to defects and environment including ambient gases and substrates. However, only limited number of studies is devoted to understanding of the effect of defects on their optical properties. It is not clear if the specific defects have their fingerprints in Raman, absorption, and PL spectra. Here, we report measurements of low temperature (4-150K) Raman and photoluminescence (PL) spectra of TMD monolayers (MoSe2, WS2) with variable and controlled concentrations of specific defects, i.e., chalcogenide atom vacancies, to reveal optical signatures of these defects. The defective TMD monolayers were synthesized using our new laser CVD approach. To identify the type of defects and their concentration the 2D crystals were transferred from a substrate to a TEM grid and atomic resolution STEM and EELS measurements were performed. Low temperature Raman and PL mapping were used to understand spatial distribution of the defects within the 2D crystals. The assignment of the observed spectral features in low temperature Raman and PL spectra was supported by ab initio theoretical modeling.

Synthesis science was supported by the U.S. Department of Energy, Office of Science, Basic Energy Sciences (BES), Materials Sciences and Engineering Division. Characterization and computational science at CNMS was supported by the Scientific User Facilities Division, BES.

10093-7, Session 2

Ultrafast charge and energy exchanges at hybrid interfaces involving 2D semiconductors

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Two-dimensional transition metal dichalcogenide (2D-TMD) semiconductors are new class of functional materials with a great promise for optoelectronics. Despite their atomic thickness, they strongly interact with light. This allows 2D-TMDs to become suitable converters of photons into useful electric charges in heterostructures involving 2D-TMDs and metallic nano-plasmonics or semiconductor quantum dots (QDs). In this talk, I will illustrate how femtosecond pump-probe spectroscopy can reveal a sub-45 fs charge transfer at a 2D/QDs heterostructure composed of tungsten disulfide monolayers (2D-WS2) and a single layer of cadmium selenide (CdSe)/zinc sulfide (ZnS) core/shell 0D-QDs. In another heterostructure involving 2D-TMDs and plasmonics, I will describe how plasmons of an array of aluminum (Al) nanoantennas are excited indirectly via energy transfer from photoexcited exciton of 2D-WS2 semiconductor. In particular, femtosecond spectroscopy measurements indicated that the lifetime of the resulting plasmon-induced hot electrons in the Al array continue as long as that of the 2D-WS2 excitons. Conversely, the presence of these excited plasmons almost triples the lifetime of the 2D-WS2 excitons from ~15 to ~44 ps. This exciton-plasmon coupling enabled by such hybrid nanostructures may open new opportunities for optoelectronic applications.

This research was conducted at the Center for Nanophase Materials Sciences, which is a DOE Office of Science User Facility. Synthesis of the two-dimensional materials was supported by the Materials Science and Engineering Division, Office of Basic Energy Sciences, U.S. Department of Energy.

10093-8, Session 2

Pulsed laser vaporization synthesis of boron loaded few layered graphene

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The bulk production of loose graphene flakes and its doped variants are important for energy applications including batteries, fuel cells, and supercapacitors as well as optoelectronic and thermal applications. While laser-based methods have been reported for large-scale synthesis of single-wall carbon nanohorns (SWNHs), similar large-scale production of graphene has not been reported. Here we explored the synthesis of doped few layered

graphene by pulsed laser vaporization (PLV) with the goal of producing an oxidation resistant electrode support for solid acid fuel cells. PLV of graphite with various amounts of boron was carried out in mixtures in either Ar or Ar/H2 at 0.1 MPa at elevated temperatures under conditions typically used for synthesis of SWNHs. Both the addition of hydrogen to the background argon, or the addition of boron to the carbon target, was found to shift the formation of carbon nanohorns to two-dimensional flakes of a new form of few-layer graphene material, with sizes up to microns in dimension as confirmed by XRD and TEM. However, the materials made with boron exhibited superior resistance to carbon corrosion in the solid acid fuel cell and thermal oxidation resistance in air compared to similar product made without boron. Mechanisms for the synthesis and oxidation resistance of these materials will be discussed based upon detailed characterization and modeling.

10093-9, Session 3

Ultra-short laser interactions with nanoparticles in different media: from electromagnetic to thermal and electrostatic effects *(Invited Paper)*

Tatiana E. Itina, Lab. Hubert Curien (France) and Ctr. National de la Recherche Scientifique (France) and Univ. de Lyon (France)

Key issues of the controlled synthesis of nanoparticles and nanostructures, as well as laser-particle interactions are considered in the context of the latest applications appearing in many fields such as photonics, medicine, 3D printing, etc. The results of a multi-physics numerical study of laser interaction with nanoparticles will be presented in the presence of several environments. In particular, attention will be paid to the numerical study of laser interactions with heterogeneous materials (eg. colloidal liquids and/or nanoparticles in a dielectric medium) and the aggregation/sintering/fragmentation processes induced by ultra-short laser pulses.

The first part of the numerical model is based on the use of the approach of finite difference time domain (FDTD) which is then coupled with several additional modules. The second additional module will describe both the heating of the electrons and the subsequent transfer of energy to the matrix, followed by thermomechanical effects and laser-induced material transformations. The set of secondary effects in the materials will be analyzed and correlated to the density of free carriers created and incident energy. In addition, the role of the number of pulses, the frequency and the scanning speed will be explained. Furthermore, simplified prediction equations will be proposed. Based both on the calculation and the available experimental data, we will explain the formation of nanoparticles by lase as well as possibilities of different structure formation.

10093-10, Session 3

Nanoscale integration of a phase-changing oxide into silicon photonic modulators *(Invited Paper)*

Richard F. Haglund Jr., Sharon M. Weiss, Vanderbilt Univ. (United States)

On-chip signal modulation, processing and routing are now largely carried out in hard-wired circuits occupying most of the area of CPU chips, creating speed bottlenecks and increasing thermal loading. We have demonstrated on-chip, all-optical modulation in hybrid silicon-vanadium dioxide (VO2) ring resonators, in which a nanoscale patch of VO2 acts as the switch, driven by the enormous change in index of refraction in the IMT (?n~1.3). In principle, the femtosecond IMT transition time of VO2 enables modulation speeds up to 500 GHz. However, the IMT is accompanied by a structural phase transition (SPT) from a monoclinic (M) to a rutile (R) phase, and nanosecond return to the M phase would reduce modulation frequencies below 1 GHz. Moreover, VO2 is lossy, so that optimizing switching contrast and power consumption simultaneously requires that the VO2 modulator should have lateral dimensions of order 100 nm, about the size of a single grain.

This talk highlights advances in fabrication and performance of ultrafast switching of the nanoscale VO2 thin-film modulator. Studies of ultrafast excitation and relaxation of VO2 confirm the existence of an excited monoclinic phase (mM) with a fast recovery time compatible with Tbps switching. We show how nanoscale modulator design, and particularly optimizing the resonant ring, can achieve power requirements compatible with systems specifications for all-optical modulators, and elaborate on the effects of dopants. Finally, we show how optical switching in the hybrid ring resonator can be achieved using near band-edge pumping of the VO2 nanopatch at wavelengths in the telecommunications band.

10093-11, Session 3

Order from the disorder, hierarchical nanostructures self-assembled from the gas phase: Applications to photonics, photovoltaics, water splitting and smart surfaces *(Invited Paper)*

Fabio Di Fonzo, Istituto Italiano di Tecnologia (Italy)

The assembly of nanoscale building blocks in engineered mesostructures is one of the fundamental goals of nanotechnology. Among the various processes developed to date, self-assembly emerges as one of the most promising, since it relays solely on basic physico-chemical forces. Our research is focused on a new type of self-assembly strategy from the gas-phase: Scattered Ballistic Deposition (SBD). SBD arises from the interaction of a supersonic molecular beam with a static gas and enables the growth of quasi-1D hierarchical mesostructures. Overall, they resemble a forest composed of individual, high aspect-ratio, tree-like structures, assembled from amorphous or crystalline nanoparticles. SBD is a general occurring phenomenon and can be obtained with different vapour or cluster sources. In particular, SBD by Pulsed Laser Deposition is a convenient physical vapor technique that allows the generation of supersonic plasma jets from any inorganic material irrespective of melting temperature, preserving even the most complex stoichiometries. One of the advantages of PLD over other vapour deposition techniques is extremely wide operational pressure range, from UHV to ambient pressure. These characteristics allowed us to develop quasi-1D hierarchical nanostructures from different transition metal oxides, semiconductors and metals. The precise control offered by the SBD-PLD technique over material properties at the nanoscale allowed us to fabricate ultra-thin, high efficiency hierarchical porous photonic crystals with Bragg reflectivity up to 85%.

In this communication we will discuss the application of these materials to solar energy harvesting and storage, stimuli responsive photonic crystals and smart surfaces with digital control of their wettability behaviour.

10093-12, Session 3

Simulation of heating in nanoparticle dispersions by optical absorption

Benjamin C. Olbricht, U.S. Army Research Lab. (United States)

With the proliferation of highly confined, nanophotonic waveguides and laser sources with increasing intensity, the effects of laser heating will begin to greatly impact the materials used in optical applications. In order to better understand the mechanism of laser heating, its timescales, and the dispersion of heat into the material, simulations of nanoparticles in various media are presented.

A generic model to describe a variety of nanoparticle shapes and sizes is desirable to describe complex phenomenon. These particles are dispersed into various solids, liquids, or gases depending on the application. To simulate nanoparticles and their interaction with their host material, the Finite Element Method (FEM) is used. Heat transfer following an absorption event is also described by a parabolic partial differential equation, and transient solutions are generated in response to continuous, pulsed, or modulated laser radiation.

The simplest physical system described by FEM is that of a broadly-absorbing round-shaped nanoparticle dispersed in viscous host fluid or solid. Many experimental and theoretical studies conveniently describe a very similar system: a carbon "black" nanoparticle suspended in water. This material is well-known to exhibit nonlinear behavior when a laser pulse carrying 0.7 J/cm2 is incident on the material. For this process the FEM simulations agree with experimental results to show that a pulse of this fluence is capable of heating the solvent elements adjacent to the nanoparticle to their boiling point. This creates nonlinear scattering which is empirically observed as a nonlinear decrease in the transmitted power at this input fluence.

10093-13, Session 4

In and out of the vapor dome: An odyssey of mixing in an ultrafast world *(Invited Paper)*

Steven M. Yalisove, Keegan J. Schrider, Ben R. Torralva, Univ. of Michigan (United States)

This work shows the relationship of ultrafast laser melting of single and two component metals to the dynamic path the material follows in the density-temperature phase diagram. What is interesting is the fact that with fluence in the range of 0.25 to 1.5 J/cm^2 we can enter and exit the two phase region, where liquid and vapor are in equilibrium, called the vapor dome. By controlling fluence we can force a material to enter the vapor dome (after 10ps) in a way that further cooling (after 20ps) permits it to escape back into the liquid region. The vapor dome contains a spinodal-like region where there is no energetic barrier to nucleation. Materials that enter the vapor dome will exhibit the properties of enhanced mixing and phase separation without any kinetic barrier. Results suggesting both of these phenomena will be presented along with simulations using a plasma - hydrodynamics code (Hyades). The first, time-resolved, result will show the role of the coexistence of vapor bubbles and liquid droplets on the ejection of a thin film of metal. The second, post-mortem, result will show how we can mix W with Ni, stabilizing nanocrystalline grains on a Ni substrate. Further work using immmiscible metal systems will demonstrate the efficacy of ultrafast laser material interaction as a novel processing method for creating new materials as well as probing this interesting region of phase space.

10093-14, Session 4

Process-stable, highly pure nanomaterials by pilot-scale, continuous high-power laser production *(Invited Paper)*

Bilal Gökce, Stephan Barcikowski, Univ. Duisburg-Essen (Germany)

Laser Ablation in Liquids is an innovative method, which is used to obtain colloidal solutions of nanoparticles that show unique properties and are not achievable by conventional synthesis methods. However, this method lacks of key parameters and scaling factors. In this work we present a strategy which utilizes a 500W, 10 MHz ps-laser in combination with a polygon scanner (500m/s) to scale up the process by enhancing the productivity of the synthesis to up to 5 gram per hour in a continuous process.

10093-15, Session 4

Novel approaches in plasmonic biosensing: From bulk to 3D nanoscale architectures

Artem Danilov, Andrei V. Kabashin, Aix-Marseille Univ. (France); Maria Manousidaki, Maria Farsari, Institute of Electronic Structure & Laser, Foundation for Research and Technology-Hellas (Greece); Alexander V. Grigorenko, The Univ. of Manchester (United Kingdom)

We overview our on-going activities on the improvement of physical sensitivity of plasmonic biosensors. Our approach is based on gaining benefit from the employment of both phase and amplitude properties of light, reflected from plasmonic transducer for increased detection limit and wide spectral range in studies of biomolecular interactions between a target analyte and its corresponding receptor. Originally, phase-sensitive biosensing concept was demonstrated in conventional Surface Plasmon Resonance (SPR) geometry using a thin Au film in Kretschmann-Raether arrangement, but the resulting sensitivity had some limitations because of a rough relief of the gold film surface. We then demonstrate the possibility for the extension of this concept to novel nanoscale 2D architectures of designed plasmonic metamaterials in order to further improve the sensitivity of plasmonic biosensing technology. The latter approach also profits from much enhanced electric field in coupled nanostructures exposed to illumination, therefore enabling spectroscopy analysis (Raman, Fluorescence, IR etc) methods to increase sensitivity level (potentially down to single molecule). Another way to extend the possibilities of modern SPR biosensors is to move from 2D geometries into 3D. Here, we explore the transition to 3D plasmon crystal metamaterial nanoarchitecture, which leads to the excitation of a novel plasmon mode, resulting in very high sensitivities in both spectral (>2600 nm/RIU) and phase (>3*10^4 deg. of phase per RIU) interrogations.

10093-16, Session 4

Photoluminescence monitored photocorrosion for metrology of GaAs/AlGaAs heterostructures at the nanoscale

Jan J. Dubowski, Srivatsa Aithal, Univ. de Sherbrooke (Canada)

We have investigated mechanisms of photocorrosion of GaAs/Al0.35Ga0.65As heterostructures immersed in aqueous solutions and excited with above-bandgap radiation. The difference in photocorrosion rates of GaAs and Al0.35Ga0.65As appears weakly dependent on the bandgap energy of these materials. The intensity of an integrated PL signal from GaAs quantum wells or a buried GaAs epitaxial layer is found dominated by the surface states and chemical reactivity of heterostructure surfaces revealed during the photocorrosion process. Under optimized photocorrosion conditions, the method allows to resolve a 1 nm thick GaAs layer sandwiched between Al0,35Ga0.65As layers. We demonstrate that this approach can be used as an inexpensive, and simple room temperature tool for post-growth diagnostics of interface locations in PL emitting quantum wells and other nano-heterostructures.

10093-21, Session PTue

Scattering properties of gold nanoparticles inside a quadrupole ion trap

Anne de Beurs, Sylvianne Roscam Abbing, Utrecht Univ. (Netherlands); Javier Hernandez Rueda, Utrecht Univ. (Netherlands) and Univ. of California, Davis (United States); Dries van Oosten, Utrecht Univ. (Netherlands)

We have studied the scattering properties of trapped gold nanoparticles by employing a quadrupole ion trap, a multi-wavelength laser-based imaging system and Mie theory. The ion trap design is based on a linear Paul trap that makes use of an oscillating electric field. The trap is built inside a vacuum chamber that reaches pressure levels of few Pa. The gold nanoparticles are injected using electrospray ionization.

The scattered light intensity dependence with the polarization state (?) and the wavelength (?) of the incident laser beam was studied by using a superachromatic half-wave plate, three pigtailed laser diodes (642 nm, 785 nm and 852 nm) and an imaging setup. The intensity of the scattered light (Is) by the suspended particles was imaged at an angle of 90º with respect to the beam propagation axis.

We discuss the influence of the characteristics of the nanoparticles (size, shape, optical properties, charge) and the laser parameters (wavelength, polarization) on the scattered light. The Stokes' parameters retrieved from the experimental Is(?,?) curves were compared with calculations based on Mie theory, providing an estimate of the diameter of the trapped gold nanoparticles (The Inverse Problem).

10093-22, Session PTue

Effect of permittivity on periodic nanostructures by femtosecond laser irradiation on Ti plate

Takahiro Ooga, Masahiro Tsukamoto, Yuji Sato, Masayoshi Miyake, Osaka Univ. (Japan)

Titanium (Ti) is one of the most used biomaterials in metals, because of its high corrosion resistance and strength. However, Ti has problems for bioinert, so it is necessary for improving the bioactivity of Ti. Recently, it is known that periodic nanostructures formation by femtosecond laser irradiation is one of the useful method for controlling the cell elongation. Period of periodic nanostructures influences the function of controlling the cell elongation, so it is required for revealing the most suitable period of periodic nanostructures for controlling the cell elongation. However, the period depends on laser wavelength and is about 80 % of wavelength, so previously the method of changing the period was only using laser with different fundamental wavelength or harmonic wave by wavelength conversion. As a result, we could get only discrete and limited period. Now we focus on Surface Plasmon Polariton (SPP) model about forming nanostructures with femtosecond laser. According to this model, period of periodic nanostructures depend on the permittivity of periphery medium on Ti.

In this study, we pressed polyethylene terephthalate (PET) against Ti plate to change the permittivity on Ti surface. Then, we tried to form periodic nanostructures on Ti by femtosecond laser irradiation to interface between Ti and PET. As a result, the period of nanostructures formed under PET medium was about 570 nm. On the other hand, the period of that under air atmosphere was about 600 nm. This result showed the permittivity of periphery medium on Ti influenced the period of periodic nanostructures.

10093-24, Session PTue

An all-optical, in situ diagnostic for large molecule and nanoparticle detection

Alexandros Gerakis, Princeton Plasma Physics Lab., Princeton Univ. (United States); Mikhail N. Shneider, Princeton Univ. (United States); Brentley C. Stratton, Yevgeny Raitses, Princeton Plasma Physics Lab., Princeton Univ. (United States)

We report on the development and application of a new laser diagnostic for the in situ detection of large molecules and nanoparticles. This four wave mixing diagnostic technique relies on the creation of an optical lattice in a medium due to the interaction between polarized particles and intense laser fields. Though this interaction, we can detect the temperature, pressure, relative density, polarizability and speed of sound of a gas and gas mixture. This diagnostic was already successfully demonstrated in atomic and molecular gaseous environments, where the different gas polarizabilities and pressures were successfully measured. We are currently conducting measurements with large molecules and nanoparticles, the results of which will be presented in this meeting.

10093-17, Session 5

Investigation of gold and bimetallic gold/silver nanoparticles in soda-lime-silicate glasses formed by means of excimer laser irradiation

Maximilian Heinz, Manfred Dubiel, Martin-Luther Univ. Halle-Wittenberg (Germany); Jörg Meinertz, Jürgen Ihlemann, Laser-Lab. Göttingen e.V. (Germany); Armin Hoell, Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (Germany)

In this study, plasmonic Au and Au/Ag nanostructures in soda-lime-silicate glasses have been generated by means of ArF-excimer laser irradiation (193 nm) below the ablation threshold of the glass. For this purpose pure and silver/sodium ion-exchanged float glasses have been coated by gold and then irradiated by the laser. The formation of Au and Au/Ag nanoparticles could be verified by the surface plasmon resonances between 420 and 620 nm, which were obtained by optical spectroscopy. Both, pure Au and Ag particles as well as bimetallic Au/Ag nanoparticles, could be observed by means of small angle X-ray scattering experiments. These results demonstrate that such procedures enable the space-selected generation of plasmonic nanostructures in glass surfaces by excimer laser irradiation. Plasmonic Au/Ag nanostructures in glasses show a tunable surface plasmon resonance in a wide range of wavelengths, which allows manifold applications in photonic and optoelectronic devices. Furthermore, due to the very small laser wavelength, arrays and micro patterns of nanoparticles could be generated, which are of great interest for nanoplasmonic applications.

10093-18, Session 6

Femtosecond laser direct writing of polyimide: self-focusing phenomenon and device application *(Invited Paper)*

Shutong Wang, The Univ. of Tennessee Knoxville (United States) and Sichuan Univ. (China); Yongchao Yu, The Univ. of Tennessee Knoxville (United States); Guoying Feng, Sichuan Univ. (China); Anming Hu, The Univ. of Tennessee Knoxville (United States)

We investigated the interaction between femotsecond laser and polyimide with a high repetition femtosecond fiber laser and a precisely motorized 3D stage. We have found that high repetition femtosecond laser pulse train can effectively fabricate double-layer electrical conductive tracks inside a polyimide (PI) sheets by a single-time irradiation. This interaction comprised multi-photon absorption, dissociation of polymer molecules and the thermal accumulation. The experiment unveiled that dual-layer carbonization was a consequence of an inside micro-lens formed instantly as laser was just focused into the inside of polyimide. This micro-lens further focused the subsequent laser pulse to carbonize the polymer through multi-photon excitation, bond breaking and graphite layer reformation and eventually form the second electronic conductive layer. The second conductive layer was generated below the focal point. With the laser irradiating is kept at the same height, the top layer at the focused plane continued to absorb laser energy then carbonized into the conductive layer. We called the process as a kind of self-focusing phenomenon. We study the focus effect of inside microlenses under different laser powers and irradiation times. The gap of double electronic tracks embedded in the polyimide matrix can be adjusted with the laser processing parameters. When the gap is more than 30 micrometer, two conductive layers are electrically insulating. While the gap is smaller than 10 micrometer, two conductive layers are electrically connected. Various applications, such as, supercapacitors, capacitive sensors and the field effect transistors were investigated in the flexible PI sheets using this 3D double-layer electrical conductive architecture.

10093-19, Session 6

Ultrafast laser patterning and defect generation in titania nanotubes for the enhancement of optical and photocatalytic properties

Rakesh Arul, Reece N. Oosterbeek, The Univ. of Auckland (New Zealand) and The Dodd-Walls Ctr. for Photonic and Quantum Technologies (New Zealand) and The MacDiarmid Institute for Advanced Materials and Nanotechnology (New Zealand); Junzhe Dong, Wei Gao, The Univ. of Auckland (New Zealand); M. Cather Simpson, The Univ. of Auckland (New Zealand) and The MacDiarmid Institute for Advanced Materials and Nanotechnology (New Zealand) and The Dodd-Walls Ctr. for Photonic and Quantum Technologies (New Zealand)

Transition metal oxides are well-known photocatalysts for the degradation of environmental pollutants or hydrogen evolution from water. However, wide-bandgap oxides like TiO2 have poor visible light absorption. Approaches like thermal annealing introduce oxygen vacancy defects and increase the visible light absorption, at the cost of reducing the electron-hole separation lifetimes.

High aspect ratio TiO2 nanotubes can be produced using electrochemical anodization of Ti sheets. By patterning the surface of Ti with laser induced periodic surface structures and subsequently anodizing the surface, we can produce arrays of TiO2 nanotubes that organize into ripples, thus acting as a grating to enhance the trapping of visible light. More efficient visible light absorption from structural enhancement will reduce the amount of oxygen vacancies needed to enhance the visible light photocatalytic activity. Hence, the disadvantage of reduced electron-hole separation lifetimes can be avoided.

To pattern the surface, a Ti:sapphire femtosecond pulsed laser (800 nm, 110 fs, 1kHz) was used. Extensive characterization was performed, including scanning electron microscopy, X-ray photoelectron spectroscopy, Raman spectroscopy, UV-Visible spectroscopy, electron paramagnetic resonance spectroscopy, X-ray diffraction, and optical profilometry.

In addition, we investigated the fundamental light-matter interaction process of femtosecond pulsed laser irradiation with amorphous, defective and crystalline titania nanotubes. By annealing TiO2 nanotubes at different temperatures, the defect density could be controlled. Preliminary investigation showed that the threshold fluence for laser ablation drastically changes as the defect density changes, which we attribute to changes in the electronic structure and morphology of the nanotubes.

10093-20, Session 6

Point defect diffusion during ultrafast laser induced lattice instability: High spatial frequency laser induced periodic surface structure formation and selective area oxidation on silicon

Rico S. Cahyadi, Ben R. Torralva, Steven M. Yalisove, Univ. of Michigan (United States)

High Spatial Frequency Laser Induced Periodic Surface Structure (HSFL) has been observed in a wide range of semiconductors. However, its formation and mechanism on silicon has not been well understood. We report the formation of HSFL structures on silicon using a 390 nm femtosecond laser irradiation at 1 kHz repetition rate to specifically access single photon absorption into the L-valley of the Brillouin zone. The HSFL structures form slightly above the single pulse melt threshold and has a characteristic wavelength of 30-50 nm. Low spatial structures are also observed indicative of surface plasmons polaritons (SPP) coupling during irradiation. Our initial hypothesis suggests that the HSFL periodicity may be related to the grating coupled SPP characteristic wavelength. Additionally, mass redistribution during the HSFL formation is linked to the formation of point defects due to the non-thermal lattice instability induced by the ultrafast laser pulse, which is accompanied by band gap collapse phenomenon. Further characterization using atomic force microscopy shows that parts of the structure form above the original material surface.

Below the single pulse melt threshold, tall silicon oxide structures are formed. Post chemical etching, deep periodic pits are exposed indicating selective area oxidation with specific length scales during the irradiation. The structure is mostly porous observed from the etched volume. We speculate that point defect accumulation and diffusion of silicon and oxygen from each subsequent laser pulse contribute largely to the enhanced kinetics of the oxidation reaction, which is consistent with the HSFL formation mechanism.

Conference 10094: Frontiers in Ultrafast Optics: Biomedical, Scientific, and Industrial Applications XVII

Sunday - Thursday 29–2 February 2017

Part of Proceedings of SPIE Vol. 10094 Frontiers in Ultrafast Optics: Biomedical, Scientific, and Industrial Applications XVII

10094-1, Session 1

Photonic crystal fiber-generated coherent supercontinuum for fast stain-free histopathology and intraoperative multiphoton imaging

Haohua Tu, Sixian You, Yi Sun, Darold R. Spillman Jr., Univ. of Illinois at Urbana-Champaign (United States); Partha S. Ray, Zheng Liu M.D., Carle Cancer Ctr., Mills Breast Cancer Institute (United States); Stephen A. Boppart, Univ. of Illinois at Urbana-Champaign (United States)

In contrast to a broadband Ti:sapphire laser that mode locks a continuum of emission and enables broadband biophotonic applications, supercontinuum generation moves the spectral broadening outside the laser cavity into a nonlinear medium, and may thus improve environmental stability and more readily enable clinical translation. Using a photonic crystal fiber for passive spectral broadening, this technique becomes widely accessible from a narrowband fixed-wavelength mode-locked laser. Currently, fiber supercontinuum sources have benefited single-photon biological imaging modalities, including light-sheet or confocal microscopy, diffuse optical tomography, and retinal optical coherence tomography. However, they have not fully benefited multiphoton biological imaging modalities with proven capability for high-resolution label-free molecular imaging. The reason can be attributed to the amplitude/phase noise of fiber supercontinuum, which is amplified from the intrinsic noise of the input laser and responsible for spectral decoherence. This instability deteriorates the performance of multiphoton imaging modalities more than that of single-photon imaging modalities. Building upon a framework of coherent fiber supercontinuum generation, we have avoided this instability or decoherence, and balanced the often conflicting needs to generate strong signal, prevent sample photodamage, minimize background noise, accelerate imaging speed, improve imaging depth, accommodate different modalities, and provide user-friendly operation. Our prototypical platforms have enabled fast stain-free histopathology of fresh tissue in both laboratory and intraoperative settings to discover a wide variety of imaging-based cancer biomarkers, which may reduce the cost and waiting stress associated with disease/cancer diagnosis. A clear path toward intraoperative multiphoton imaging can be envisioned to help pathologists and surgeons improve cancer surgery.

10094-2, Session 1

Fabrication of 3D micro-structured scaffolds by direct laser writing in pre-polymers for in vitro and in vivo studies

Sima Rek?tyt?, Vilnius Univ. (Lithuania); Justinas Ma?iulaitis, Romaldas Ma?iulaitis, Lithuanian Univ. of Health Sciences (Lithuania); Mangirdas Malinauskas, Vilnius Univ. (Lithuania)

Over the last decade DLW (direct laser writing) lithography employing ultrashort-pulsed lasers has become a well-established technique for the creation of custom-made free-form three-dimensional (3D) microscaffolds out of a variety of materials ranging from proteins to biocompatible glasses. Its potential applications for manufacturing a patient specific scaffold seems unlimited in terms of spatial resolution and geometry complexity. However, despite just a few exceptions in which live cells or primitive organisms were encapsulated into a polymer matrix, no demonstration of an in vivo study case of scaffolds generated with the use of such a method was performed so far. Here, we report a preclinical study of 3D artificial ordered-microstructure scaffolds out of hybrid organic-inorganic (HOI) material SZ2080 fabricated using the DLW 3D lithography technique. The created 2.1 ? 2.1 ? 0.21 mm^3 membrane constructs are tested both in vitro by growing isolated allogeneic rabbit chondrocytes (Cho) and in vivo by implanting them directly into rabbit organisms for one, three and six months. An ex vivo histological examination shows that certain pore geometry and the pre-growing of Cho prior to implantation significantly improve the performance of the created 3D scaffolds. The achieved biocompatibility is comparable to the commercially available collagen membranes. The successful outcome of this study supports the idea that hexagonal-pore-shaped HOI microstructured scaffolds in combination with Cho seeding may be successfully implemented for modelling of cartilage tissue engineering as well as offer solution for patient specific injuries.

[1] J. Maciulaitis et al., Preclinical study of SZ2080 material 3D microstructured scaffolds for cartilage tissue engineering made by femtosecond direct laser writing lithography, Biofabrication 7, 015015 (2015).

[2] M. Malinauskas et al., Ultrafast laser processing of materials: from science to industry, Light: Sci. Appl. 5, e16133; (2016).

[3] J. Maciulaitis et al., Characterization of tissue engineered cartilage products: recent developments in advanced therapy, Pharmacol. Res., in press, (2016); 10.1016/j.phrs.2016.02.022

10094-3, Session 1

Fabrication of silver periodic microstructure in hydrogel by femtosecond laser direct writing

Manan Machida, Keio Univ. (Japan); Maria L. Torres-Mapa, Leibniz Univ. Hannover (Germany); Yasutaka Nakajima, Keio Univ. (Japan); Dag Heinemann, Laser Zentrum Hannover e.V. (Germany); Toshihiko Uemura, Keio Univ. (Japan); Alexander Heisterkamp, Leibniz Univ. Hannover (Germany); Mitsuhiro Terakawa, Keio Univ. (Japan)

Hydrogel-based materials have been attracted as promising biocompatible materials owing to their high water retention and flexibility. Novel devices have been proposed with the integration of metal microstructures inside hydrogels. We have demonstrated the fabrication of silver microstructure inside poly (ethylene glycol) diacrylate (PEGDA) hydrogel by femtosecond laser-induced photoreduction. In this study, we investigated the effect of molecular weight of PEGDA on the fabrication of metal microstructures. The shrinkage capability of metal microstructures was dependent on the average molecular weights of PEGDA, which is attributable to the different water contents. PEGDA hydrogel having average molecular weight 20,000 showed higher degree of shrinkage compared to that with 6,000 in molecular weight. Preservation of the desired shape of the metal microstructure after drying depends on the molecular weight and concentration of PEGDA. Under appropriate experimental conditions, the fabricated metal microstructure shrank in size while maintaining its shape. Optical properties of the hydrogel containing the metal structure will also be presented in addition to the fundamental studies on the fabrication.

10094-5, Session 1

Precision resection of lung cancer in a sheep model using ultrashort laser pulses

Rainer J. Beck, Syam P. C. Mohanan, Wojciech S. Gora, Heriot-Watt Univ. (United Kingdom); Chris Cousens, Jeanie Finlayson, Mark P. Dagleish, David Griffiths, Moredun Research Institute (United Kingdom); Jonathan D. Shephard, Heriot-Watt Univ. (United Kingdom)

Recent developments and progress in the delivery of high average power ultrafast laser pulses enables a range of novel minimally invasive surgical procedures. Lung cancer is the leading cause of cancer deaths worldwide and here the resection of lung tumours by means of picosecond laser pulses is presented. This implies a potential alternative to mitigate limitations of existing surgical treatments in terms of precision and collateral thermal damage to the healthy tissue.

Robust process parameters for the laser resection are demonstrated using ovine pulmonary adenocarcinoma (OPA). OPA is a naturally occurring lung cancer of sheep caused by retrovirus infection that has several features in common with some forms of human pulmonary adenocarcinoma, including a similar histological appearance, which makes it ideally suited for this study.

The picosecond laser was operated at a wavelength of 515 nm to resect square cavities from fresh ex-vivo OPA samples using a range of scanning strategies. Process parameters are presented for an efficient ablation of the tumour with clear margins and only minimal collateral damage to the surrounding tissue. The resection depth can be controlled precisely by means of the pulse energy. By adjusting the overlap between successive laser pulses, deliberate heat transfer to the tissue and thermal damage can be achieved. This can be beneficial for on demand haemostasis and laser coagulation.

Overall, the application of ultrafast lasers for the resection of lung tumours has potential to enable significantly improved precision and reduced thermal damage to the surrounding tissue compared to conventional techniques.

10094-6, Session 1

Multiphoton signal increase due to repetition rate doubling in a photonic crystal rod

Ke Wang, Jiexing He, Ping Qiu, Shenzhen Univ. (China)

Multiphoton microscopy (MPM) has benefitted dramatically from the development of fiber-based technology. Among these technologies, soliton self-frequency shift (SSFS) in photonic crystal (PC) rods uniquely combines high soliton energy (~100 nJ) and broad wavelength tuning range (~100 nm). Recently, high-energy, 1700-nm femtosecond pulses generated by SSFS in a PC rod enabled 3-photon microscopy of mouse hippocampus in vivo. Below damage threshold, acquisition speed is proportional to the repetition rate of the laser. Here we demonstrate a technique for increasing the soliton repetition rate in a PC rod. Through polarization division and polarization multiplexing, we can double the repetition rate of the optical solitons generated in a PC rod. The orthogonally polarized solitons have virtually the same spectrum, pulse width and energy. As an application, we demonstrate that compared with single-polarization soliton, imaging signals are increased by two fold in MPM using our technology, corresponding to the repetition rate doubling of the optical solitons. We expect this technology will help increase the imaging speed or signal levels in MPM. Besides, this technology may overcome the signal generation limit due to the maximum available soliton energy from solid-core PC rods.

10094-8, Session 2

Unified model of plasma formation, bubble generation, and shock wave emission in water for femtosecond to nanosecond laser pulses

Xiao-Xuan Liang, Univ. zu Lübeck (Germany) and Xi'an Jiaotong Univ. (China); Sebastian Freidank, Norbert Linz, Univ. zu Lübeck (Germany); Günther Paltauf, Karl-Franzens-Univ. Graz (Austria); Zhenxi Zhang, Xi'an Jiaotong Univ. (China); Alfred Vogel, Univ. zu Lübeck (Germany)

We developed modeling tools for optical breakdown events in water that span various phases reaching from breakdown initiation via solvated electron generation, through laser induced-plasma formation and temperature evolution in the focal spot to the later phases of cavitation bubble dynamics and shock wave emission and applied them to a large parameter space of pulse durations, wavelengths, and pulse energies.

The rate equation model considers the interplay of linear absorption, photoionization, avalanche ionization and recombination, traces thermalization and temperature evolution during the laser pulse, and portrays the role of thermal ionization that becomes relevant for $T > 3000$ K. Modeling of free-electron generation includes recent insights on breakdown initiation in water via multiphoton excitation of valence band electrons into a solvated state at Eini = 6.6 eV followed by up-conversion into the conduction band level that is located at 9.5 eV.

The ability of tracing the temperature evolution enabled us to link the model of laser-induced plasma formation with a hydrodynamic model of plasma-induced pressure evolution and phase transitions that, in turn, traces bubble generation and dynamics as well as shock wave emission. This way, the amount of nonlinear energy deposition in transparent dielectrics and the resulting material modifications can be assessed as a function of incident laser energy. The unified model of plasma formation and bubble dynamics yields an excellent agreement with experimental results over the entire range of investigated pulse durations (femtosecond to nanosecond), wavelengths (UV to IR) and pulse energies.

10094-9, Session 2

Wavelength dependence of femtosecond laser-induced breakdown in water, and implications for laser surgery *(Invited Paper)*

Norbert Linz, Sebastian Freidank, Xiao-Xuan Liang, Alfred Vogel, Univ. zu Lübeck (Germany)

Studying the wavelength dependence of femtosecond optical breakdown in water helps resolving an ongoing controversy on the relative importance of multiphoton, tunneling and avalanche ionization. Measurements of the bubble formation threshold at 50 wavelengths from UV to near-IR revealed a continuous decrease of the irradiance threshold with increasing wavelength. This is indicative for a dominant role of avalanche ionization, which gains strength with wavelength whereas the multiphoton ionization rate decreases.

Fitting data by a model considering breakdown initiation via a solvated electron state yielded an effective Drude electron collision time of 1 fs. Modeling predicts that the threshold continues to decrease up to 1.3 μm but levels out for longer wavelengths. It remains low in the mid IR because wavelength-independent tunneling ionization ensures a constant level of seed electrons for the ionization avalanche even though the influence of multiphoton ionization ceases.

The low breakdown threshold opens promising perspectives for ultrashort-pulsed laser surgery at wavelengths around 1.3 μm and 1.7 μm, which are attractive due to a favorable combination of low scattering and moderate water absorption. The wavelength dependence of the irradiance threshold together with tissue optical data was used to estimate the wavelength dependence of the energy threshold at various cutting depths. For focusing depths up to 200 μm, pulse energies required for surgery are smallest for < 800 nm. However, the energy minimum shifts to wavelengths around 1350 nm for z = 500 μm, and to the region around 1700 nm for z = 1 mm.

10094-10, Session 2

Single cell manipulation utilizing femtosecond laser-induced shock and stress waves *(Invited Paper)*

Yoichiroh Hosokawa, Nara Institute of Science and Technology (Japan)

No Abstract Available

10094-11, Session 2

Ultrafast laser based optical transfection of opsins and non-linear optogenetic stimulation *(Invited Paper)*

Samarendra K. Mohanty, Nanoscope Technologies, LLC (United States)

No Abstract Available

10094-7, Session 3

Laser transfection and optical reprogramming with sub-20fs NIR laser *(Invited Paper)*

Karsten König, Univ. des Saarlandes (Germany)

No Abstract Available

10094-12, Session 3

Reusable titanium nitride plasmonic microstructures for intracellular delivery

Alexander J. Raun, Nabiha Saklayen, Christine M. Zgrabik, Harvard Univ. (United States); Daryl I. Vulis, Harvard School of Engineering and Applied Sciences (United States); Marinna Madrid, Weilu Shen, Evelyn L. Hu, Harvard Univ. (United States); Eric Mazur, Harvard School of Engineering and Applied Sciences (United States)

Efficient drug and biomolecular delivery into cells is an important area of biomedical research. Intracellular delivery relies on porating cell membranes to allow exterior molecules to enter the cell efficiently and viably. Various methods, including optoporation, electroporation, and viral techniques, can deliver molecules to cells, but come with significant drawbacks such as low efficiency, low throughput, and low viability. We present a new laser-based delivery method that uses laser pulses to excite plasmonic, Titanium Nitride (TiN) microstructures for cell poration and offers high efficiency, throughput, and viability. TiN is a promising plasmonic material for laser-based delivery methods due to its high levels of hardness and thermal stability. We fabricate these microstructures by sputtering thin films of TiN on patterned sapphire substrates. We then optimize plasmonic enhancement and stability by investigating different fabrication conditions. We deliver dye molecules, siRNA, and microspheres to cells to quantify poration efficiency and viability by using flow cytometry and by imaging the target cells at defined time intervals post laser irradiation. Additionally, we study temperature effects via simulations and experiments, as well as oxidation of the TiN films over time. We also use scanning electron microscopy (SEM) techniques to study microstructure damage and cell adhesion. Overall, TiN presents a promising opportunity for use as a reusable material in future biomedical devices for intracellular biomolecular delivery and regenerative medicine.

10094-13, Session 3

Intracellular localization of plasmid-DNA on dielectric microsphere-mediated gene transfection using femtosecond laser

Atsuhiro Ishii, Yuki Hiruta, Keio Univ. (Japan); Dag Heinemann, Laser Zentrum Hannover e.V. (Germany); Alexander Heisterkamp, Leibniz Univ. Hannover (Germany) and Leibniz Univ. Hannover (Germany); Hideko Kanazawa, Mitsuhiro Terakawa, Keio Univ. (Japan)

Precise laser processing using micro- or nano particles shows attractive applications in the biomedical field. We investigated the cellular delivery of exogenous molecules by using enhanced optical field excited by the irradiation of femtosecond laser pulse to biodegradable polymer microspheres. In the present study, we demonstrate the delivery of a plasmid-DNA/cationic-liposome complexes into cells. The effects of surface charge of a complex on intracellular behavior of the complexes and gene expression were investigated. As the zeta potential increases, the number of labelled complexes delivered into cytoplasm increased. Interestingly, the gene expression was observed in the cells treated by the laser pulse, while the expression was not obtained for cells without laser irradiation under the same zeta potential. This may be due to the different routes of the delivery in which plasmid-DNA was uptaken via endocytosis in the case of liposome-mediated transfection, while plasmid-DNA was delivered into cytoplasm directly in the case of laser transfection. In addition, the effect of enhanced optical intensity distribution on intracellular localization of complexes and that on gene expression was also investigated by using polystyrene microspheres of different diameters. Although labelled complexes were delivered into cytoplasm in both cases, gene expression was obtained only with large diameter of microspheres under the condition of same enhanced optical intensity, which may be attributable to the Rayleigh length under the microspheres.

10094-14, Session 3

Picosecond opto-acoustics for the remote ultrasonography of single cells with micron resolution *(Invited Paper)*

Maroun Abi Ghanem, Thomas Dehoux, Univ. Bordeaux, I2M, CNRS (France); Marie-Christine Durrieu, Univ. Bordeaux, CBMN, CNRS (France); Bertrand Audoin, Univ. Bordeaux, I2M, CNRS (France)

In this presentation, we report on an inverted pulsed opto-acoustic microscope (iPOM) that that uses fs light pulses to both induce and detect acoustic pulses in the 10 to 100 GHz frequency range. These frequencies allow mapping quantitatively cell structures as thin as 10 nm and resolving the fibrillar details of cells. Using this non-invasive all-optical system, we produce high-resolution images based on mechanical properties as the contrast mechanisms, and we can observe the stiffness and adhesion of single migrating stem cells. The technique should allow transferring the diagnostic and imaging abilities of ultrasonic imaging to the single-cell scale, thus opening new avenues for cell biology and biomaterial sciences.

10094-15, Session 4

Shining light on cells to cure diseases *(Invited Paper)*

Eric Mazur, Harvard School of Engineering and Applied Sciences (United States)

No Abstract Available

10094-16, Session 4

Modeling ultrafast laser-induced nanocavitation around plasmonic nanoparticles

Michel Meunier, Adrien Dagallier, Rémi Lachaine, Christos Boutopoulos, Étienne Boulais, Ecole Polytechnique de Montréal (Canada)

Vapor nanobubbles generated around plasmonic nanoparticles (NPs) by ultrafast laser irradiation are efficient for inducing localized damage to living cells. Killing targeted cancer cells or gene delivery can therefore be envisioned using this new technology [1,2]. The extent of the damage and its non-lethal character are linked to the size of the nanobubble. Precise understanding of the mechanisms leading to bubble formation around plasmonic nanostructures is necessary to optimize the technique. In this presentation, we present a complete model that successfully describes all interactions occurring during the irradiation of plasmonics nanostructures by an ultrafast laser of various pulse widths and fluences.

Nanoavitation is caused by the interplay between heat conduction at the NP-medium interface and non-linear plasmon-enhanced photoionization of a nanoplasma in the near-field [3-5], the former being dominant for in-resonance and the latter for off-resonance irradiation. Modeling of the whole laser-nanoparticle interaction, together with the help of the shadowgraphic imaging and scattering techniques [3-5], give valuable insight on the mechanisms of cavitation at the nanoscale, leading to possible optimization of the nanostructure for bubble-based nanomedicine applications.

1- E. Boulais, R. Lachaine, A. Hatef, and M. Meunier, Journal of Photochemistry and Photobiology C: Photochemistry Reviews 17, 26-49 (2013).

2- E. Bergeron, S. Patskovsky, D. Rioux, and M. Meunier, Nanoscale 7,17836-17847 (2015).

3- E. Boulais, R. Lachaine, and M. Meunier, Nano Letters 12, 4763-4769 (2012).

4- R. Lachaine, E. Boulais, and M. Meunier, ACS Photonics 1, 331-336 (2014).

5- C. Boutopoulos, A. Hatef, M. Fortin-Deschênes, and M. Meunier Nanoscale 7,11758-11765 (2015).

10094-17, Session 4

The effect of femtosecond pulses on nanoparticle-targeted cells in a three-dimensional culture

Limor Minai, Dvir Yelin, Technion-Israel Institute of Technology (Israel)

Numerous studies on the effect of short laser pulses and gold nanoparticles on cells in two-dimensional cultures have demonstrated the potential of phototherapy for damaging cancer cells. Two-dimensional cultures; however, are very different from in vivo environments that are generally much more complex. In an attempt to study the effect of plasmonic femtosecond phototherapy on small solid tumors, breast cancer cells were cultured on a natural extra cellular matrix-based hydrogel (Matrigel) extracted from mouse sarcoma cells. Cells were specifically targeted by gold nanospheres and irradiated with amplified 45 fs pulses at 800 nm wavelength. Cell viability was estimated by staining the cell for necrosis and apoptosis, and by tracking the formation and sustainability of the cell colonies. Initial experimental results reveal that following laser irradiation, cells sustain noticeable damage and the colonies gradually (and consistently) disintegrate over time. The talk will present our experimental system and time-lapse microscopy results, discuss the challenges in plasmonic phototherapy of cancerous cells in three-dimensional cultures, and outline the potential therapeutic processes that could be induced using plasmonic phototherapy.

10094-18, Session 4

Rational design of durable nanoparticles with optimal material, shape and size for ultrafast plasmon-enhanced nanocavitation

Rémi Lachaine, Étienne Boulais, Ecole Polytechnique de Montréal (Canada); Christos Boutopoulos, Univ. of St. Andrews (United Kingdom) and Ecole Polytechnique de Montréal (Canada); David Rioux, Michel Meunier, Ecole Polytechnique de Montréal (Canada)

The recent emergence of plasmonic nanoparticles (NP) has enabled to concentrate light at the nanoscale. At high laser intensity, the plasmonic excitation can result in a nanoplasma around the NP that can trigger a nanocavitation [1]. These nanobubbles can be used as precise nanoscalpels for biomedical applications. This highly nonlinear process is controlled by the NP material, shape and size. There is currently no systematic design approach that enables to engineer the optimized NPs that will not be damaged upon laser irradiation. We thus developed a computational framework to efficiently screen a large library of spherical nanostructures [2].

Using this framework, we were able to define general principles for the design of durable nanoantennas. In the near-infrared (NIR) with wavelength (?), we show that CuNPs, TiNNPs, AgNPs and AuNPs offer similar performance, with optimal diameters ~?/5. In contrast, only AgNPs and AlNPs are appropriate for irradiation in the UV-visible. We also demonstrate that silica-metal nanoshells (NS) have the potential to reduce the bubble generation threshold in the NIR compared to homogeneous NPs, due to their extensive spectral tunability.

AuNS optimized for NIR irradiation have been used to validate our design framework [3]. Using time-resolved bubble spectroscopy, shadowgraphy imaging and electron microscopy, we were able to confirm the particle structural integrity and a cavitation threshold reduction of 51% relative to optimal AuNP. AuNS have also been used to perforate cancer cells with an efficiency of 61%, using 33% less energy compared to AuNP, which demonstrate the use of our design method for biomedical applications.

[1] Boulais, É.; Lachaine, R.; Meunier, M. Plasma Mediated off-Resonance Plasmonic Enhanced Ultrafast Laser-Induced Nanocavitation. Nano Lett. 2012, 12, 4763–4769.

[2] Lachaine, R.; Boulais, É.; Rioux, D.; Boutopoulos, C.; Meunier, M. Computational Design of Durable Spherical Nanoparticles with Optimal Material, Shape and Size for Ultrafast Plasmon-Enhanced Nanocavitation. Prep. 2016.

[3] Lachaine, R.; Boutopoulos, C.; Lajoie, P.-Y.; Boulais, É.; Meunier, M. Rational Design of Plasmonic Nanoparticles for Enhanced Cavitation and Cell Perforation. Nano Lett. 2016, 16, 3187–3194.

10094-19, Session 4

Photothermal gold nanoparticle mediated stimulation of cardiomyocyte beating

Stefan Kalies, Lara Gentemann, Laser Zentrum Hannover e.V. (Germany); Michelle Coffee, Robert Zweigerdt, Medizinische Hochschule Hannover (Germany); Dag Heinemann, Laser Zentrum Hannover e.V. (Germany); Alexander Heisterkamp, Leibniz Univ. Hannover (Germany)

Photothermal manipulation of cells via heating of gold nanoparticles has proven to be an efficient tool for molecular delivery into cells via cell perforation with short laser pulses. We investigated a potential extension of this technique for cell stimulation of cardiomyocytes using a 532 nm and 850 ps laser system and a surface concentration of 0.5 µg/cm? of

200 nm gold nanoparticles. The gold nanoparticles were unspecifically attached to the cardiomyocytes after an incubation period of three hours. The laser irradiation leads to a temperature rise directly at the particles of several hundred degrees K which evokes bubble formation and membrane perforation. We examined the effect of laser based photothermal manipulation at different laser powers, with different calcium concentrations, and for a cardiomyocyte-like cell line (HL1 cells), neonatal rat cardiomyocytes and human embryonic stem cell (hESC)-derived cardiomyocytes. Fast calcium oscillations in HL1 cells were observed in the presence and absence of extracellular calcium and most pronounced in the area next to the laser spot after irradiation. Within the laser spot, in particular high laser powers led to a single rise in calcium over a time period of several seconds. These results were confirmed in stem cell-derived cardiomyocytes. In the presence of normal and high calcium concentrations, the spontaneous contraction frequency increased after laser irradiation in neonatal rat cardiomyocytes. Consequently, gold nanoparticle mediated photothermal cell manipulation via pulsed lasers may serve as a potential pacemaker-technique in regenerative approaches, next to optogenetics.

10094-20, Session 5

Metal micro-additive manufacturing based on parallel femtosecond laser machining and electrodeposition

Dien Wang, Chenyang Wen, Yina Chang, Shih-Chi Chen, The Chinese Univ. of Hong Kong (Hong Kong, China)

In this work, we present a parallel laser machining method using femtosecond lasers for additively printing high precision metal devices via electrodeposition. In recent years, there have been increasing demands for fabricating small-scale 3-D metal devices with complex structures across different fields, e.g., medical, and aerospace industry etc. Although metal additive manufacturing technologies, such as selective laser sintering or selective laser melting, have been around for a while, they lack the precision and throughput to meet the requirements of many emerging applications, e.g., blood vessel stents, microdevices, and ultra-light metal foam.

To achieve parallel laser micromachining, a femtosecond laser amplifier (Spitfire: pulse width 150fs; repetition rate 1 kHz; 800nm) is first projected to a digital micromirror device (DMD), which spatially disperses the spectrum of the laser into different directions. After a collimating lens, an objective lens recombines all the dispersed spectrum to the focal region, forming a high-intensity thin light sheet, i.e., temporal focusing, for micromachining. The patterns on the light sheet can be arbitrarily controlled by the DMD. Preliminarily, we processed a 1 micron thick electrodeposited nickel layer on a substrate with 40 pulses of ~ 50mW. The parallel processing area is 100?60 μm2, determined by the laser power and magnification of objective lenses. Complex 3-D metal structures can be fabricated by repeating the micromachining and electrodeposition processes. Compared with the electrochemical fabrication (EFAB) process, the temporally focused light sheet can simultaneously micromachine and planarize the target with better resolution (~800nm), realizing 3-D metal additive manufacturing.

10094-21, Session 5

High speed ultrafast laser surface processing

Girolamo Mincuzzi, Rainer Kling, John Lopez, ALPhANOV (France); Clemens Hönninger, Eric Audouard, Eric P. Mottay, Amplitude Systèmes (France)

Surface functionalization is a rapidly growing application for industrial ultrafast lasers. There is an increasing interest for high throughput surface processing, especially for texturing and engraving large manufacturing tools for different industrial fields such as injection molding, embossing and printing. Hydrophobic and hydrophilic surfaces, colored or deep black metal surfaces can now be industrially produced. The engraving speed is continuously improving following improvements in beam scanning technology and high average power industrial ultrafast lasers. Several tenths of MHz for the laser repetition rate and several hundreds of meter per second for the beam speed are available. More than 100 m/s scanning speed is then possible for laser surface structuring. But these surfaces are quite hard to produce since it is necessary to have a good compromise between high removal rate and high surface quality (low roughness, burr-free, narrow heat affected zone). In this work, we apply a simple engineering model based on the two temperature description of ultra-fast ablation to estimate key processing parameters. In particular, the pulse-to-pulse overlap which depends on the scanning velocity, the spot size, and the laser repetition rate all have to be adjusted to optimize the depth and roughness, otherwise heat accumulation and heat affected zone may appear. Optimal sequences of time and spatial superposition of pulses are determined and applied with a polygonal scanner. Ablation depth and processing speed obtained are compared with experimental results.

10094-22, Session 5

Beam engineering for zero-conicity cutting and drilling with ultrafast lasers

Amelie Letan, Konstantin Mishchik, Eric Audouard, Clemens Hönninger, Eric P. Mottay, Amplitude Systèmes (France)

With the development of high average power, high repetition rate, industrial ultrafast lasers, it is now possible to achieve a high throughput with femtosecond laser processing, providing that the operating parameters are finely tuned to the application. Femtosecond lasers play a key role in these processes, due to their ability to high quality micro processing. They are able to drill high thickness holes (up to 1 mm) with arbitrary shapes, such as zero-conicity or even inversed taper, but can also perform zero-taper cutting. A clear understanding of all the processing steps necessary to optimize the processing speed is a main challenge for industrial developments. Indeed, the laser parameters are not independent of the beam steering devices. Pulses energy and repetition rate have to be precisely adjusted to the beam angle with the sample, and to the temporal and spatial sequences of pulses superposition. The purpose of the present work is to identify the role of these parameters for high aspect ratio drilling and cutting not only with experimental trials, but also with numerical estimations, using a simple engineering model based on the two temperature description of ultra-fast ablation. Assuming a nonlinear logarithmic response of the materials to ultrafast pulses, each material can be described by only two adjustable parameters. Simple assumptions allow to predict the effect of beam velocity and non-normal incident beams to estimate profile shapes and processing time.

10094-23, Session 5

Development of a dynamic interferometric focusing system for femtosecond laser machining

Marcus Paulo Raele, Lucas R. De Pretto, Ricardo E. Samad, Anderson Z. de Freitas, Wagner de Rossi, Nilson Dias Vieira Junior, Niklaus Ursus Wetter, Instituto de Pesquisas Energéticas e Nucleares (Brazil)

The applications of femtosecond (1 fs = 10^-15s) lasers for machining and surface treatment have been researched for a few decades. Among its advantages are the virtual absence of thermal processes during ablation, resulting in spatial accuracy, and the independence of physical characteristics of the material under treatment (metal or dielectric). The virtual absence of thermal effects in the ablation process with ultrashort pulses implies the possibility of producing machined structures with dimensions close to the diffraction limit for the laser wavelength used. For this, we must use focusing lenses with very short focal length and high numerical aperture. Thus, a precise and dynamic control to overlap confocal region and the surface under treatment is essential. Changes as small as tens of microns in the relative position of the surface treated, either by moving the sample or by its own relief characteristics, are often sufficient to significantly impair the accuracy of machining. Therefore, we present a novel interferometry system that takes advantage of the inherent characteristics of fs laser for evaluation of the focal position with an accuracy of few microns, using a technique based on low coherence interferometry. This approach measures the exact same spot that the laser is machining, in real time, and is sensitive to any sample that acts as a scatterer at the wavelength used. For smooth and tilted surfaces we achieved 98% of the machining within the confocal parameter, as well as 90% for surfaces with discontinuities, in contrast to 29% and 35%, respectively, achieved without the focusing control.

10094-24, Session 5

Analysis of ultrafast material processing using flexible beam delivery

Sebastian Eilzer, Max C. Funck, Björn Wedel, PT Photonic Tools GmbH (Germany)

Flexible beam delivery can significantly simplify the necessary effort to connect a laser source to an application. While already a standard in high power cw-applications, ultrashort pulse applications in the ps to fs regime mainly relies on free space beam delivery to date. In the last years we have introduced and characterized a modular beam delivery system for ultrashort high energy pulses. It is based on micro structured hollow core fibers that confine the light into a hollow core and thereby allow pulse delivery way above the damage threshold of silica with minimal influence on the pulse. Ultrafast pulses with pulse energies of several 100 µJ and average powers of several 100 W can be transmitted with high single mode beam quality. Additionally, nonlinear effects inside the fiber can be actively used to adjust pulse parameters on the fly, e.g. an effective pulse compression which increases the peak power even further.

Here we show the systematic analysis of short pulse material processing using the flexible beam delivery. Results for polarization sensitive processes as well as the active use of nonlinear spectral broadening are shown.

10094-25, Session 6

Ferroelectric domain engineering with ultrafast light *(Invited Paper)*

Wieslaw Z. Krolikowski, The Australian National Univ. (Australia)

No Abstract Available

10094-26, Session 6

Plasmonic coloring of noble metals rendered by picosecond laser exposure

Jean-Michel Guay, Antonino Calà Lesina, Univ. of Ottawa (Canada); Peter G. Gordon, Carleton Univ. (Canada); Joshua Baxter, Univ. of Ottawa (Canada); Seán T. Barry, Carleton Univ. (Canada); Lora Ramunno, Pierre Berini, Arnaud Weck, Univ. of Ottawa (Canada)

We show the angle-independent coloring of metals in air arising from nanoparticle distributions on metal surfaces. Each of the colors is linked to a unique total accumulated fluence, rendering the process compatible with industry. We report the coating of the colored metal surfaces using atomic layer deposition which is shown to preserve colors and provide mechanical and chemical protection. We report on the formation of a full color palette on gold from red to violet using burst laser technology. Laser burst are composed on closely time-spaced pulses separated by 12.8 ns. The coloring of silver using burst versus non-burst is shown to increase the Chroma, or color saturation, by 50% and broaden the color Lightness range by up to 60%. The increase in Chroma and Lightness are accompanied by the creation of 3 kinds of different laser-induced periodic surface structures (LIPSS). One of these structures is measured to be 10 times the wavelength of light and cannot be explained by conventional theories. Two temperature model simulations of laser bursts interacting with the metal surface show significant increase in the electron-phonon coupling responsible for the well-defined LIPSS observed on the surface of silver. Finite-difference time-domain simulations of nanoparticles distributed on the high-spatial frequency LIPSS (HSFL) explain the increase in color saturation (i.e. Chroma of the colors) by the enhanced absorption and enriched plasmon resonances.

10094-27, Session 6

Picosecond laser ablation of polyamide electrospun nanofibers

Marco Götze, Olaf Krimig, Hochschule Merseburg (Germany); Tobias Kürbitz, Hochschule Anhalt (Germany); Sven Henning, Fraunhofer-Institut für Mikrostruktur von Werkstoffen und Systemen (Germany); Andreas Heilmann, Hochschule Anhalt (Germany) and Fraunhofer-Institut für Mikrostruktur von Werkstoffen und Systemen (Germany); Georg Hillrichs, Hochschule Merseburg (Germany)

Electrospun nanofibers mats have a great potential in tissue engineering and regenerative medicine. Their high porosity and enormous volume to surface ratio stimulate the growth and adhesion of mammalian cells and serve as a stable support structure. These suitable properties can be further optimized by structuring of the nanofibers. Ultrashort pulsed lasers can be used for modifying of the electrospun nanofibers without significant heat exposure. It seems also possible to generate very fine cuts from the fiber mats.

In this study, polyamide electrospun nanofibers samples were processed with picosecond uv-laser irradiation (? = 355 nm, ? = 15 ps). The samples were processed in dry, wet and immersed condition. To optimize cutting and structuring of nanofiber tissue flakes, the influence of different laser parameters on line widths, edge quality, heat-affected zone (HAZ) and the contamination of the fibers by ablated particles (debris) were examined. One additional aim was the minimization of the flake size. It was possible to generate nanofiber flakes in the sub-millimeter range. The quality of the nanofiber flakes could be improved by ablation near the ablation threshold of the material. For cutting under wet conditions shrinking of the flakes has to be taken into account .

10094-28, Session 7

Multi-functional laser fabrication in diamond *(Invited Paper)*

Patrick S. Salter, Martin J. Booth, Univ. of Oxford (United Kingdom)

Ultrafast laser fabrication enables micro-structuring of diamond in 3D with a range of functionality. An ultrashort pulsed beam focused beneath the diamond surface induces structural modifications which are highly localised in three dimensions. At high pulse energy, the laser breaks down the diamond lattice at focus to form a graphitic phase. We demonstrate high resolution analysis of the structural changes revealing the graphitic phase to be formed of small clusters (~100 nm in size) of amorphous sp2 bonded carbon accompanied by localised cracking of the diamond. When the laser

focus is traced through the diamond, continuous graphitic wires are created which are electrically conductive. We have used such wires to fabricate large-area 3D radiation sensors which have been employed for the detection of high energy protons. Such graphitic wires have an associated stress field and a related localised modulation of the refractive index. We have recently written combinations of graphitic tracks in diamond to engineer stress fields to give a desired refractive index distribution and form an optical waveguide. Type III waveguides are demonstrated that allow guiding of both polarization states. We also show that by reducing the laser pulse energy, it is possible to avoid complete breakdown of the diamond lattice and simply introduce an ensemble of vacancies within the focal volume. This can be used to create single coherent NV centres in diamond isolated in 3D. All these processes are improved by processing at high numerical aperture (NA), for which adaptive optics aberration correction is essential.

10094-29, Session 7

Control of femtosecond laser interference ejection with angle and polarisation

David M. Roper, Stephen Ho, Peter R. Herman, Univ. of Toronto (Canada)

The nonlinear interactions of femtosecond lasers is driving multiple new application directions for nanopatterning and structuring of thin transparent dielectric films that serve in range of technological fields. Fresnel reflections generated by the film interfaces were recently shown to confine the strong nonlinear interactions at the Fabry-Perot fringe maxima to generate thin nanoscale plasma disks of 20 to 45 nm thickness, stacked on half-wavelength, ?/2nfilm, spacing inside the film (refractive index, nfilm). The resulting phase-explosion and ablation dynamics have resulted in a novel means for intrafilm processing that includes 'quantized' half-wavelength machining steps and formation of blisters with embedded nanocavities.

This paper presents an extension in the control of interferometric laser processing around our past study of SiNx and SiOx thin films at 522nm, 800nm and 1044nm laser wavelengths. The role of laser polarization and incident angle is explored on fringe visibility and improving interferometric processing inside the film to dominate over interface and/or surface ablation. Various combinations of transparent film and substrates were irradiated with femtosecond laser pulses at 0° to 70° angles presented at the film-substrate interface. A significant contrast in the film visibility is reported for p and s polarised light that is promising to improve control and expand the versatility of the technique to a wider range of applications and materials. The research is aimed at creating novel bio-engineered surfaces for cell culture, bacterial studies and regenerative medicine and in creating nanofluidic structures that underpin lab-in-a-film. Similarly, the formation of intrafilm blisters and nanocavities offers new opportunities in structuring existing thin film devices, such as CMOS microelectronics, LED, lab-on-chips and MEMS.

10094-30, Session 7

Femtosecond laser assisted three-dimensional freeform fabrication of electrodes embedded in fused silica

Fatmah Ebrahim, Raphaël Charvet, Cyril Dénéréaz, Andreas Mortensen, Yves Bellouard, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

Femtosecond laser exposure of fused silica combined with chemical etching has opened up new opportunities for three-dimensional freeform processing of micro-structures that can form complex micro-devices of silica, integrating optical, mechanical and/or fluidic functionalities.

Here, we demontrate an expansion of this process with an additional fabrication step that enables the integration of three-dimensional embedded metallic structures out of useful engineering metals such as silver, gold, copper as well as some of their alloys. This additional step is an adaptation of the pressure infiltration for the insertion of high conductivity, high melting point metals and alloys into topologically complex, femtosecond laser-machined cavities in fused silica. This produces truly 3-dimensional microstructures, including microcoils and needles, within the bulk of glass substrates. Combining this added capability with the existing possibilities of femtosecond laser micromachining (i.e. direct written waveguides, microchannels, resonators, etc.) opens up a host of potential applications for the contactless fabrication of highly integrated monolithic devices that include conductive element of all kind.

We present preliminary results from this new fabrication process, including prototype devices that incorporate 3D electrodes with aspect ratios of 1:100 and a feature size resolution down to 2 ?m. We demonstrate the generation of high electric field gradients (of the order of 1013 Vm-2) in these devices due to the 3-dimensional topology of fabricated microstructures.

10094-31, Session 7

Towards optical quality micro-optic fabrication by direct laser writing and chemical etching

Calum Ross, David G. MacLachlan, Debaditya Choudhury, Robert R. Thomson, Heriot-Watt Univ. (United Kingdom)

Here we demonstrate the use of an advanced laser manufacturing technique, known as ultrafast laser inscription (ULI), for the fabrication of pre-aligned, freeform micro-optic systems. ULI is an advanced laser micromachining tool which relies on the high peak intensities associated with focused femtosecond pulses of light to locally modify the structure of a dielectric material. One manifestation of this modification is that the etch rate of the modified regions can be increased by between two and three orders of magnitude compared to the pristine material, depending on the specific ULI parameters and the chemical etchant used. This capability means that ULI facilitate the repeatable production of three dimensional freeform structures in glass with micrometre sized feature resolution. At the conference, we will present the results of investigations aimed at optimising the fabrication process. We will also demonstrate the characterisation of microlenses fabricated in this way, including measurements of the lens surface profile, surface roughness, focal length, and throughput, both with and without post-manufacture flame polishing. Finally, we demonstrate a simple integrated optical device for collimating light emerging from an optical fibre, which bypasses the usual requirement for manual alignment.

10094-32, Session 7

Monolithically integrated micro-fluidic channels for silicon chip cooling

Ahmet Turnali, Onur Tokel, Bilkent Univ. (Turkey); Tahir Colakoglu, Mona Zolfaghari, Middle East Technical Univ. (Turkey); Ihor Pavlov, Bilkent Univ. (Turkey); Alpan Bek, Rasit Turan, Middle East Technical Univ. (Turkey); Fatih Ömer Ilday, Bilkent Univ. (Turkey)

The main challenge in scaling microprocessor sizes and increasing clock rates is due to limitations in removing the excess heat. Due to this problem, the electronics industry is forced to abandon Moore's law. Available chip cooling methods are based on air and liquid cooling, and rely on cooling fans, heat sinks and metallic cooling plates, which unavoidably reduce heat-removal efficiency and add unwanted thermal resistance. In order to overcome these problems, microfluidic chip cooling approaches are emerging, which exploit microchannels positioned on chip surfaces.

Here, we report a laser-based method, which enables the fabrication of microfluidic channels embedded deep inside silicon chips. The method relies on a recent advance we have shown, which allows for the creation of controllable modifications inside silicon wafers. The laser modified subsurface areas are then etched away with a custom-designed chemical etchant to create the microfluidic channels. This allows fabricating microchannels directly below the surface (and inside the chip), which are used to show the first monolithically-cooled wafers with truly embedded channels.

We exploit the nonlinear self-interaction of laser pulses to create structural changes in the bulk of silicon. The dimensions of these structures depends on the number of laser pulses, details of the nonlinear interaction, and the exposure time, which allows creating controlled 3D subsurface patterns. The microchannels carrying liquid coolant have been shown to experimentally cool silicon wafers. We believe this is a disruptive approach that can facilitate multi-level integration of chips, chip miniaturization and increased clock rates.

10094-33, Session 8

The art of ultrafast laser writing *(Invited Paper)*

Peter G. Kazansky, Univ. of Southampton (United Kingdom)

No Abstract Available

10094-34, Session 8

Effects of space-time couplings during interactions of ultrashort pulses with transparent media

Yagiz Morova, Berna Yalizay, Istanbul Technical Univ. (Turkey); Nadezhda M. Bulgakova, HiLASE Ctr. (Czech Republic) and Institute of Thermophysics (Russian Federation); Vladimir P. Zhukov, Institute of Computational Technologies (Russian Federation) and Novosibirsk State Technical Univ. (Russian Federation); Selcuk Akturk, Istanbul Technical Univ. (Turkey)

Spatio – temporal couplings (STC) in femtosecond laser pulses can have distinct physical effects on their nonlinear optical interactions with transparent media. One of the most primary and commonly observed effects is directional dependence of laser-writing process. It is observed by several research groups that when ultrashort laser pulses exhibit pulse-front tilt (PFT), the permanent modifications generated in the bulk of transparent materials exhibit different morphologies, depending on the writing direction and laser polarization.

On the other hand, the physical origin of the dependence of material modifications on STC are still unclear and much debated. The matters are further complicated by the fact that there are several distinct STC, happening in the intensity and phase of the laser pulses. Furthermore, the couplings continuously evolve as the beam approaches focus.

In this work, we present an experimental approach where we introduce STC in a controllable manner. By independently controlling temporal-only and spatio-temporal properties of the laser pulse, we were able obtain various distinct intensity profiles in the focal region. We than perform glass modification with these pulses and observe the relations between the couplings introduced and corresponding changes in glass modification behavior.

Finally, we also perform Maxwell's equations – based simulations to better understand the broken symmetries with STC and explain the origin of our observations. We observe that, it is possible to imprint asymmetries resulting from STC to the distribution of nonlinear absorption around the focus, which than translates into permanent modifications.

10094-35, Session 8

Manipulating femtosecond laser interactions in bulk glass and thin-film with spatial light modulation

Ehsan Alimohammadian, Stephen Ho, Erden Ertorer, Sebastian Gherghe, Jianzhao Li, Peter R. Herman, Univ. of Toronto (Canada)

Spatial Light Modulators (SLM) are emerging as a power tool for laser beam shaping whereby digitally addressed phase shifts can impose computer-generated hologram patterns on incoming laser light. SLM provide several additional advantages with ultrashort-pulsed lasers in controlling the shape of both surface and internal interactions with materials. Inside transparent materials, nonlinear optical effects can confine strong absorption only to the focal volume, extend dissipation over long filament tracks, or reach below diffraction-limited spot sizes. Hence, SLM beam shaping has been widely adopted for laser material processing applications that include parallel structuring, filamentation, fiber Bragg grating formation and optical aberration correction.

This paper reports on a range of SLM applications we have studied in femtosecond processing of transparent glasses and thin films. Laser phase-fronts were tailored by the SLM to compensate for spherical surface aberration, and to further address the nonlinear interactions that interplay between Kerr-lens self-focusing and plasma defocusing effects over shallow and deep focusing inside the glass. Limits of strong and weak focusing were examined around the respective formation of low-loss optical waveguides and long uniform filament tracks. Further, we have employed the SLM for beam patterning inside thin film, exploring the limits of phase noise, resolution and fringe contrast during interferometric intra-film structuring.

Femtosecond laser pulses of 200 fs pulse duration and 515 nm wavelength were shaped by a phase-only LCOS-SLM (Hamamatsu X10468-04). By imposing radial phase profiles, axicon, grating and beam splitting gratings, volume shape control of filament diameter, length, and uniformity as well as simultaneous formation of multiple filaments has been demonstrated. Similarly, competing effects of spherical surface aberration, self-focusing, and plasma de-focusing were studied and delineated to enable formation of low-loss optical waveguides over shallow and deep focusing conditions.

Lastly, SLM beam shaping has been successfully extended to interferometric processing inside thin transparent film, enabling the arbitrary formation of uniform or non-uniform, symmetric or asymmetric patterns of flexible shape on nano-scale dimensions without phase-noise degradation by the SLM patterning. We present quantized structuring of thin films by a single laser pulse, demonstrating ?/2nfilm layer ejection control, blister formation, nano-cavities, and film colouring. Closed intra-film nanochannels with high aspect ratio (20:1) have been formed inside 3.5 um thick silica, opening new prospects for sub-cellular studies and lab-in-film concepts that integrate on CMOS silicon technologies.

10094-36, Session 8

Non-ablative femtosecond laser exposure of fused silica in the sub-50 fs regime

Erica K. Block, Ben W. McMillen, Ecole Polytechnique Fédérale de Lausanne (Switzerland); Julien Nillon, Clemens Hönninger, Amplitude Systèmes (France); Yves Bellouard, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

In the non-ablative regime, femtosecond laser pulse duration is known to affect the nature of the modification induced in the microstructure of fused silica. It has been demonstrated than below 200 fs, two different regimes are found, one at low energy, leading to bulk densification while the second one – for higher energy, leading to self-organized structure - nicknamed nanogratings - that induce a net and localized volume expansion

of the material. The first regime is particularly interesting for waveguides fabrication, although, so far, the reported refractive index gain remains modest, typically within 10-3 relative net increase that limits the level of compactness for photonics circuits making use of it. Here, we investigate further how shorter pulses, i.e. in the sub-50 fs range, can increase the level of densification and in turn, the net refractive index gain, and possibly lead to an improve process for photonics device fabrication. First results show that indeed, higher level of densification can be obtained, level that we quantify, and that can be further correlated to a net increase of refractive index.

10094-37, Session 8

Ultrashort pulse laser welding of glasses without optical contacting

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Stable bonding of glass is of great industrial interest due to its potential applications in fields such as optics, microfluidics, optofluidics and precision machinery. A promising technique is the application of ultrashort laser pulses at high repetition rates in order to achieve heat accumulation of successive pulses and to locally melt the focal volume as well as the surrounding material. Using a fiber-based ultrahort pulse laser system by TRUMPF we were able to maximize the size of the molten volume in order to generate a large pool of molten material with a length of up to 450 µm and a diameter of around 160 µm. To this end, we used bursts of ultrashort laser pulses with an individual pulse energy of up to 10 µJ, effectively multiplied by the number of intraburst pulses. If the laser focus is placed near the surface of a glass sample the low viscosity of the material induces bulging of the surface and ejection of the molten material. This molten material can be used to fill a gap between two samples enabling successful laser welding.

Thus, one can realize strong bonds between two glasses without previously optically contacting the samples. In our experiments we were able to bridge gaps of up to 3 µm between fused silica samples. We also determined the breaking strength by a three-point bending test. The determined value of up to 73 MPa is equivalent to 85 % of the stability of the pristine bulk material.

10094-38, Session 8

Fabrication of low loss waveguide using fundamental light of Yb-based femtosecond laser

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Laser direct writing of optical devices and circuits is attracted attention because of its ability of three-dimensional fabrication without any mask[1]. Recently, Yb-fiber or solid-state laser has been commonly used for fabrication in addition to traditional Ti:S laser. However, it is reported that waveguide cannot be fabricated in fused silica by using the fundamental light from Yb-based femtosecond laser[2]. Some groups reported on waveguide fabrication by using second-harmonic beam of such lasers[3], but wavelength conversion using nonlinear process has drawbacks such as destabilization of laser power and beam deformation by walk off.

In this study, we investigated fabrication of low-loss waveguide in fused silica by using the fundamental beam (1030nm) from an Yb solid-state femtosecond laser with a pulse duration of 250 fs. The NA of focusing objective lens was 0.42. The fabricated waveguide was made to have a circular cross-section by shaping laser beam with a slit[4]. We fixed repetition rate to 150 kHz, and identified appropriate scan speed and pulse energy for fabrication of low loss waveguide. Waveguide fabricated with appropriate condition had a propagation loss of 0.2 dB/cm, and this is the first report on optical waveguides in a fused silica fabricated by femto-second laser pulses at a wavelength of 1030nm.

[1]K. M. Davis, et. al., Opt. Lett 21, 1729(1996)

[2]J. Canning, et. al., Opt. Mater. Express 1, 998(2011)

[3]L. Shah, et. al., Opt. Express 13, 1999(2005)

[4]M. Ams, et. al., Opt. Express 13, 5676(2005)

10094-39, Session 9

Femtosecond laser written Bragg gratings: Novel devices and applications *(Invited Paper)*

Michael J. Withford, Macquarie Univ. (Australia)

No Abstract Available

10094-40, Session 9

Femtosecond laser direct-write of optofluidics in polymer-coated optical fiber

Kevin A. J. Joseph, Moez Haque, Stephen Ho, Stewart J. Aitchison, Peter R. Herman, Univ. of Toronto (Canada)

Optofluidic lab-on-chip (LOC) technology, the miniaturization and integration of multiple biological and chemical processes onto a single chip, has been a hallmark of nanotechnology research for over thirty-five years. While it has led to an array of promising applications, deploying and monitoring LOC can be challenging over vast, expansive systems such as municipal water supplies, and in tightly confined and sinuous spaces such as human blood vessels. Silica fiber is a ubiquitous optical platform which has already been deployed over billions of kilometers worldwide. Translating fluidic LOC technology to fiber allows for devices which can take advantage of the fiber's low loss, robustness, and flexibility, and that can be seamlessly integrated into existing fiber-optic networks or confined environments.

Lab-in-fiber (LIF) technology is made possible through femtosecond-pulse driven nonlinear modifications that provide highly localized refractive index change and volume nanogratings. In this way, femtosecond-laser direct writing enables highly flexible, rapidly prototypeable 3D optical waveguides to form and efficiently connect with the pre-existing core waveguide to provide fiber-cladding photonics. Additionally, differential chemical etching of the nanograting tracks provides new means to form optical resonators, microfluidic channels and MEMS structures that can be further integrated with the 3D optical circuits to open a broad base of new in-fiber microsystems for optofluidic analysis, in-fiber cytometry, biomedical catheters, and telecommunication applications.

A limitation to these LIF approaches thus far is the increased processing time and reduced fiber strength resulting from stripping the fiber's protective polymer buffer jacket prior to laser-processing. In particular, chemically-etched fluidic devices cannot be recoated with a protective coating without blocking access ports for analyte. In this paper, we extend the 3D structuring of optical fiber to femtosecond-laser writing both of and through the urethane-acrylate buffer coating of Corning SMF-28 fibers. Immersion lens focusing removed astigmatism and spherical aberration to enable undistorted and damage free writing of optofluidic components in both the fiber core waveguide and cladding. LIF devices are presented together with the processing parameters for selectively machining the fiber buffer and for minimizing machining damage in the polymer jacket when writing in the underlying glass fiber.

10094-41, Session 9

Femtosecond filaments for rapid and flexible writing of Fiber-Bragg grating

Erden Ertorer, Moez Haque, Jianzhao Li, Peter R. Herman, Univ. of Toronto (Canada)

No Abstract Available.

10094-42, Session 10

Ultrashort pulse laser scribing and cutting of thin brittle materials: The influence of the process parameters on the cutting speed and quality

Matthias Domke, FH Vorarlberg (Austria); Benjamin Bernard, Victor V. Matylitsky, Spectra-Physics Rankweil (Austria)

Much research in recent years has focused on scribing or cutting of brittle materials using ultrafast lasers. The advantage of the ultra-short pulse duration is that thermal side effects can be minimized. Nowadays the challenge is to find the right laser parameters to achieve the highest throughput and quality. Chippings, cracking of the sample, or the rise of periodic structures such as ripples, cones or holes, all of which should thereby be avoided because they reduce the mechanical stability of the cut sample

In this study an ultrafast laser Spirit® HE from Spectra-Physics® with pulse energies of >120 µJ and average output powers of >16 W was used. The tuneable pulse duration and burst mode features available from Spirit® HE laser were applied for investigation of the influence of these parameters on both scribing speed and quality of Si and Pyrex wafers. The pulse duration was stretched from 340 fs to 10 ps (FWHM). The maximum pulse energy was 120 µJ at a fixed pulse repetition rate of 100 kHz. In burst mode, each pulse is converted into a burst of 5 pulses. The wavelength was 1040 nm.

The results showed that chippings occurred at the scribes in Pyrex when the pulse duration was set to 10 ps, but they disappeared at a pulse duration of 340 fs. The results for Silicon scribing showed that the depth of the periodic holes in the bottom of the scribe decreased when the pulse duration was reduced from 10 ps to 340 fs. Their depth was reduced even further when the laser was operated in burst mode.

10094-43, Session 10

Latest advances in machining of transparent, brittle materials using non-ablative femtosecond laser processing from Spectra-Physics

Victor V. Matylitsky, Frank Hendricks, Spectra-Physics Rankweil (Austria)

Established mechanical methods for machining of brittle materials such as saw cutting and scribing often do not satisfy the industrial needs in terms of quality and throughput, and/or require extensive post processing. Nowadays, lasers are increasingly used for machining of different types of materials. Laser cutting processes such as melting, vaporization and fusion cutting are used for cutting of ductile materials. However, these methods are not appropriate for cutting of brittle materials with the required high quality and cutting speed.

Non-ablative, femtosecond laser process ClearShapeTM from Spectra-Physics® for cutting transparent brittle materials is based on producing a micron-sized material modification track with well-defined geometry, which subsequently can be used for controlled cleaving along the desired cutting path. Although this process allows cutting by using relatively low average power of 4 W, the key point for further improvement of the process is an efficient usage of high average power and high pulse energy from commercially available femtosecond laser systems. An industrial femtosecond Spirit® HE laser system from Spectra-Physics® with pulse duration <400 fs, pulse energies of >120 µJ and average output powers of >16 W is an ideal tool for many industrial applications. The laser offers process flexibility with programmable pulse energy, repetition rate, and pulse width. In this paper, we will give an overview of different optical technologies which in combination with femtosecond Spirit® HE laser allow us to achieve unprecedented cutting speed and quality for wide variety of transparent brittle materials such as unstrengthened glass, sapphire, and silicon carbide.

10094-44, Session 10

Novel approach for high quality and high speed glass cutting with femtosecond lasers

Konstantin Mishchik, Amplitude Systèmes (France); John Lopez, ALPhANOV (France); Guillaume Duchateau, Univ. Bordeaux 1 (France); Rainer Kling, Bruno Chassagne, ALPhANOV (France); Clemens Hönninger, Eric P. Mottay, Amplitude Systèmes (France)

In recent years, inorganic transparent materials such as glass, quartz, sapphire and others are more and more used for mass markets such as consumer electronics, flat display panels, optics, optoelectronics or watchmaking industry. So glass processing, and especially glass cutting, is a subject of high interest for worldwide industry. The key issue is to combine high throughput, low residual stress and good sidewall quality in order to avoid chipping and any post-processing step such as grinding or polishing. Despite a huge number of technics proposed, especially using picosecond pulses, only few results are based on a deep knowledge of pulses interactions with glasses. We investigated the interaction of trains of femtosecond laser pulses with dielectric materials by means of a multi-scale model. Our theoretical predictions are directly confronted with experimental observations. The role of pulse duration is clearly evidenced as critical to control the laser energy accumulation in the absorption region. Our comprehension of interaction leads us to propose a new cutting technic. It is based on a time and spatial control of energy deposition of femtosecond pulses, using simple optical arrangements, compatible with industrial usual operations. Using today available high power up to 100 W with high repetition rate, high throughput with high quality is available thanks to this original technical approach.

10094-45, Session 11

Ultrafast pump-probe ellipsometry setup for the measurement of transient optical properties during laser ablation

Stephan Rapp, Hochschule für Angewandte Wissenschaften München (Germany); Heinz P. Huber, Munich Univ. of Applied Science (Germany); Michael Schmidt, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany)

Ultrashort pulsed lasers offer a high potential in precise and efficient material processing. Deep understanding of the fundamental laser-material interaction aspects is of great importance. The transient pulse reflectivity during and after laser irradiation in conjunction with the transient absorption influences decisively the laser-material interaction. Direct measurements of the absorption properties by ultrafast time-resolved ellipsometry are

missing to date. In this talk, a unique pump-probe ellipsometry microscope will be presented allowing the determination of the transient complex refractive index with a sub-ps temporal resolution. The functionality and the accuracy of the setup will be demonstrated. Measurements on molybdenum show ultrafast optical penetration depth changes of ?6% to +77% already within the first 10 ps after the laser pulse impact. This indicates a significant absorption variation of the pump pulse or subsequent pulses irradiating the sample on this timescale and paves the road towards a better understanding of pulse duration dependent laser ablation efficiency, double or burst mode laser ablation and lattice modifications in the first ps after the laser pulse impact.

10094-46, Session 11

Transient states of quantized ablation of SiOx thin films

Matthias Domke, FH Vorarlberg (Austria); Stephen Ho, Univ. of Toronto (Canada); Heinz P. Huber, Munich Univ. of Applied Science (Germany); Peter R. Herman, Univ. of Toronto (Canada)

Recently, femtosecond laser quantized structuring of thin transparent dielectric films of refractive index, nfilm, was shown in SiNx or SiOx to originate from highly contrasting Fabry-Perot fringes and formation of periodic thin nanoscale plasma disks of 20 to 45 nm width, separated on half-wavelength, ?/2nfilm, spacing. The nano-disk explosions enable intra-film cleaving of subwavelength cavities at single or multiple periodic depths, and digital ejection at fractional film depths with quantized-depth thickness defined by the laser wavelength and refractive index of the thin film material.

In order to obtain a deeper understanding of the physical mechanisms, the transient stages of quantized ablation of SiOx thin films were investigated in this study. For this purpose, a pump-probe microscopy setup with high temporal dynamic range was used to capture the ablation dynamics in the time-frame between 100 fs and 10 µs.

The results reveal the transient dynamics of intra-film absorption, pressure wave propagation, nanovoid and blister formation, disk ejection and fragmentation. The findings provide a deep insight into the complex dynamics of quantized ablation.

10094-47, Session 11

Holographic tracking of quantized intra-film segments during interferometric laser processing of SiOx thin films

Stephen Ho, Univ. of Toronto (Canada); Matthias Domke, FH Vorarlberg (Austria); Heinz P. Huber, Hochschule für Angewandte Wissenschaften München (Germany); Peter R. Herman, Univ. of Toronto (Canada)

Interferometric femtosecond laser processing of thin dielectric films has recently opened the novel approach for quantized nanostructuring from inside the film, driven by the rapid formation of periodic thin nanoscale plasma disks of 20 to 45 nm width, separated on half-wavelength, ?/2nfilm, spacing (refractive index, nfilm). The nano-disk explosions enable intra-film cleaving of subwavelength cavities at single or multiple periodic depths, enabling the formation of intra-film blisters with nanocavities and the digital ejection at fractional film depths with quantized-depth thickness defined by the laser wavelength.

For this paper, the physical mechanisms and ablation dynamics underlying the intra-film cleavage of SiOx thin films were investigated by laser pump-probe microscopy with high temporal dynamic range recorded in a wide time-frame between 100 fs and 10 µs. The long time scales revealed a new observation method as Newton's Rings (observed <~50 ns) gave way to holographic recording (>~50 ns) of the laser-ablated film fragments. For the first time to our knowledge, the holographic tracking reveals the clustering of large mechanically ejected nano-film planes into distinct speed groups according to the multiple of ?/2nfilm in the film. The observation verifies a new 'quantized' form of photo-mechanical laser "lift-off".

10094-48, Session 12

Time-resolved microscopy using variable probe wavelengths for ultra-short pulse interaction

Klaus Bergner, Friedrich-Schiller-Univ. Jena (Germany); Malte Kumkar, TRUMPF Laser- und Systemtechnik GmbH (Germany); Andreas Tünnermann, Stefan Nolte, Friedrich-Schiller-Univ. Jena (Germany) and Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Brian Seyfarth, Friedrich-Schiller-Univ. Jena (Germany)

I would like to participate in the student competition.

Glass processing with ultrashort laser pulses allow for different material modifications, ranging from smooth refractive index changes which can be used for the generation of waveguides up to large disruptions due to accumulates stress for glass separation. These disruptions, generated by a dense electron plasma, are favored for glass dicing applications. To tailor the resulting material response a fundamental understanding of the laser/material interaction is of interest.

Therefore, we analyze the spatio-temporal evolution of free carriers induced by ultrashort laser pulses using a pump-probe setup with high temporal and spatial resolution and various probe wavelengths.

Single laser pulses with 1026nm wavelength, 6ps (FWHM) pulse duration and 200µJ pulse energy were applied to fused silica, Borofloat 33 and Gorilla glass. Electron densities around 1 x 1020cm-3 in the focal plane and 1 x 1019cm-3 in front of the focus are obtained, independent from the glass type used.

The free carriers slowly decay within several ns, while the decay time depends on both the maximum electron densities reached and glass species. In this process a part of the excited electrons relax within several 10ps into a long-living stage where a transient effect is observed. Here, various probe wavelengths show differences in the recorded signal.

A further carrier relaxation leads to permanent (stress, voids) and non-stable (color center) modifications crucial for precise glass dicing applications.

10094-49, Session 12

Reproducing space weathering of olivine by using high-energy femtosecond laser pulses

Gabor Matthäus, Agnese Fazio, Dennis Harries, Harald Mutschke, Falko Langenhorst, Stefan Nolte, Friedrich-Schiller-Univ. Jena (Germany)

Atmospheric-free bodies in space are undergoing several processes that alter their original spectral characteristics. One of these processes is the so-called space weathering. Here, the surface of the body is exposed to interstellar radiation and ongoing micrometeorite bombarding yielding material modifications in the micro- and nanometer range. In order to understand these processes and consequently to further clarify the influence on spectral reflectance and absorption, over the years, different approaches using ion and laser irradiation have been presented to mimic space weathering effects. But, up to now, basic damaging mechanisms are still unclear and require further investigations.

In this work, we present the application of ultra-short laser pulses as a tool to reproduce space weathering effects. In our experiments, olivine samples were cut perpendicular to the crystallographic axes, polished and afterwards irradiated under vacuum condition using single-shot laser pulses. In order to perform spectral measurements, the laser damaged regions were distributed over the sample surface using a grid geometry. After laser processing a comprehensive study was performed by using spectroscopic measurements in the NUV-vis-NIR range, white light interferometry and SEM analysis. The cross section of the laser generated craters reveal three different layers starting from a single glass layer at the top, a polycrystalline layer in the middle and defect-rich single crystal structure beneath. Moreover, iron nanoparticles occur at the interface between glass and polycrystalline layer. We can show, that exactly the same layered structure and iron nanoparticles were found in samples from the moon and from the asteroid Itokawa.

10094-50, Session 12

Two-beam femtosecond rotational coherent anti-Stokes Raman spectroscopy for one-dimensional thermometry in a turbulent, sooting jet flame

Daniel R. Richardson, Sukesh Roy, Spectral Energies, LLC (United States); James R. Gord, Air Force Research Lab. (United States); Sean Kearney, Sandia National Labs. (United States)

Single-laser-shot femtosecond rotational coherent anti-Stokes Raman scattering (fs-RCARS) temperature measurements are performed across a 6-mm line in a turbulent, sooting ethylene jet flame to characterize temperature gradients. A 60-fs pulse is used to excite many rotational Raman transitions in N2, and a 200-ps pulse is used to probe the Raman coherence. The spatial resolution of the measurements is 800 ?m in the direction of beam propagation and 50 ?m in the transverse directions. Measurements have been performed at multiple locations in the jet flame. Future analysis will include statistics of the temperature gradients at several flame locations.

10094-51, Session 12

Femtosecond, fully resonant electronically enhanced CARS (FREE-CARS) for simultaneous single-shot thermometry and detection of minor combustion species

Hans Stauffer, Jacob B. Schmidt, Daniel R. Richardson, Sukesh Roy, Spectral Energies, LLC (United States); Paul J. Wrzesinski, James R. Gord, Air Force Research Lab. (United States)

Femtosecond time-resolved, fully resonant electronically enhanced coherent anti-Stokes Raman scattering (FREE-CARS) spectroscopy, incorporating a two-color ultraviolet excitation scheme, is used to demonstrate chemically selective and sensitive detection of gas-phase species, including nitric oxide (NO) and the hydroxyl (OH) radical. The observed time-dependent, spectrally resolved CARS signal contains rich structure that depends both on the rovibronic states accessed within the bandwidth of the initial (pump) excitation pulse and the Raman-active rovibrational levels within the vibrationally excited ground electronic state that are accessed following interaction with the second (Stokes) excitation pulse. By comparing experimental spectra to computational simulations, therefore, this approach also allows simultaneous determination of local temperature associated with the thermal distribution of initial states under single-laser-shot conditions. For OH radical detected in a reacting flow, spectral resolution of the emitted FREE-CARS signal allows simultaneous single-shot detection of relative OH mole fraction and temperature in a laminar ethylene–air flame at high repetition rates (1 kHz). By comparison to previously reported OH concentration and temperature measurements, we demonstrate excellent single-shot temperature accuracies (~2% deviation from adiabatic flame temperature) and precisions (~2% standard deviation), with simultaneous relative OH concentration measurements that demonstrate high detection sensitivity (100–300 ppm).

10094-52, Session 12

Time-resolved correlated measurement of laser-induced-breakdown spectroscopy and electron number density: Application to high-pressure hydrocarbon flames

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Simultaneous and correlated measurement of time-resolved ultrashort-laser–based laser-induced breakdown spectroscopy (LIBS) and electron number density is proposed for diagnostics of hydrocarbon flames at elevated pressure. Recently, nanosecond-laser–based LIBS was employed for quantitative local fuel to air (F/A) ratio measurements in well-characterized methane-air flames at pressures of 1 – 11 bar. Nitrogen and hydrogen atomic-emission lines at 568 nm and 656 nm, respectively, were selected to establish a correlation between the line intensities and the F/A ratio. From the detailed parametric study, it was observed that ns-LIBS shows very high instability in F/A ratio measurement at high pressures. The proposed simultaneous measurement of LIBS and the electron number density (N) enables developing an understanding for the source of the aforesaid measurement instability. The results obtained from experiment clearly show that both LIBS and N are very highly correlated at low pressure but the correlation is almost lost at high pressures. Also, from current observations it is clearly observed that the high instability in the LIBS signal and hence instability in F/A ratio measurement at high pressures are caused by the highly unstable avalanche ionization, in addition to the presence of high level of soot. Preliminary experiments employing picosecond-LIBS have shown that there is a significant potential for ultrashort-laser–based LIBS for reduction of instability in the F/A ratio measurement. The planned correlated measurements of LIBS and electron density with short ps to longer fs excitations are expected to reduce the instability in F/A ratio measurements at high pressure.

10094-59, Session PTue

Study on parameters of fiber loop mirrors as artificial saturable absorbers

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This work focuses on practical analysis of the nonlinear optical loop mirror (NOLM) and nonlinear amplifying loop mirror (NALM). Those novel all-fiber devices serve as saturable absorbers for passive mode-locking in ultrashort pulse generation. Both devices have great potential for further development as they are made in all fiber technology, and can be easily adapted to custom system. The experimental setup consist of all-PM-fiber laser system

working in femtosecond regime, a thermal power sensor and optical spectrum analyzer. In our work we investigate and provide experimental results as well as characteristics of NOLM and NALM devices in different working conditions. We present transmission as a function of input power and as a function of the coupler's coupling ratio for NOLM. For amplifying mirrors, we show transmission as a function of pump power. These results may be useful in further studies in the field of fiber saturable absorbers.

10094-60, Session PTue

Ultrafast pulsed Bessel beams for enhanced laser ablation of bone tissue for applications in LASSOS

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Previous studies using a femtosecond pulsed laser system (pulse width = 100fs, repetition rate = 500 Hz, ?=800nm) have shown ultrafast lasers to be an ideal candidate for a LASer Scalpel for Orthopaedic Surgery (LASSOS). However, in order to maximise the machining ability of the LASSOS tool, we propose the integration of spatially shaped beams to increase machining efficiency. Using a LCOS-Spatial light modulator (LCOS-SLM), Bessel beams of varying orders are generated and used to micromachine fresh, living bone tissue from bovine and ovine species. Standard metrics of laser micromachining (ablation threshold, tissue removal rate, incubation effects and structural analysis of cut features) are investigated. Previous studies of a variety of materials have observed significant decreases in the ablation threshold whilst using Bessel beams. Using the diagonal scan technique redesigned for Bessel beams, we investigate if this trend extends to biological hard tissues such as bone. Meanwhile, the non-diffracting behaviour of Bessel beams are expected to show increased cutting depths and aspect ratios compared to traditional lasers with Gaussian intensity profiles. We have previously shown that femtosecond laser ablation of cortical and skull bone with Gaussian beams does not result in collateral damage to the surrounding tissue. Structural analysis of the ablation features created with Bessel beams are performed using scanning electron and optical microscopy to assess the features for signs of heat damage, thermal cracking or other types of damage to the surrounding bone tissue.

10094-61, Session PTue

Control of nonlinear instabilities in Bessel beams using shaped longitudinal intensity profiles

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Bessel beams are now widely used for laser material processing. Their conical energy flow yields a near-uniform intensity distribution along a line focus which is highly advantageous in reducing nonlinear instabilities during propagation of intense pulses in transparent media. However, nonlinear Kerr coupling can still induce significant intensity modulation, which is detrimental to generate longitudinally-uniform structures in materials. Previous studies showed that these nonlinear oscillations are modified depending on whether the Bessel beam is formed before entering the nonlinear medium or if it is progressively forming in the sample. Here, we report a convenient approach to control the growth of instabilities along propagation. It is based on shaping the longitudinal intensity profile of the incident Bessel beam. We analytically and numerically analyze four-wave mixing interactions and specifically investigate the role of the spatial spectral phase. We show that the growth of unstable modes can be attenuated depending on the initial spectral phase distribution of the beam, which in turn is related to the beam longitudinal intensity profile. In addition, we numerically investigate the propagation of pulsed Bessel beams in the filamentation regime with Kerr and plasma effects. We show that attenuated Kerr nonlinearity noticeably reduces the pulse temporal reshaping during propagation which allows to generate uniform plasma channels. This work opens very novel routes for stabilizing ultrashort pulse propagation in transparent nonlinear media.

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program (grant agreement No 682032-PULSAR).

10094-62, Session PTue

Improving the fidelity of absolute two-photon absorption reference standards

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Use of two-photon absorption (2PA) reference standards allows bypassing tedious characterization of the photon flux of femtosecond laser pulses, and thus facilitates accurate measurement of nonlinear-optical spectra of fluorescent probes and determining the strength of intra- and intermolecular electric fields.

We have recently reported absolute 2PA cross-sections of nine standards in the 680-1050 nm wavelength range with estimated accuracy 8%. These error estimates need however further critical evaluation, especially because the laser beam parameters as well as the sample properties involved can vary in ways that are difficult to control with sufficient accuracy. Here we carry out relative comparison between different 2PA standards with overlapping fluorescence emission spectra, with the aim of improving the fidelity and revealing potential inconsistencies in the reference data set. We selected 6 pairs of chromophores with partially overlapping 2PA and fluorescence emission spectra: (1) BDPAS in DCM vs. prodan in DMSO; (2) BDPAS in DCM vs. Coumarin 153 in toluene; (3) AF455 in toluene vs. Coumarin 153 in toluene; (4) AF455 in THF vs. Coumarin in toluene; (5) AF455 in THF vs. Coumarin in DMSO and (6) Rhodamine 6G in methanol vs. Coumarin 153 in DMSO. For each pair the relative 2PA cross section was evaluated by measuring the 2PA-induced fluorescence at identical excitation conditions. In case of BDPAS, prodan and Coumarin 153 the values were consistent with the previously estimated 8% error margin, whereas the statistical spread was larger in case of AF455 in THF, which however does not invalidate our previously published results.

10094-63, Session PTue

Determination of the limits of detection of the elements in aqueous solutions by femtosecond LIBS depending on the laser pulse repetition rate

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Femtosecond laser-induced breakdown spectroscopy (LIBS) is currently developed actively for the analysis of the elemental composition of aqueous medium. The possibility of using a high laser repetition rate up to 1 kHz cansignificantly reduce analysis time of water solution with a good sensitivity. However, it was recently shown that a change in the repetition rate of the laser affectson the intensity of the emission lines of Ca in the analysis of aqueous solutions of calcium. Namely, the maximum value of the intensity of spectral lines has been achieved when the value of the pulse repetition rate was 20 Hz. Thus, purpose of this work is an investigation of the influenceof laser repetition rate on the limit of detection of the elements in aqueous solutions by femtosecond laser-induced breakdown spectroscopy.As a main result the limits of detection was obtained for Ag, Al, B, Mg, Mn, Sr, Pb, Fe in water solutions in dependence on laser repetition rate. As a source of femtosecond laser pulses was used a Ti:Sapphire ultrafast amplifier system (Spitfire Pro XP, Spectra-Physics) with a central wavelength of 800 nm, pulse duration 45 fs, pulse energy 0.5-3 mJ, pulse repetition rates: 20 Hz, 100 Hz, 200 Hz, 500 Hz and 1 kHz.Laser radiation was focused by the plano-convex lens (KPX094AR.16, NewPort) on the surface of the investigated water solution. Plasma radiation emitted from the sample was sent by optical fiber (Ocean Optics, quarts, UV-VIS, 600 ?m) onto the 50-µm input slit of the 300 mm focal length spectrometer (Spectra Pro 2300, Princeton Instruments) coupled with gated ICCD camera (PI-MAX3 1024i, Princeton Instruments).Processing of the results of experiments was carried out in WinSpec and Matlabsoftware systems.

10094-64, Session PTue

High-resolution targeted DNA damage in live cells with a multicolor compact femtosecond fiber laser system

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Preserving the integrity of DNA is fundamental for the survival of biological systems. DNA repair research has a high demand for methods to induce DNA damage with high spatial and temporal selectivity. To this end, we have developed a high-efficiency, low-drift and multicolor nonlinear photomanipulation system based on femtosecond fiber laser technology combined with either holographic or galvanometric scanning. The single-mode fiber system synchronously provides 40 MHz-clocked pulses at 517nm, 780nm and 1035nm. The output of a femtosecond Erbium:fiber oscillator with subsequent amplification is split for second harmonic generation (SHG) at 780nm and for seeding a 2-Watt Ytterbium:fiber amplifier via frequency conversion in a highly nonlinear fiber. Chirped pulse amplification with dispersion management up to fourth order by a fiber Bragg grating and free-space pulse compression in transmission gratings provides bandwidth-limited 80-fs pulses at 1035nm. SHG of this output simultaneously generates femtosecond pulses at 517nm. Illumination patterning is achieved either via serial point-scanning or by holography using a liquid-crystal-on-silicon phase modulator. DNA damage is detected by immunocytochemistry. DNA repair in live cells is monitored via confocal imaging of the recruitment of DNA repair factors. We aim at the selective induction of different types of DNA lesions by precisely controlling pulse parameters such as center wavelength or peak intensity. Efficient pulse compression and optimized NIR optics reduce parasitic heating and collateral damage. This scheme demonstrates that reliable and compact femtosecond fiber laser technology can be successfully employed for power-demanding applications in the life sciences like nonlinear photomanipulation by digital holography.

10094-65, Session PTue

Acceleration of biodegradation by ultraviolet femtosecond laser irradiation to biodegradable polymer

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Biodegradation is one of key properties for biodegradable polymer-based tissue scaffolds because biodegradation can provide suitable space for cell growth as well as controlling its sustainability tailored for applications. Although UV lasers have been attracting considerable interest because of the ability to process the surface layer of the materials, the biodegradability after UV laser irradiation has yet to be elucidated in detail. In this study, we investigated the biodegradability of poly(lactic-co-glycolic acid) (PLGA), which is a widely-used biodegradable polymer, after femtosecond laser irradiation compared to that with nanosecond laser irradiation at the wavelength of 266 nm. The remaining mass of PLGA films irradiated with nanosecond laser were almost constant after 10 days of immersion, while that irradiated with femtosecond laser decreased significantly in the initial 6 days of immersion. The results with X-ray photoelectron spectroscopy (XPS) analysis showed a significant dissociation of chemical bonds in PLGA via multiphoton absorption after femtosecond laser irradiation, indicating that the acceleration of biodegradation would be attributable to the chemical bonds dissociation. The effect of femtosecond laser irradiation with IR wavelength to the biodegradability is negligible, which was shown in our previous study. The femtosecond laser processing has potential to control the biodegradation by applying laser pulses with different wavelength.

10094-66, Session PTue

Enhancement of laser machining resolution using the two photon absorption effect

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Ultrafast laser micromachining as a manufacturing technique is able to produce cut widths of just a few hundred nanometres wide, while keeping the locally affected area to less than a micron. This allows very precise feature creation due to the high resolution. Implementing the two photon absorption (TPA) effect offers the opportunity to further increase this resolution. TPA is where molecules can simultaneously absorb two photons, where the probability of this occurring for two identical photons is proportional to intensity. This allows for a higher level of spatial selectivity and hence a further improved spatial resolution. Here we present results of laser micromachining of amorphous polycarbonate (APC) films doped with two different TPA molecules with a range of concentrations. These molecules are R1 (E,E-1,4-bis[40-(N,N-di-n-butylamino)styryl]-2,5-dimethoxybenzene) and R2 (E,E-1,4-bis-[40-(N,N-di-n-butylamino) styryl]benzene). The femtosecond laser ablation was carried out using an amplified Ti:Sapphire laser (Mantis (oscillator) and Legend Elite (amplifier), Coherent Inc., USA), which provides 110 fs pulses at a repetition rate of 1 kHz, and a maximum pulse energy of 3.5 mJ. These samples were measured using optical profilometry (Contour GT-K, Bruker USA). Initial results show that an increased concentration of either TPA molecule results in decreased ablation threshold with a reduction of up to 45% in threshold. Additionally, an increase in concentration of both of these molecules result in improved resolution, with R2 having the greater effect. The 10% doped R2 sample gave a 42% improvement over the reference sample.

10094-67, Session PTue

Ultrafast laser parameters to avoid self-focusing in deep tissue ablation

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Ultrafast pulsed lasers are a useful tool for noninvasive and precise tissue surgery. High intensity pulses interact with tissue nonlinear to ablate in a confined volume without thermal effects. However, subsurface ablation has been limited to a few scattering lengths because of beam attenuation; as pulse energies are increased to overcome extinction, unwanted nonlinear effects such as self-focusing can occur. Self-focusing manifests in a spatially dependent refractive index, causing long filaments of damage or complete beam collapse before the focus.

Here, we investigate self-focusing in tissue through third-harmonic generation imaging of ablation voids. We show that pulses on the order of 2 ps are able to ablate deeper and avoid filamentation when compared to 200 fs pulses. We also present guidelines for the minimum focusing numerical aperture that should be used for a given target ablation depth. Additionally, we simulate beam propagation in tissue and show that wavelengths beyond the typically used Ti-sapphire spectral range can ablate deeper due to decreased scattering in tissue.

10094-68, Session PTue

Generation of superhydrophobic rose leaf surfaces by a combined laser ablation-wet oxidation process

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The wetting behaviour of a surface is a complex problem where both, material properties and the surface topography influences the interaction of a liquid with the substrate surface. The wettability of a surface can be classified by measuring the contact angle ? of a drop of liquid (water) placed on the material surface. To achieve high values of ?, the influence of the surface texture is of high importance. Most work found in literature describes the generation of so called “Lotus leaf” surfaces where the superhydrophobic behaviour is accompanied by an extreme water repellence functionality. In this work we demonstrate a fabrication process for the generation of quartz surfaces showing both, superhydrophobic behaviour combined with extreme adherence of water droplets on the surface – the so called “Rose petal effect”.

The patent-pending fabrication process (ClearSurfaceTM from Spectra-Physics®) is a combination of thin film structuring with a femtosecond laser followed by a wet oxidation step.

The sample is based on a quartz wafer where a layer of a-Si was deposited by sputtering. The a-Si layer was selectively structured by a femtosecond laser. After laser structuring the sample was thermally (wet) oxidized until the coating is fully converted into quartz. The final surface shows superhydrophobic behaviour with values of contact angle of up to 163° together with a remarkable high hysteresis value of up to 151° leading to extreme adhesion of water droplets on the surface.

Such “smart” surfaces may be used in microfluidic systems that operate in “open space” where a one-dimensional “smart” contact surface has to substitute the function of a three-dimensional device

10094-69, Session PTue

Optical characterization of the mM state in vanadium dioxide thin films from second harmonic generation

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Vanadium dioxide (VO2) undergoes a semiconductor–to–metal phase transition (SMT) when heated slightly above room temperature or upon excitation with an ultrafast optical pulse. The SMT is accompanied by a non-congruent structural phase transition (SPT) from a non-centrosymmetric monoclinic structure (M1) to a centrosymmetric tetragonal/rutile phase (R). While there is experimental evidence for an intermediate monoclinic state (mM), little is known about its structure. One possible probe of the symmetry and structure of this phase is angle-resolved, polarization-sensitive second-harmonic generation (SHG). In this experiment, we probe the SMT in epitaxial VO2 thin films by monitoring the SHG (400 nm) when excited by a 15 fs pulse from a Ti:sapphire laser (800 nm). Varying laser polarization with respect to the VO2 crystallographic c-axis provides a sensitive probe of the symmetries and temporal evolution of the M1 and mM transient states. Moreover, since bulk second-harmonic generation (SHG) is forbidden in centrosymmetric crystals, the temporal evolution of the SHG signal is a sensitive indicator of the onset of the rutile crystal structure. Thus this measurement will provide a new window into the M1-mM and M1-R structural phase transitions with unprecedented temporal resolution. Furthermore, comparisons of the symmetries in the optically- and thermally-induced transient mM phases will elucidate the relationship between these two observed mM phases. By generating new insights into the electron-electron correlations of VO2 and the dynamical evolution of the mM and R phases, this information will drive ultrafast switching applications in fields such as optical detection, telecommunications, and nanophotonics.

10094-70, Session PTue

Plasma dynamics during surface ablation of fused silica using fs-laser pulses

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We have investigated surface ablation of fused silica upon single femtosecond (fs) laser pulse irradiation. The laser-induced electron plasma dynamics has been experimentally studied using a pump and probe arrangement and theoretically using a physical model that combines multiple rate equations (MRE) with a finite difference time domain (FDTD) method.

Experimentally, we have studied the laser-induced electron plasma by recording the time-integrated reflectivity and the transient reflectivity for temporal delays ranging from hundreds of femtoseconds to the nanosecond regime. Besides, the influence of the temporal intensity distribution of the laser was studied by using different pulse durations. The simulations make use of a 2D-FDTD routine that allows for solving the Maxwell's equations and calculating the transient dielectric function of fused silica during single pulse irradiation. We combine the FDTD simulation with MRE method that describes the temporal evolution of the carrier density (driven by Keldysh strong field ionization and avalanche ionization) and its distribution in the conduction band.

We discuss the temporal evolution of the surface reflectivity at different local fluences by comparing the experiments and simulations. We find a realistic simulation of the electron plasma's rise time and maximum reflectivity observed when using a pump and probe fs-microscopy arrangement.

10094-71, Session PTue

The influence of femtosecond laser wavelength on waveguide writing features inside fused silica

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We have investigated the influence of the laser wavelength on the features of fs laser-inscribed waveguides in fused silica both theoretically and experimentally. We study the diameter of the machined lines, the laser energy thresholds and the waveguide fabrication energy range. The theoretical calculations are based on the propagation of Gaussian beams combined with Keldysh's strong field ionization (SFI) and multiple rate equations (MRE) method. Based on these calculations an estimate of the laser affected volume was obtained. Experimentally, the laser direct writing technique was used to fabricate both waveguides and tracks of damaged material inside fused silica. To this end the wavelength of the laser was detuned using an optical parametric amplifier (OPA), ranging from ultraviolet (400 nm) to near infra-red (1300 nm). The cross-section of the inscribed lines was inspected using white light optical microscopy. Besides, the near and far field profiles of the waveguides were imaged using a CW laser (660 nm) and a microscopy setup. The comparison of the experimental results and the calculations shows good agreement. We remark that using the plasma excitation description given by MRE provides more accurate predictions than those using SFI-only or a single rate equation.

This study yields insight on how to predict and design optical waveguide features and also aids to understand the underlying physical mechanisms linked to laser-glass interaction when using different laser wavelengths.

10094-72, Session PTue

Quantitative iterative back-projection algorithm for image reconstruction from time-of-flight measurements

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Time-of-flight imaging techniques allow reconstruction of images from scattered light. The scene of interest is illuminated with short light pulses and different spatial patterns, and light returning from the scene is recorded with a time resolution high enough to observe the photon time of flight through the scene. With this additional information, light transport analysis of multiply scattered photons is possible, allowing for imaging through scattering environments and around corners. Back-projection type algorithms are an important numerical method used in non-line of sight image reconstruction. However, currently used methods are not quantitative. Furthermore, back-projection does not make use of all information available in the data and produces imaging artifacts. We present an iterative algorithm for back-projection that better incorporates time-of-flight information and achieves more quantitatively correct image reconstruction. The incorporation of correction factors for physical effects allows the algorithm to account for factors such as the albedo of targets. Portions of our algorithm, including iteration, filters, and corrections for distance and Lambertian shading effects, are shown to improve the accuracy of reconstructed images. Results are presented for simulated data consisting of randomly spaced point targets and more complex geometries with Poisson and random background noise added. In addition, the iterative back-projection algorithm is shown to be similar to the multiplicative algebraic reconstruction technique (ART), a popular method for computed tomography reconstruction. We present a detailed comparison of our methods and problem statement with typical ART applications. Methods to improve resolution and more consistently determine target shape are currently being investigated.

10094-73, Session PTue

Monostatic and Bistatic lidar systems: Simulation to improve SNR and attainable range in daytime operations

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The impacts of aerosol in the human health with diseases such as lung cancer, bronchitis, and asthma have been essential motivations to record aerosol properties and transportation in the atmosphere. Many studies investigate the relationship between the traffic pollution and the damage in human brain and analyze the effects of traffic pollution on the genome of a newborn, and prematurity and preeclampsia issues. Light Detecting and Ranging (Lidar) is widely used for probing the earth's atmosphere. Lidar system is capable of providing vertical distribution of aerosol and cloud. Lidar daylight measurements are limited by sky background noise (BGN). Reducing the BGN is essential to improve Lidar signal-to-noise ratio (SNR). We report on an optimization technique to improve SNR in a monostatic and bistatic Lidar systems by redesigning the geometrical scheme of Lidar receiver. A series of simulations to calculate the overlap area between both transmitter and receiver field of view (FOV) is conducted to determine optimal receiver aperture shapes and sizes within different lidar ranges. Techniques to vary receiver aperture shape, position, and size to accommodate backscattering signals over a given range, to maximize Lidar SNR, is introduced. This approach of improving Lidar SNR can be translated to an improvement in Lidar attainable range for backscatter schemes including Raman Lidar and Differential Absorption Lidar (DIAL).

10094-53, Session 13

Ultra-short pulse delivery at high average power with low-loss hollow core fibers coupled to Trumpf's TruMicro laser platforms for industrial applications

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Multi-megawatt ultrafast laser systems at micrometer wavelength are commonly used for material processing applications, including ablation, cutting and drilling of various materials or cleaving of display glass with excellent quality. There is a need for flexible and efficient beam guidance, avoiding free space propagation of light between the laser head and the processing unit. Solid core step index fibers are only feasible for delivering laser pulses with peak powers in the kW-regime due to the optical damage threshold in bulk silica. In contrast, hollow core fibers are capable of guiding

ultra-short laser pulses with orders of magnitude higher peak powers. This is possible since a micro-structured cladding confines the light within the hollow core and therefore the spatial overlap between silica and the electro-magnetic field is very small. We report on recent results of single-mode ultra-short pulse delivery over several meters in a low-loss hollow core fiber packaged with industrial connectors. Trumpf's ultrafast TruMicro laser platforms equipped with advanced temperature control and precisely engineered opto-mechanical components provide excellent position and pointing stability. They are thus perfectly suited for passive coupling of ultra-short laser pulses into hollow core fibers. Neither active beam launching components nor beam trackers are necessary for a reliable beam delivery in a space and cost saving packaging. Long term tests with weeks of stabile operation, excellent beam quality and an overall transmission efficiency of above 85 percent even at high average power confirm the reliability for industrial applications.

10094-54, Session 13

High power mid-IR OPCPA system pumped by a femtosecond Yb-doped fiber amplifier

Philippe Rigaud, Aymeric Van de Walle, Marc Hanna, Lab. Charles Fabry (France); Nicolas Forget, Fastlite (France); Florent Guichard, Yoann Zaouter, Amplitude Systèmes (France); Khmaies Guesmi, Frédéric Druon, Patrick Georges, Lab. Charles Fabry (France)

We describe an optical parametric chirped pulse amplifier (OPCPA) architecture built around a state of the art Yb-doped fiber femtosecond pump source delivering 300 fs 400 μJ pulses at a repetition rate 125 kHz (50 W average power) and a central wavelength of 1030 nm. The short pump pulse duration compared to bulk Yb:YAG or Nd:YVO4 based systems results in a number of important advantages. First, it allows efficient seeding at 1550 nm using supercontinuum generation directly from the pump pulses in a bulk YAG crystal, resulting in extremely robust passive pump – signal synchronization. The short pump pulse duration also allows the use of millimeter to centimeter lengths of bulk materials to provide stretching and compression for the signal and idler, which minimizes the accumulation of higher-order spectral phase. Finally, the shorter pump pulse duration increases the damage peak intensity, permitting the use of shorter nonlinear crystals to perform the amplification, which increases the spectral bandwidth of the parametric process. Additional experiments are performed to sort out the phenomena that limit power scaling in MgO:PPLN crystals. The OPCPA stages are all operated in collinear geometry, allowing the use of both signal and idler without the introduction of angular chirp on the latter. These points result in the dual generation of 70 fs 23 μJ signal pulses at 1550 nm and 60 fs 10 μJ idler pulses at 3070 nm from a simple setup, with the added benefit of inherent CEP stability of the idler pulses.

10094-55, Session 13

>100-W femtosecond laser for high productivity

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Femtosecond lasers are pushing new heights for industrial laser processes. Outstanding laser processing results using femtosecond lasers have opened a wide spectrum of industrial applications across a variety of sectors, especially the semiconductor and consumer electronics industry. Femtosecond lasers provide superior precision when it comes to extremely tiny structures, eliminating costly and wasteful post-processing in existing applications, but moreover, open the door to new applications that cannot be realized by any other existing laser technology. Industrial applications, such as high precision laser cutting, scribing, or texturing, not only need the ultrashort pulse duration, but also require a high average power in order to achieve a high throughput and productivity.

In this contribution we report on an industrial femtosecond laser with >100W average power and pulses as short as 400fs. The concept is flexible in pulse energy and pulse repetition rate. Femtosecond pulse trains reaching from 300kHz over 2MHz to 40MHz can be generated with pulse energies of >300μJ, 50μJ, and 2.5μJ, respectively. High energies are interesting to translate high average power into high throughput by beam splitting and parallelization. On the other hand, high pulse repetition rates, burst mode operation, and synchronization to a polygon scanner are possible as well. The combination of the laser source with a polygon scanner impressively showed the gain in productivity when power scaling comes along with an adapted and fast scanner technology. The femtosecond laser concept is scalable to >200W average power and >500μJ pulse energy.

10094-56, Session 13

Concepts for industrial femtosecond lasers around 100-fs

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Femtosecond lasers have entered a significant number of industrial applications thanks to their unique properties in laser-matter interaction, and, most specifically, thanks to the cold ablation process triggered by the ultrashort pulse duration which is typically on the order of a few hundred femtoseconds. One of the most popular sectors for femtosecond lasers is the semiconductor and consumer electronics industry with its specific requirements of machining brittle or dielectric materials. Especially in this dynamic industry, new materials and material combinations emerge that contain e.g. organic components and tend to require more and more sophisticated lasers. Moreover, it was shown that machining or modifying glass with femtosecond pulses of 100-fs or shorter opens entirely new perspectives, e.g. to create photonics components. One of the identified trends in ultrafast laser development is therefore the requirement for ever shorter pulses, on the order of 100-fs or even below.

In this contribution we report different concepts for industrial femtosecond laser around 100-fs. This reaches from broadband oscillators and seed lasers with the capability of sub-100-fs pulse generation to amplifier concepts supporting the amplification of 100-fs pulses to energy levels exceeding 100-μJ. Even shorter pulses down to sub-50-fs are obtained from an industry-grade optical parametric amplifier.

10094-57, Session 13

Kagome fiber based industrial laser beam delivery

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Reliable and robust fiber-based laser-beam delivery of ultra-short-pule (USP) lasers is turning into an essential technology driver as the lasers pulses are becoming shorter and more powerful, and their use spreading in industrial applications is growing wider. Inhibited-coupling Kagome hollow-core PCF (HC-PCF) has proved to be an extremely promising means for USP delivery owing to its unprecedented laser power and energy handling, very low optical nonlinearity and dispersion. However, its use

has so far been limited to optical fiber "literate" community because of its specific properties compared to the conventional fibers, and the difficulty in controlling the gas inside the HC-PCF. Here, we report GLO-Beam Delivery System (GLO-BDS), which is a HC-PCF based USP laser beam delivery module that combines ease-of-use, high laser-coupling efficiency, robustness and industrial compatible cabling. GLO-BDS comprises a pre-aligned laser-injection head, a sheath cable protected HC-PCF and a modular fiber-output head. Moreover, the GLO-BDS comprises a system for fiber gas-loading and evacuation, allowing in-fiber gas management, and thus controlling non-linear effect for ultra-high energy USP. The HC-PCF is fully protected from external mechanical stress or harsh ambient environment for long-life and continuous industrial applications. Yb-doped fiber-laser optimized GLO-BDS of 5 meter long fiber (Kagome PMC-C-YB-7C) exhibits a transmission efficiency > 85%, a laser output profile close to single mode (M2 <1.3) and a polarization extinction ratio of more than 40:1. The GLO-BDS is also available for frequency-doubled Yb-doped fiber lasers or Nd:Yag lasers and Ti:Sapphire lasers.

10094-58, Session 13

Ultra-low loss (8.5 dB/km @ Yb-laser region) inhibited-coupling Kagome HC-PCF for laser beam delivery applications

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Ultra-short pulse (USP) lasers with sub-picosecond and Giga-Watt peak-power level optical pulses are now available in compact tabletop and turn-key physical packages. Their growing and spreading use in industrial applications as various as biophotonics, micro-machining and micro-surgery call for flexible and robust beam delivery systems (BDS) over several meters with no temporal or modal distortions. Inhibited coupling (IC) hypocycloid Kagome hollow-core photonic crystal fibers (HC-PCF) has proved to be an excellent fiber for guiding these USP with low attenuation and low temporal and spectral distortion. This is illustrated in the transport of 600 femtosecond pulses at milliJoule energy level in robustly single-mode fashion [1] using a IC Kagome HC-PCF with the loss figure down to 17 dB/km at 1 μm [2]. In this context, it is desirable to reduce further the attenuation of such fiber to increase the length capability of the BDS whilst keeping the same delivery performances.

Here, we report on an optimized IC Kagome HC-PCF for Yb and Nd:Yag laser beam delivery applications exhibiting record loss level (8.5 km at 1030 nm) associated with a 225 nm wide 3-dB bandwidth and low bend sensitivity. This new loss figure represents a factor of 2 improvements over the current state-of-the-art. Finally, the modal properties (S2 and PER) have been studied, demonstrating a quasi single mode operation.

References

[1] B. Debord et al., Opt. Exp. 22(9), 10735-10746 (2014)

[2] B. Debord et al., Opt. Exp. 21(23), 28597-28608 (2013)

10095-1, Session 1

Laser direct writing of viscous liquids by flow focusing

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Inkjet printing of viscous functional or biological materials remains challenging using conventional thermal and piezo-actuation, mainly due to nozzle clogging and aggregation of the particles in solution. Alternatively, laser-actuation has the potential to overcome these limitations, for instance LIFT allows printing highly viscous materials thanks to its unconfined geometry. However, LIFT remains a time-consuming process since it requires the pre-coating of substrates with thin-films of ink.

Here, we present another approach of laser-actuation with a continuous refill of the ink for direct writing of viscous liquids. A nanosecond laser pulse is focused on an open glass capillary filled with the dyed viscous ink. Upon absorption of the laser light, a shockwave is generated which results in a flow-focused jet and the generation of a low velocity (1-2 m/s) satellite-free viscous (1-200 mPa s) micro-droplet with a diameter smaller than the orifice from which it originated (200 µm). We experimentally demonstrated that this novel laser direct writing technique significantly extends the range of printable liquids in comparison to conventional inkjet printers. Moreover, the jetting regimes of Newtonian and non-Newtonian inks were investigated and showed that viscosity tends to stabilize droplet generation. Biologically relevant samples were printed without degrading their functional properties, thus demonstrating that this laser jetting technique is potentially suitable for bio-printing.

10095-2, Session 1

Fabrication of 3D gold/polymer conductive microstructures via direct laser writing *(Invited Paper)*

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During the last years there has been significant interest in the fabrication of conductive three-dimensional (3D) structures on the micrometer scale due to their potential applications in microelectronics or emerging fields such as flexible electronics, nanophotonics, and plasmonics. Two-photon direct laser writing (DLW) has been proposed as a potential tool for the fabrication of 3D microstructures in various contexts. The majority of these two-photon processes involve the preparation of insoluble polymeric networks using photopolymerizable photoresins based on acrylate or epoxy groups. Nevertheless, the preparation of conductive 3D microstructures is still very challenging.

The aim of the current work has been the preparation of conductive 3D microstructures via DLW by employing a newly developed photoresist. The photoresist consists of acrylate-functionalized poly(ethylene glycol) derivates and $HAuCl_4$ as the gold precursor. By varying the gold content of the photoresist, different structures have been prepared and characterized by SEM and XPS. Conductivity of individual wires between prefabricated macroelectrodes has been measured too. Subsequently, the material has been employed to demonstrate the possibility of true 3D microscale connections.

10095-3, Session 1

High-speed imaging and evolution dynamics of laser induced deposition of conductive inks

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During the last decade there is an ever-increasing interest for the study of laser processes dynamics and specifically of the Laser Induced Forward Transfer (LIFT) technique, since the evolution of the phenomena under investigation may provide real time metrology in terms of jet velocity, adjacent jet interaction and impact pressure.

The study of such effects leads to a more thorough understanding of the deposition process, hence to an improved printing outcome and in these frames, this work presents a study on the dynamics of LIFT for conductive nanoparticles inks using high-speed imaging approaches. Moreover, in this study, we investigated the printing regimes and the printing quality during the transfer of copper (Cu) nanoink, which is a metallic nanoink usually employed in interconnect formation as well as the printing of silver nanowires, which provide transparency and may be used in applications where transparent electrodes are needed as in photovoltaics, batteries, etc. Furthermore, we demonstrate the fabrication of an all laser printed resistive chemical sensor device that combines Ag nanoparticles ink and graphene oxide, for the detection of humidity fabricated on a flexible polyimide substrate. The sensor device architecture was able to host multiple pairs of electrodes, where Ag nanoink or nanopaste were laser printed, to form the electrodes as well as the electrical interconnections between the operating device and the printed circuit board. Performance evaluation was conducted upon flow of different concentrations of humidity vapors to the sensor, and good response (500 ppm limit of detection) with reproducible operation was observed.

10095-4, Session 1

Modeling of selective laser sintering/ selective laser melting

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Selective laser sintering and selective laser melting are powder based AM process that can rapidly manufacture parts with comparable mechanical properties to conventional manufacturing methods directly from digital files. However, the processing recipe development and design optimization of AM parts are often based on trial and error which erodes the benefit of AM. Modeling is a powerful tool to enable faster development cycle by significantly reducing the experimental efforts. In this paper we discussed two aspects of selective laser sintering/melting modeling: 1) the process modeling, in which the laser and powder interaction was studied to understand and predict the properties of fabricated parts; 2) the mechanical properties of the micro-architectured structure, in which tailored mechanical properties can be achieved through optimization of the lattice design. A review of the current approach is presented followed by case studies and future directions.

10095-5, Session 1

How post-processing by selective thermal reflow can reduce the roughness of 3D lithography in micro-optical lenses *(Invited Paper)*

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Polymer microlenses are used in various devices, including smartphones. Since they are so small, they have to be processed using novel 3D lithographic methods that build the lenses out of thin layers (e.g. grayscale electron or laser writing) by scanning a beam. However, the trajectories and layering during the direct writing process often results in roughness in the range of the writing increment, which has adverse effects for optical applications. If a surface has to be subsequently smoothed out, it must be achieved using a method that only modifies the surface and does not change the structural details or the overall shape. For this a method known as TASTE was developed, which works particularly well with thermoplastic polymers such as PMMA. It involves the selective modification of the material properties of the part of the sample that needs modification. We have tested different methods known for defined modification of PMMA. By using high energy exposure the polymer is modified at a defined depth of the surface by chain scission followed by molecular weight dependent reflow at elevated temperatures. For surface smoothening of microlenses and –prisms we have found 172 nm UV exposure to be the ideal method for this application. A roughness of 100 nm could be removed while preserving the concave shape with up to 40 um high structures and deep central sags surrounded by high aspect ratio tips between adjacent lenses in array configuration. This was also confirmed optically for a microlens array with several 100 microlenses.

10095-6, Session 2

Laser-directed three-dimensional assembly of aligned carbon nanotubes using two-photon polymerization *(Invited Paper)*

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Precise assembly of carbon nanotubes (CNTs) in arbitrary 3D space with proper alignment is critically important and desirable for CNT applications but still remains as a long-standing challenge. Using the two-photon polymerization (TPP) technique, it is possible to fabricate 3D micro/nanoscale CNT/polymer architectures with proper CNT alignments in desired directions, which is expected to enable a broad range of applications of CNTs in functional devices. To unleash the full potential of CNTs, it is strategically important to develop TPP-compatible resins with high CNT concentrations for precise assembly of CNTs into 3D micro/nanostructures for functional device applications. We investigated a thiol grafting method in functionalizing multiwalled carbon nanotubes (MWNTs) to develop TPP-compatible MWNT-thiol-acrylate (MTA) composite resins. The composite resins developed had high MWNT concentrations up to 0.2 wt%, over one order of magnitude higher than previously published work. Significantly enhanced electrical and mechanical properties of the 3D micro/nanostructures were achieved. Precisely controlled MWNT assembly and strong anisotropic effects were confirmed. Microelectronic devices made of the MTA composite polymer were demonstrated. The nanofabrication method can achieve controlled assembly of MWNTs in 3D micro/nanostructures, enabling a broad range of CNT applications, including 3D electronics, integrated photonics, and micro/nanoelectromechanical systems (MEMS/NEMS).

10095-7, Session 2

Selective laser melting of copper using ultrashort laser pulses

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Laser assisted additive manufacturing gained increasing attention during the last decade due to the potential of creating three-dimensional freeform structures with almost any desired geometry. Selective laser melting using the so-called powder bed method is one of the most promising approaches, especially for metal based products. So far, cw laser sources and pulsed laser systems with ns pulse duration serve as radiation sources nearly exclusively.

Recently, the application of ultrashort pulse lasers came into focus. In particular, these lasers provide extremely high peak power and offer the potential to control the heat accumulation at the vicinity of the focal region by using adapted repetition rates. Therefore, also the processing of materials with extraordinary high melting points or the application of new composites come in reach. Additionally, based on the ultrashort pulse durations which are orders of magnitudes shorter than any thermal relaxation processes the exploitation of thermal non-equilibrium regimes by using extremely fast cooling rates enables the generation of new material systems and the fabrication of highly resolved geometric structures.

Here, we present selective laser melting of copper by using ultrashort laser pulses with 500 fs pulse duration at a center wavelength of 1030 nm and a repetition rate of 200 kHz.

This work involves a comprehensive study for evaluating suitable processing windows. Therefore, copper with different grains sizes was processed under different atmospheric conditions. In this frame also the influence of so-called laser burst trains is carried out, which allows the investigation of thermal accumulation impact during laser melting.

10095-8, Session 2

Additive manufacturing of borosilicate glass

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Glasses including have significant scientific and engineering applications including optics, communications, electronics, and hermetic seals. This paper investigates a filament fed process for Additive Manufacturing (AM) of borosilicate glasses. Compared to soda-lime glasses, borosilicate glasses have improved coefficient of thermal expansion (CTE) and are widely used because of thermal shock resistance. In this work, borosilicate glass filaments are fed into a CO_2 laser generated melt pool, smoothly depositing material onto the workpiece. Single tracks are printed to explore the effects that different process parameters have on the morphology of printed glass as well as the residual stress trapped in the glass. The transparency of glass allows residual stress to be measured using a polariscope. The effect of the substrate as well and substrate temperature are analyzed. We show that if fracture due to thermal shock can be avoided during deposition, then the residual stress can be relieved with an annealing step, removing birefringence. When combined with progress toward avoiding bubble

entrapment in printed glass, we show the AM approach has the potential to produce high quality optically transparent glass for optical applications.

10095-24, Session 2

Optical microdevices fabricated using femtosecond laser processing

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Femtosecond laser processing techniques have been widely employed to produce micro or nanodevices with special features. These devices can be selectively doped with organic dyes, biological agents, nanoparticles or carbon nanotubes, increasing the range of applications. Acrylate polymers can be easily doped with various compounds, and therefore, they are interesting materials for laser fabrication techniques. In this work, we use multiphoton absorption polymerization (MAP) and laser ablation to fabricate polymeric microdevices for optical applications. The polymeric sample used in this work is composed in equal proportions of two three-acrylate monomers; while tris(2-hydroxyethyl)isocyanurate triacrylate gives hardness to the structure, the ethoxylated(6) trimethyl-lolpropane triacrylate reduces the shrinkage tensions upon polymerization. These monomers are mixed with a photoinitiator, the 2,4,6-trimetilbenzoiletoxifenil phosphine oxide, enabling the sample polymerization after laser irradiation. Using MAP, we fabricate three-dimensional structures doped with fluorescent dyes. These structures can be used in several optical applications, such as, RGB fluorescent microdevices or microresonators. Using azo compounds like dopant in the host resin, we can apply these structures in optical data storage devices. Using laser ablation technique, we can fabricate periodic microstructures inside polymeric bulks doped with xanthene dyes and single-walled carbon nanotubes, aiming applications in random laser experiments. In structured bulks we observed multi-narrow emission peaks over the xanthene fluorescence emission. Furthermore, in comparison with non-structured bulks, we observed that the periodic structure decreased the degree of randomness, reducing the number of peaks, but defining their position.

10095-31, Session 2

3D printed microfluidic diffusivity meter: A tool to optimize CO2 driven enhanced oil recovery (EOR)

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As the energy demands continue to swell, there persists a lack of unexploited and partially-exploited oil-fields; the prime focus of any nation would be to maximize the oil recovery factor. Evidently, CO2 fed Enhanced oil recovery (EOR) is a process to improve crude-oil recovery as CO2 and crude-oil are miscible at high pressure, resulting in low viscosity and in turn swelling and enhanced recovery of crude-oil. This swelling can be measured based on CO2-Oil diffusion coefficient in real time and is correlated with the CO2 concentration. Currently, various methods such as, X-ray tomography, PVT measurements etc are used for this purpose, which are weighed down by disadvantages like the requirement of large samples for testing and trained manpower, high cost and complexity. This elicits the need for a Microfluidic based diffusivity meter capable of analysing nano-litre sample volumes besides being more precise, robust, automatic and affordable.

The scope of this work involves the simulation, design and development of a Microfluidic diffusivity meter using a 3D printer and endorsing its performance by comparison of results with known diffusivity range. Using COMSOL based Multiphysics simulation; we understand the behaviour of two-miscible fluids in the microfluidic co-laminar environment. The measurement of the oil swell will be measured by non-optical method and supervision of the results with an electronic microscope coupled to PC and Data Acquisition System. The prototype produced at the end of the work is expected to outweigh disadvantages in existing products in terms of sample size, efficiency and time saving.

10095-32, Session PTue

Development of 100W class blue direct diode laser system for laser metal deposition

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Multi- beam combined laser cladding system [MCLC]with blue direct diode laser has been developed at an output power of 100W and wavelength of 445nm.

Laser cladding technique is widely used for industrial application such as oil, energy industry, and aircraft and so on because it is able to repair and to form a near net shape. This process was employed infrared lasers with 0.8-10.6um wavelength, since output power of these lasers have over 1000W. Metal processing efficiency was, however, low in these wavelength, because the absorption was low. High efficiency and high quality processing method for laser cladding is required.

Thus, we developed the multi beam combined laser cladding system with blue direct diode laser. This system composed of a laser oscillator, a laser processing head, and a powder feeder. The laser was delivered from the oscillator to the laser processing head by optical fiber. The laser processing head combined 6 laser modules on the focusing spot by a lens, which one laser module was maximum power of 20W.

A copper film coating was tried on a SUS304 stainless steel plate by using the MCLC from a copper powder which diameter was 30?m. As the result, the copper layer was formed on SUS304 stainless steel plate at the output power of 50W, a sweep speed of 0.5mm/s, and power feeding rate of 30 mg/s. The layer thickness and width were 100um and 393um by single sweep, respectively.

10095-33, Session PTue

Laser induced forward transfer (LIFT) of chalcogenide glasses with femtosecond pulses

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The usage of Laser induced forward transfer (LIFT) as a direct laser writing method has experienced significant growth in the last years due to its ability to print functional materials over a variety of surfaces. The method consists on the backside irradiation of a donor substrate containing the target material to be transfer for a second substrate, called receptor, located in close proximity or in contact with the first one. Usually, pulsed UV laser are applied to transfer metallic films, such as Cu, Au, Al, Ni, enabling the write of high-resolution patterns for microelectronics. Recent advances made possible the LIFT of several classes of materials, including polymers,

ceramics and biomaterials, or even fluids and complex suspensions. Nonetheless, the transfer of glassy materials has not received proper attention despite of its relevance for the development of photonic devices. Thus, in this study, we have investigated the LIFT of chalcogenide glasses (ChG) aiming its application in all-optical circuits for nonlinear optics. In addition, LIFT has been applied with femtosecond laser pulses, which is particularly interesting due to the ability to improve the resolution of the deposited structures due to multiphoton absorption effect and for maintaining the properties of the source material by minimizing thermal effects. Thin films of arsenic trisulfide have been used as target material for fs-LIFT, which has enabled the produce microstructure of this ChG with promising applications on all-optical and spectral broadening devices for the mid-infrared. The authors acknowledge FAPESP, CAPES, CNPq and USP-Princeton partnership for the financial support.

10095-34, Session PTue

Effect on beam profile of Ti alloy plate fabrication from powder by sputter-less selective laser melting

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Titanium alloy ,which has a crystal orientation of alpha ? + ? type, are clinical employed for an artificial bone and a hard tissue implant for human body because of light, nonmagnetic, weather resistance and biocompatibility, but it is difficult to form a complicated structure, as a bionic structure, owing to a difficult-to-cut machine material.

Titanium alloy plates were fabricated by SLM in vacuum owing to investigation of the phase transformations for Ti64. Melting and solidification process were captured with high speed video camera, it was found that sputter was depended on the surface roughness. The sputter-less fabrication for SLM in vacuum was developed to minimize the surface roughness to 0.40μm at the laser scanning speed of 10mm/s. It was also determined the crystal orientations of fabricated Ti64 plates. From the results, it can be seen from the powder peaks of ? (0002) and ? (1010) that the crystal orientation is composed mainly of martensitic alpha. Diffraction peaks corresponding to ? (110) were detected in vacuum SLM processed samples at baseplate temperature of 50?. Increasing the baseplate temperature to 100?, peak intensity for ? (110) was decreased. At the 150?, ? (110) was disappeared. It was clarified that the phase transformation for Ti64 was controlled by changing the baseplate temperature.

10095-35, Session PTue

Production of polymeric microstructures connected to fiber tapers for incorporation to photonic circuits

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The incorporation of polymeric platforms to photonic devices is interesting because different compounds can be added to the polymeric matrix, changing the material physical properties and allowing the introduction of new functionalities to photonic circuits. Furthermore, the two-photon polymerization technique allows the production of three-dimensional polymeric microstructures with resolution below the diffraction limit. In order to effectively incorporate these microstructures to photonic devices, it is necessary to develop ways to connect them to excitation sources and analysis instruments. Fiber tapers are a suitable tool for this task as their diameter matches the size of the microstructures. We have already reported on the use of fiber tapers to perform the excitation and emission collection of fluorescent microstructures. However, it is still necessary to develop ways to connect different microstructures to each other, so the complexity of the optical circuits based on polymeric microstructures can be increased. To perform such task, fiber tapers were incorporated to the unpolymerized resin and the polymeric microstructures were produced by two-photon polymerization, excited by a Ti:sapphire laser oscillator. Two galvanometric mirrors move the beam laterally and a translation stage moves the sample axially. The sample was carefully positioned so the microstructures were produced surrounding the fiber taper. In this work, we report on the viability of this method for the production of polymeric microstructures physically connected to fiber tapers and on the initial tests regarding the efficiency of the optical connections. We would like to acknowledge FAPESP (2011/12399-0, 2015/22392-3) for the financial support.

10095-36, Session PTue

Multifunctional cube-like system for biomedical applications featuring 3D printing by dual deposition, scanner, and UV engraving

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A cubic-like structure is proposed in order to scan tools used as medical equipment and printed them at low cost for under development countries. The structure uses a 3 axis plane frame that uses high-precision step motors. At “x” and “y” axis are driven by an actuator and serrated bands with 2 mm pitch. Those give and accuracy of 2.5 microns tops. Z-axe is driven by and inductive sensor that allows to keep the focus to the printing bed as well as to search for smoothless areas to correct it and deliver an homogeneous impression. The 3D scanner as well as the entire gears are placed underneath in order to save space. As extrude tip, we are using a 445 nm UV laser with 2000 mW of power. The laser system is able to perform the following functions crystallizing, engraving or cut though a set of mirror arrays. Crystallization occurs when the laser is guided towards the base. This process allows to be directed towards the polymer injector and as a result it crystalizes on the spot. The engraving process occurs while the base moves. The movement allows the beam to pass freely towards the base and engrave it.

10095-37, Session PTue

Galvanometer scanning technology for laser additive manufacturing

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A galvanometer laser beam scanning system is an essential element in many laser additive manufacturing technologies including Stereolithography (SLA), Selective Laser Sintering (SLS) and Selective Laser Melting (SLM), therefore understanding the scanning technology and recent innovations in this field will greatly benefit the 3D laser printing system integration and technology advance.

Delivering uniform laser density on the powder bed is often required to achieve a high quality finish part. The conventional method to control the galvanometer movement typically involves acceleration and deceleration at ends of the hatching and outlining patterns. This can lead to non-uniform laser power density on the power bed affecting the melting characteristics.

One strategy to solve the problem is to modulate the laser power as the function of the scanner velocity during the acceleration or decoration

periods. Another strategy is to use smart control algorithm to maintain the constant speed throughout the job. This is done by dynamically planning the scanning trajectory and coordinating the laser on and off operations with this trajectory planning. In this paper, we demonstrate the high accuracy and low drift digital scanning technology that incorporates both techniques to achieve uniform laser density with minimal additional process development. With the dynamic trajectory planning method, the scanner not only delivers high quality and uniform results, but the overall throughput processing a typical LAM job can also be improved by 20% compared to that of the conventional control method.

10095-39, Session PTue

Integrated two-photon and direct write lithography for 3D structure production

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Two-photon (2PL), holographic and direct write lithographic techniques, in positive and negative tone photoresists, have been combined to produce 3D nano and microscale structures for photonic and mechanical applications. The lithographic processes are detailed as well as the conversion techniques used to convert the 3D polymeric structures into higher index of refraction materials for photonic applications and higher modulus materials for mechanical applications by atomic layer deposition, chemical vapor deposition, chemical etching and ion etching techniques.

Optical measurements include visible and infrared reflectivity to characterize optical bandgaps and to evaluate structural uniformity and quality. The experimental results are compared to theoretical predictions of optical properties of the 3D structures. The structures are also characterized by serial focused ion beam (FIB) milling and imaging. The 3D structures engineered for mechanical applications are characterized static and dynamic local mechanical measurements to investigate size and structure dependent mechanical properties.

10095-40, Session PTue

Coordinate measuring system based on microchip lasers for reverse prototyping

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According to the current great interest concerning Large-Scale Metrology applications in many different fields of manufacturing industry, technologies and techniques for dimensional measurement have recently shown a substantial improvement. Ease-of-use, logistic and economic issues, as well as metrological performance, are assuming a more and more important role among system requirements. The project is planned to conduct experimental studies aimed at identifying the impact of the application of the basic laws of chip and microlasers as radiators on the linear-angular characteristics of existing measurement systems. The project is planned to conduct experimental studies aimed at identifying the impact of the application of the basic laws of microlasers as radiators on the linear-angular characteristics of existing measurement systems. The system consists of a distributed network-based layout, whose modularity allows to fit differently sized and shaped working volumes by adequately increasing the number of sensing units. Differently from existing spatially distributed metrological instruments, the remote sensor devices are intended to provide embedded data elaboration capabilities, in order to share the overall computational load.

10095-502, Session Plen

Printing Hybrid Electronics by Laser Direct-Write

Alberto Piqué, U.S. Naval Research Lab. (United States)

The use of laser direct-write (LDW) techniques for printing functional materials for a wide-range of applications is growing as additive manufacturing or AM becomes more established. With LDW, precise control of a wide range of processing steps — from subtractive to additive — is possible over a wide range of scales with an extensive materials palette. These non-lithographic processes constitute some of the earliest demonstrations of?3D printing or AM at the microscale. This talk will review the current status of micro-fabrication processes based on LDW, such as laser-induced forward transfer or LIFT, and their use to fabricate “hybrid” structures comprising both printed and embedded electronic components. These examples will illustrate the role that LDW is poised to play in the additive micro-fabrication of hybrid circuits for the development of the next generation of 3D printed electronics.

10095-9, Session 6

Application of laser ultrasonic pulse-scripts to material processing *(Invited Paper)*

Henry Helvajian, Jeffrey K. Wuenschell, The Aerospace Corp. (United States)

Prior studies have shown that the presence of ultrasonic waves can influence the kinetics of phase transitions through changes in rates for nucleation and diffusion. This work explores the utility of using a laser-generated ultrasonic excitation as a perturbation in phase transition process and realize better control in laser material processing. A laser material processing experiment has been developed whereby laser generated ultrasonic waves are placed in close proximity (within 100 microns) to a CW laser which drives the material out of equilibrium (i.e. processing laser). The small spatial distance between the source of the pulsed ultrasonic excitation and the process region enables the interaction of high frequency waves (>50MHz) with the material that is transforming. Moreover, amplitude modulation of the processing laser and the ultrasonic source laser, coupled with time synchronization, allows the ultrasonic perturbation to influence the dynamics of the material transformation process. Material systems characterized by multiple achievable final states are being investigated, with the goal of tailoring scripted excitations to drive the final state of the system into the desired configuration. Two systems are examined wherein precise control over the processed crystal structure is valuable: yttria-stabilized zirconia – an important material in thermal-barrier coating and fuel cell applications – and thin-film (< 10 nm) molybdenum disulfide – which is of great interest in the field of flexible electronics.

10095-10, Session 6

Enabling additive manufacturing qualification *(Invited Paper)*

Mark D. Benedict, Air Force Research Lab. (United States)

While Additive Manufacturing (AM) is beginning to deliver on the promise of revolutionizing the aerospace manufacturing industry, one of the largest barriers to broader adoption of AM for producing aerospace parts is the lack of a standardized qualification process. By leveraging investments with industry driven consortia such as the Metals Affordability Initiative and America Makes, the Air Force Research Laboratory is supporting research that enables the transition from slow and costly point qualifications to more general qualification and certification approaches. Key areas of targeted research that inform the qualification of additive materials and processes include: enabling fully characterized process definition, developing in-situ process monitoring and sensing, identifying the limits of AM part inspectability, and quantifying of the drivers of manufacturing variability in AM production parts. Recent progress made in three representative programs will be presented.

10095-12, Session 7

Effect of AM printing parameters and thermal transport on solidification structure and mechanical behavior of 316L stainless steel prototypes *(Invited Paper)*

Nancy Yang, Josh Yee, Kyle Gaiser, Wei-Yang Lu, Tom Reynolds, Lee Clemon, Richard Karnesky, Sandia National Labs. (United States); Baolong Zheng, Yizhang Zhou, Enrique J. Lavernia, Julie M. Schoenung, Univ. of California, Irvine (United States)

Additive manufacturing (AM) enables the building of a complex components that are otherwise impossible to be built using traditional technologies. Our AM technology maturation efforts focus on process-structure-property relationships, a necessary knowledge base for ensuring material reliability, property consistency, and predictability. The present study shows the physical metallurgy of prototypes built by 3-D Laser Engineered Net Shaping (LENS) is geometry, dimension, and location dependent, attributed to local thermal transport and heat distribution. We found that Vickers microhardness increases with 3-D LENS feature dimension due to the reduction in solidification cell size due to interpass boundary pinning. In this presentation, we will discuss the effect of 3-D LENS process parameters and condition on solidification structure and mechanical behavior of 316L stainless steel prototypes. In addition, we will present the material science findings related to other AM printings such as 3-D Powder Bed Fusion (PBF) of 316L stainless steel.

10095-13, Session 7

Laser additive manufacturing of multimaterial tool inserts: A simulation-based optimization study

Sankhya Mohanty, Francesco G. Biondani, Jesper H. Hattel, Technical Univ. of Denmark (Denmark)

Selective laser melting is fast evolving into an industrially applicable manufacturing process. While components produced from high-value materials, such as Ti6Al4V and Inconel 718 alloys, are already being produced, the processing of multi-material components still remains to be achieved by using laser additive manufacturing. The physical handling of multi-material in a SLM setup continues to be a primary challenge along with the selection of process parameters/plan to achieve the desired results – both challenges requiring considerable experimental undertakings. Consequently, numerical process modelling has been adopted towards tackling the latter challenge in an effective manner.

In this paper, a numerical simulation based optimization study is undertaken to enable selective laser melting of multi-material tool inserts. A standard copper specimen covered by a thin layer of nickel is chosen, over which a layer of steel has been deposited using cold-spraying technique, such as to protect the microstructure of Ni during selective laser melting. The process modelled thus entails additively manufacturing a steel tool insert around the multi-material specimen with a goal of achieving a dense product while preventing recrystallization in the Nickel layer. The process is simulated using a high-fidelity thermo-microstructural model with constant processing parameters to capture the effect on Nickel layer. Based on results, key structural and process parameters are identified, and subsequently an optimization study is conducted using evolutionary algorithms to determine the appropriate process parameter values as well as processing sequence. The optimized process plan is then used to manufacture real multi-material tool insert samples by selective laser melting.

10095-14, Session 7

Direct measurements of laser absorptivity during metal melt pool formation associated with powder bed fusion additive manufacturing (AM) processes

Johannes Trapp, TU Dresden (Germany); Alexander M. Rubenchik, Gabriel M. Guss, Crumb Michael, Manyalibo J. Matthews, Lawrence Livermore National Lab. (United States)

Knowledge of the effective absorptivity in selective laser melting is crucial for the efficient selection of build parameters as well as modelling and simulation of the process. The complex physics of laser-metal interaction and the non-ideal shape and surface constitution of metal powders makes any modeling of absorption unreliable.

We designed an experimental setup to directly measure the effective absorptivity for various metal powders deposited onto substrates (316l stainless steel, aluminum, Ti6Al4V, tungsten) under conditions close to the conditions of AM process. With our calorimetric approach, we measured the effective absorptivity for scanning velocity and laser power ranging from 100 to 1500 mm/s and 30 to 500 W, respectively.

After careful validation of the applicability of the proposed method, we demonstrate the evolution of the effective absorptivity starting from laser-powder interaction below the melting point of the to well-developed keyhole formation. We demonstrate that laser power increase results in a drop of absorptivity which can be attributed to evaporation, and then the steep absorptivity increase and saturation due to keyhole formation. Modeling and ex situ examination of the meltpool geometry support the interpretation of the experimental results.

10095-15, Session 7

Brillouin micro-elastography of laser-processed materials

Vladislav V. Yakovlev, Texas A&M Univ. (United States)

3D laser processing is becoming a mainstream of micro- and nano-fabrication. However, very little is known how physical, chemical and/or structural changes induced by laser irradiation affects local mechanical properties. In this report, we, for the first time, utilized Brillouin microspectroscopy to assess and image the variation of viscoelastic properties induced by laser irradiation. While the primary focus of our research is related to biological tissues and laser surgery applications, the newly developed methodology for assessing those mechanical variations in bulk of laser processed materials is broadly applicable to any other system of interest. In my talk I will introduce Brillouin spectroscopy as an emerging tool to quantify microscopic viscoelastic properties [1] and illustrate its applicability to characterize the variation of mechanical properties in response to laser irradiation.

References:

[1] Z. Meng et al, Advances in Optics and Photonics 8 (2), 300-327 (2016).

10095-16, Session 7

3D scanning and printing of airfoils for modular UAS

Robert P. Dahlgren, Ethan A. Pinsker, CSUMB/NASA Ames Research Ctr. (United States); Omar G Dary, Purdue Univ. (United States); Joab A. Ogunbiyi, Morgan State Univ. (United States); Arash Alex Mazhari, NASA Ames Research Ctr. (United States) and Millenium Engineering and Integration Co. (United States)

The NASA Ames Research Center has been developing small unmanned airborne systems (UAS) based upon recycled military aircraft such as the RQ-14 DragonEye and RQ-11 Raven manufactured by AeroVironment. The first step is replacing OEM avionics with COTS avionics that do not use military frequencies for command and control. 3D printing and other rapid prototyping techniques are used to graft RQ-14 components into new "FrankenEye" aircraft and RQ-11 components into new "FrankenRaven" airframes. To that end, it is necessary to design new components to concatenate wing sections into elongated wingspans, construct biplane architectures, attach payload pods, and add control surfaces. When making components such as wing splices it is critical that the curvature and angles of the splice identically match the existing wing at the mating surfaces. The RQ-14 has a thick, simple airfoil with a rectangular planform and no twist or dihedral which make splice development straightforward. On the other hand the RQ-11 has a much thinner sailplane-type airfoil having a tapered polyhedral planform. 3D scanning of the Raven wings with a NextEngine scanner could not capture the complex curvature of the high-performance RQ-11 airfoil, resulting in non-matching and even misshapen splice prototypes. To characterize the airfoil a coordinate measuring machine (CMM) was employed to measure the wing's shape, fiducials and mounting features, enabling capture of the subtle curves of the airfoil and the leading and trailing edges with high fidelity. In conclusion, both rapid and traditional techniques are needed to precisely measure and fabricate wing splice components.

10095-17, Session 8

Optofluidic label free sensor fabricated by hybrid femtosecond laser micromachining

Eugenia Lepera, CNR-Istituto di Fotonica e Nanotecnologie (Italy); B. Horváth, Institute of Biophysics, Hungarian Academy of Sciences (Hungary) and Biological Research Ctr., Hungarian Academy of Sciences (Hungary); Lorand Kelemen, Pál Ormos, Biological Research Ctr., Hungarian Academy of Sciences (Hungary) and Institute of Biophysics, Hungarian Academy of Sciences (Hungary); Roberto Osellame, Rebeca Martínez Vázquez, CNR-Istituto di Fotonica e Nanotecnologie (Italy)

Femtosecond laser manufacturing (FLM) has a high potential for the fabrication of Lab-On-a-Chip (LOC) devices; it can directly produce 3D buried microfluidic networks by laser irradiation followed by chemical etching (FLICE), photonic circuits by direct laser writing and 3D micro/nanostructures by two-photon polymerization (2PP). Separately these methods have inherent fabrication limitations that can be overcome combining them in a hybrid approach for the fabrication of LOCs.

Polymer micro-resonators are known to be high-sensitive biological label-free sensors, but it is also challenging to integrate them inside microfluidic chips. In this work, we propose a microfluidic device with an integrated label free sensor fabricated by the combination of (2PP) and FLICE techniques.

The label free sensor consists of 3D suspended micro-resonators and adjacent optical waveguides fabricated in SU8 photopolymer by 2PP, in such a geometry that allows us to directly couple light into them by optical fibers. Different fabrication parameters and geometries have been explored in order to obtain the highest quality factor.

Afterwards we have integrated these freestanding 2PP structures inside a microfluidic chip composed of a central channel and two perpendicular fibers lodging horizontally shifted by 16um improve the signal to noise ratio. This approach allows us to have a compact and fully integrated LOC for refractive index change sensing. The final device has been validated using different refractive index solutions.

10095-18, Session 8

Two-component 3D printed microlattices allowing sign reversal of thermal expansion *(Invited Paper)*

Martin Wegener, Karlsruher Institut für Technologie (Germany)

In many situations, uncontrolled thermal expansion is a nuisance and can lead to destruction or failure of structures and materials. It is thus desirable to control the thermal length-expansion coefficient of 3D printed materials. Here, following theoretical suggestions by Lakes, we design, fabricate, and characterize 3D microstructured metamaterials allowing for negative or zero thermal expansion from two different constituents, both with positive thermal expansion. The two different constituents are obtained by dip-in 3D laser lithography, a single photoresist, and gray-tone lithography. The characterization is based on cross-correlation analysis of optical microscopy images taken at different sample temperatures.

10095-19, Session 8

Ultra-strong mechanical metamaterials by two-photon lithography *(Invited Paper)*

Jens Bauer, Univ. of California, Irvine (United States); Stefan Hengsbach, Almut Schroer, Ruth Schwaiger, Oliver Kraft, Karlsruher Institut für Technologie (Germany); Lorenzo Valdevit, Univ. of California, Irvine (United States)

Loosely spoken, light materials are weak, and strong materials are heavy, strength and density are considered to be coupled. However, due to their specifically designed architecture, lattice materials have been shown to reach remarkable strength at low density, which may not be achievable by classical material design such as optimizing the chemistry and the microstructure of monolithic materials.[1] Inspired by natures hierarchical cellular materials and triggered by the recent evolution of high-resolution additive manufacturing technologies a miniaturization of such lattice structures took place in the last years,[2,3] yielding a class of light-weight mechanical metamaterials whose effective properties in addition to their topology, significantly depend on the microscopic length-scale of their pattern.[4–6]

In our work, we have fabricated nano-architected lattice materials from ceramic-polymer-composites as well as from carbon, by applying 3D direct laser writing and subsequent techniques such atomic layer deposition and pyrolysis. The materials achieve extremely high effective strengths of up to 1 GPa at densities well below 1 g/cm?.[6] Due to the small dimensions of their individual structural features, with diameters in the range of 200 nm they are able to make use of size-dependent material strengthening effects.

An overview of applied manufacturing routs and relevant processing details will be given.[7,6] The interplay of size-dependent strengthening effects with different topological and material design approaches are shown.[4,6,8,9] Up scaling methods, such as multi-level hierarchy approaches as well as limitations in practical application will be discussed.

1. Fleck, N. A., Deshpande, V. S. & Ashby, M. F. Micro-architectured materials: past, present and future. Proc. R. Soc. A Math. Phys. Eng. Sci. 466, 2495–2516 (2010).

2. Schaedler, T. A. et al. Ultralight metallic microlattices. Science 334, 962–965 (2011).

3. Zheng, X. et al. Ultralight, ultrastiff mechanical metamaterials. Science 344, 1373–1377 (2014).

4. Bauer, J., Hengsbach, S., Tesari, I., Schwaiger, R. & Kraft, O. High-strength cellular ceramic composites with 3D microarchitecture. Proc Natl Acad Sci USA 111, 2453–2458 (2014).

5. Meza, L. R., Das, S. & Greer, J. R. Strong, lightweight, and recoverable three-dimensional ceramic nanolattices. Science 345, 1322–1326 (2014).

6. Bauer, J., Schroer, A., Schwaiger, R. & Kraft, O. Approaching theoretical strength in glassy carbon nanolattices. Nat. Mater. 15, 438–443 (2016).

7. Valdevit, L. & Bauer, J. in Three-Dimensional Microfabrication Using Two-Photon Polymerization: fundamentals, technology, and application (ed. Baldacchini, T.) 345–373 (Elsevier, 2015).

8. Bauer, J., Schroer, A., Schwaiger, R. & Kraft, O. The Impact of Size and Loading Direction on the Strength of Architected Lattice Materials. Adv. Eng. Mater. (2016). doi:10.1002/adem.201600235

9. Bauer, J. et al. Push-to-pull tensile testing of ultra-strong nanoscale ceramic-polymer composites made by additive manufacturing. Extrem. Mech. Lett. 3, 105–112 (2015).

10095-20, Session 8

Influences of exposure strategies and focusing optics on the fabrication of large scale microlenses via two-photon polymerization

Daniel Kuehn, Ruth Houbertz, Alexander Krupp, Benedikt Stender, Multiphoton Optics GmbH (Germany); Willi Mantei, Julius-Maximilians-Univ. Würzburg (Germany)

Entering the industrial level, high-precision 3D printing via two-photon polymerization (2PP) offers a wide range of applications with novel design opportunities for different fields in optics, photonics, biomedicine, and life sciences. Due to the highly flexible fabrication process of 2PP, arbitrary freeform structures like micro-optical elements are feasible. However, certain challenges have to be met in order to fabricate large scale, high quality microlenses. Especially for high-quality imaging applications, the surface roughness of the microlenses needs to be better than ?/10 of the operation wavelength to avoid aberrations. Furthermore, deviations in the shape of the printed lenses compared to the design should be kept at a minimum or even be negligible.

As it will be demonstrated in this work both, quality and fabrication time of microlenses crucially depend on the used focusing optics, and thereby the voxel dimension, as well as on the underlying exposure strategy. The influence of different exposure parameters on the final high-quality microlenses will be demonstrated and discussed. Commercially available hybrid polymers, ORMOCER®s, were used to additively fabricate the microlenses via a controlled polymerization process. We demonstrate the writing of large microoptical components in the range of several hundred micrometers in height and diameter which are manufactured as a single object without stitching. Furthermore, we show that the exposure path has to be adapted to obtain the predesigned shape of the microlens for the use of different focusing optics during the fabrication process.

10095-21, Session 8

Laser beam diagnostics in laser 3D manufacturing applications

Otto W. Märten, Stefan Wolf, Nicholas J. Harrop, PRIMES GmbH (Germany)

3D Laser manufacturing applications, like selective laser melting, have generated multiple applications even in safety sensitive applications like aerospace and car manufacturing. While the laser beam is the driver of the melting process, a lot of system components e.g. optics in the beam path and the galvo head influence these beam properties, usually negatively. Optics are heated up by small amounts of absorbed power, resulting in focus shift.

Lasers used for selective laser melting are often triggered to emit their power corresponding to the position of the laser beam where the melting should take place, in order to generate a certain detail of the produced part. Because of the delay between trigger pulse and laser emission, the trigger has precede the positioning of the laser beam. The delay of the laser has to be programmed in the machine controller to achieve a perfect synchronization of laser emission and beam position.

We have performed a study on the performance of the pulse emission of a 400 W single mode fiber laser often used for selective laser melting processes and on the focus shift of the beam path and the optics in the galvo head. We will show results on the delay between trigger laser emission and the influence of power level on the delay. For the focusshift we will show the influence of optical components in beam path and galvo head on the beam properties and the focus shift in several optical setups commonly used in machines for selective laser melting.

10095-22, Session 9

High-strength, light-weight mechanical metamaterials based on 3D direct laser writing *(Invited Paper)*

Ruth Schwaiger, Karlsruher Institut für Technologie (Germany)

Cellular materials with designed three-dimensional architectures and characteristic features in the micro-to-nanometer range exhibit superior strength-to-density ratios. Miniaturizing the characteristic features benefits from mechanical size effects, which can be exploited even further to improve the properties of mechanical metamaterials. The current lithography technologies, though, are often limited by their resolution and by the use of polymer resins, which typically exhibit rather poor mechanical properties. Different strategies can be pursued to expand the properties and, thus, the applicability of the lattice materials. First of all, annealing treatments after the fabrication may result in higher strengths because of increased cross-linking of the polymer. Then, coating with ceramic films, 10 - 100 nm thick deposited by atomic layer deposition, takes advantage of mechanical size effects as the strength of such thin films exceeds the strength of the corresponding bulk material. Furthermore, the whole polymeric microlattice can be treated by pyrolysis and undergoes isotropic shrinkage, thereby reducing strut diameters down to 200 nm and transforming the polymer lattice into glassy carbon. The micro and nanolattices are characterized using nanomechanical testing methods. Deformation and failure of these designed cellular materials depend sensitively on details of the architecture. We demonstrate that their specific strength is significantly improved compared to all other engineering foams with a density below 1 g/cm?.

10095-23, Session 9

Bulk diamond optical waveguides fabricated by focused femtosecond laser pulses *(Invited Paper)*

J.P. Hadden, Univ. of Calgary (Canada); Belen Sotillo, Vibhav Bharadwaj, Politecnico di Milano (Italy); Stefano Rampini, CNR-Istituto di Fotonica e Nanotecnologie (Italy); Federico Bosia, Federico Picollo, Univ. degli Studi di Torino (Italy); Masaaki Sakakura, Kyoto Univ.

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Diamond's nitrogen-vacancy (NV) centers show great promise in sensing applications and quantum computing due to their long electron spin coherence time and their ability to be located, manipulated and read out using light. The electrons of the NV center, largely localized at the vacancy site, combine to form a spin triplet, which can be polarized with 532-nm laser light, even at room temperature. The NV's states are isolated from environmental perturbations making their spin coherence comparable to trapped ions. An important breakthrough would be in connecting, using waveguides, multiple diamond NVs together optically. However, the inertness of diamond is a significant hurdle for the fabrication of integrated optics similar to those that revolutionized silicon photonics. In this work we show the possibility of buried waveguide fabrication in diamond, enabled by focused femtosecond high repetition rate laser pulses. We use microRaman spectroscopy, post-etching methods, transmission electron microscopy and stress-field simulations to gain better insight into the structure and refractive index profile of the optical waveguides. Using optically detected magnetic resonance and confocal photoluminescence characterization, high quality NV properties are observed in waveguides formed in both optical and quantum grade diamond, making them promising for integrated magnetometer or quantum information systems, respectively.

10095-25, Session 9

Micro and nano printing of carbon materials by pulsed laser deposition at atmospheric pressure

Luis V. Ponce, Ctr. de Investigación en Ciencia Aplicada y Tecnología Avanzada, Instituto Politécnico Nacional (Mexico)

In this work, we present selected results on 3D microprinting departing from carbon nanomaterial targets by using Pulsed Laser Deposition technique at atmospheric pressure. As a laser source, a Nd:YAG Q:Switched laser emitting in burst-mode is used for target ablation.Atomic force microscopy and optical results indicate that is possible to obtain micro and nanostructured layers and structures such as graphene oxide films and carbon quantum dots with interesting properties for energy and health applications, such as tunable luminescence between other. The discussed results provide new opportunities for designing and producing micro and nanodevices of diverse nature by a rapid and non-vacuum technique.

10095-41, Session 9

Selective laser melting of hypereutectic AlSi40 using ultrashort laser pulses

Tobias Ullsperger, Gabor Matthäus, Lisa Schade, Markus Rettenmayr, Friedrich-Schiller-Univ. Jena (Germany); Stefan Risse, Fraunhofer Institute for Applied Optics and Precision Engineering (Germany); Andreas Tünnermann, Stefan Nolte, Friedrich-Schiller-Univ. Jena (Germany) and Fraunhofer Institute for Applied Optics and Precision Engineering (Germany)

In recent years, selective laser melting (SLM) evolved into one of the most promising techniques for future fabrication of highly sophisticated freeform structures covering a wide range of materials. However, the processing of specific material compositions like hypereutectic alloys involves fundamental problems. In particular, during fabrication, using conventional cw lasers, the cooling rate of these alloys is too low resulting in a decomposition of different material components. Consequently, an inhomogeneous micro-structure is generated with highly degraded mechanical properties. Furthermore, the thermal influence arising from the application of cw lasers limits the achievable processing resolution significantly.

In this work, we present the additive manufacturing of hypereutectic AlSi40 elements based on the common powder-bed method. In contrast to conventional laser radiation, we used ultrashort laser pulses in order to exploit extremely high peak intensities at extraordinary short interaction times. This laser radiation allows non-equilibrium solidification based on highly confined spatiotemporal energy deposition. The laser system is based on a high repetition rate fiber laser amplifier delivering 500 fs laser pulses at a center wavelength of 1030 nm allowing a wide range of parameter sets covering repetition rates up to 20 MHz.

Consequently, completely different melting regimes can be addressed which we applied for the fabrication of several AlSi40 elements. We can show that fast solidification processes can be realized which lead to highly uniform micro-structures. Moreover, the potential for controlling the heat affected zone enables high resolution processing which is basically only limited by the corn size itself.

10095-26, Session 10

Adopting additive manufacturing for critical applications *(Invited Paper)*

Richard P. Martukanitz, Sanjay S. Joshi, Frederick Lia, Zachary Snow, The Pennsylvania State Univ. (United States)

Additive manufacturing defines a range of processes that involve novel formative means to transform feed stock into functional parts. As applied to metallic materials, these processes are relevant to the manufacture of engineered parts and encompass the use and manipulation of precise high energy heat sources, such as laser or electron beams, for consolidation of powder or wire stock provided at the point of addition or through a continually recharged powder bed. Although these processes offer huge incentives, the utilization of additive manufacturing for critical components will be dictated by the ability to consistently produce material that will meet the performance requirements established for the intended application.

This presentation will discuss factors that may influence the adoption of additive manufacturing for these applications, with emphasis on current activities at the Center for Innovative Materials Processing through Direct Digital Deposition (CIMP-3D) at Penn State in developing techniques and practices for meeting the functionality, reliability, and assurance of parts produced using these processes. This will include discussions involving engineering relationships that may define mechanical properties based on process attributes, sensing and control strategies that may be used to assure process consistency, and management of additive manufacturing data that may be used to document and verify important parameters that define the process and the material produced.

The additive manufacturing process, in conjunction with post processing conditions, has a profound impact on material performance due to the potential for creating process related defects and influencing the development of microstructures. Hence, recent research in establishing relationships between processing conditions, microstructures, and mechanical properties of two alloys commonly used in additive manufacturing (Ti-6Al-4V and Inconel 625) will be discussed. Upon establishment of optimal additive manufacturing conditions for producing a part that will meet the intended requirements established by the design, the process must also provide sufficient reliability to assure that these requirements are met throughout the manufacturing state. This may be achieved through the definition of the process in terms of essential

variables, the monitoring of these important parameters, and sensing of ancillary characteristics that may augment validation of the process. Several current activities involving the development of techniques for improving process reliability will also be discussed. Finally, the conditions and parameters used to produce components through additive manufacturing must be sufficiently documented for quality assurance. To address this need, a comprehensive process data management plan under development for additive manufacturing will be described.

10095-27, Session 10

Wire-based laser metal deposition for additive manufacturing of Ti6Al4V: Basic investigations of microstructure and mechanical properties from build up parts

Fritz Klocke, Kristian Arntz, Nils Klingbeil, Martin Schulz, Fraunhofer-Institut für Produktionstechnologie IPT (Germany)

The wire-based laser metal deposition (LMD-W) is a new technology which enables to produce complex parts made of titanium for the aerospace and automotive industry. For establishing the LMD-W as a new production process it has to be proven that the properties are comparable or superior to conventional produced parts. The mechanical properties were investigated by analysis of microstructure and tensile test. Therefore specimen were generated using a 4.5 kW diode laser cladding system integrated in a 5-Axis-machining center.

The structural mechanical properties are mainly influence by crystal structure and thereby the thermal history of the workpiece. Especially the high affinity to oxide, distortion and dual phase microstructure make titanium grade 5 (Ti6Al4V) one of the most challenging material for additive manufacturing. By using a proper local multi-nozzle shielding gas concept the negative influence of oxide in the process could be eliminated. The distortion being marginal at a single bead, accumulated to a macroscopic effect on the workpiece. The third critical point for additive processing of titanium, the bimodal microstructure, could not be cleared by the laser process alone. All metallurgical probes showed ?'-martensitic-structure. Therefore a thermal treatment became a necessary production step in the additive production chain. After the thermal treatment the microstructure as well as the distortion was analyzed and compared with the status before.

Although not all technical issues could be solved, the investigation show that LMD-W of titanium grade 5 is a promising alternative to other additive techniques as electronic beam melting or plasma deposition welding.

10095-28, Session 10

New horizons in advanced manufacturing for naval applications *(Invited Paper)*

Jennifer Wolk, U.S. Naval Research Lab. (United States)

No Abstract Available

10095-29, Session 10

Additive manufacturing with laser metal fusion: Part production and generation of 3D features onto preformed structures

Frank Geyer, TRUMPF Inc. (United States)

Additive manufacturing (AM) is a hot trend that is discussed amongst many industries. In the field of AM with metal powders the methods Laser Metal Deposition (LMD) and Laser Metal Fusion (LMF) and are widely used. Each process offers a variety of advantages as well as limitations.

Typically the process LMF is used to generate complete structures build on a substrate plate. This presentation will show an application where preformed parts get complex 3D features added through laser metal fusion in a production setup. With this process high production volumes can be achieved by combining conventional manufacturing methods with LMF for the higher complexity features, thus reducing the print and cycle times.

Conference 10096: Free-Space Laser Communication and Atmospheric Propagation XXIX

Monday - Wednesday 30–1 February 2017

Part of Proceedings of SPIE Vol. 10096 Free-Space Laser Communication and Atmospheric Propagation XXIX

10096-1, Session 1

Beam wander and scintillation measured on a terrestrial range

Rita Mahon, Mike S. Ferraro, James L. Murphy, William S. Rabinovich, U.S. Naval Research Lab. (United States)

The combined effects of beam wander and scintillation are studied for a Gaussian beam that has propagated along a terrestrial range. The beam had a nominal 1/e2 radius of 20mm at the exit of the optical interrogator and its divergence could be varied by adjustment of the fiber to lens spacing. The beam was allowed to freely expand over a range of 4.2km and was imaged as it illuminated a 64"x 80"screen. The wavelength was 1.55μm and an InGaAs windowing camera was used to record the beam at 200 frames per second. Two sets of data are analyzed: a set taken in low turbulence where Cn2 was in the range of 4 x 10-15 to 1 x 10-14 and a high turbulence set of data with Cn2 ~ 1.4 x 10-13. The angular position of the intensity centroid is mapped in space and time and comparison made with model predictions of the short term and long term beam parameters.

10096-2, Session 1

A scintillation playback system for quantum links

William S. Rabinovich, Rita Mahon, Mark Bashkansky, U.S. Naval Research Lab. (United States); John F. Reintjes, Sotera Defense Solutions, Inc. (United States)

Quantum key distribution (QKD) using free space optical (FSO) systems will, in most applications, involve atmospheric propagation. As is well known from classical FSO communication links, turbulence can cause large power variation in the link strength,. In this paper we present a system for recording scintillation fluctuations in the field and playing them back in a laboratory based quantum communications testbed.

10096-3, Session 1

Impact of atmospheric anisoplanaticity on earth-to-satellite time transfer over laser communication links

Aniceto Belmonte, Univ. Politècnica de Catalunya (Spain); Michael Taylor, Leo Hollberg, Joseph M. Kahn, Stanford Univ. (United States)

The need for an accurate time reference on orbiting platforms motivates the study of time transfer over satellite optical communication links. The transfer of precise optical clock signals to space would benefit many fields in fundamental science and applications. However, the precise role of atmospheric turbulence during the optical time transfer process is not well-known and documented. In free-space optical links, atmospheric turbulence represents a major impairment, since it causes degradation of the spatial and temporal coherence of the optical signals. We present possible link scenarios in which the atmospheric channel behavior for time transfer between ground and space can be investigated, and have identified the major challenges to be overcome.

We found in our analysis that, despite the limited reciprocity in uplink and downlink propagation, partial two-way cancellation of atmospheric effects still occurs. We established that laser communication links make possible high-quality time transfer in most practical propagation scenarios and over a single satellite visibility period. Our results demonstrate that sharing of optical communication resources for optical time transfer and range determination is an effective and relevant scheme for space clock developments.

10096-4, Session 1

Atmospheric free-space coherent optical communications with adaptive optics

Chueh Ting, New Mexico State Univ. (United States); Chengyu Zhang, Tianjin Univeristy (China); Zikai Yang, Tianjin University (China)

In order to meet the needs of modern multimedia information access, the next generation of wireless area networks (WANs) require a fast data transmitting rate, high receiving sensitivity, and large channel capacity. Free-space coherent optical communication technology has the potential to offer a solution for the next-generation WANs due to the many advantages it offers, including freedom from licensing, no electromagnetic interference, huge modulation bandwidth, high security, and lower power consumption. Coherent optical communications successfully achieved a long-haul tens Giga bits per second transmission rate via guided-wave structure like optical fiber, but it is not yet available in free space due to unreliability in the atmospheric channel. To improve free-space coherent optical communications reliability affected by atmospheric channel, a novel free-space coherent optical communication system based on high spectral efficiency digital modulation schemes with adaptive optics is proposed. In this paper, the system architecture of free-space coherent optical communications with adaptive optics is introduced, followed by a proposal for a theoretical model of free-space coherent optical communications with adaptive optics. Finally, the theoretical performance evaluation of free-space adaptive coherent optical communications in terms of bit error rate (BER) versus atmospheric turbulence strength is presented.

10096-5, Session 1

Multi-beam laser beacon propagation over lunar distance: comparison of predictions and measurements

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The time series of beacon power recorded on-board LLST was analyzed. The beacon mean power is compared to link predictions while the fluctuations are presented along with the prevailing atmospheric conditions during the link. Data gathered when varying the number of beams and the beam divergence transmitted from teh ground are also presented. The irradiance inferred from the power measurements are presented as histograms and fitted to statistical distributions. The temporal power spectral density is also presented. Wave propagation simulations were used to generate a predicted time series of the fluctuations expected under prevailing atmospheric conditions, the scintillation index derived from the simulation is compared to the measured scintillation index.

10096-6, Session 1

Optical ground station optimization for future optical geostationary satellite feeder uplinks

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An optical link based on a multiplex of wavelengths at 1.55µm is foreseen to be a valuable alternative to the conventional radio-frequencies for the feeder link of the next-generation of high throughput geostationary satellite. Considering the limited power of lasers envisioned for feeder links, the beam divergence has to be dramatically reduced. Consequently, the beam pointing becomes a key issue.

During its propagation between the ground station and a geostationary satellite, the optical beam is deflected (beam wandering), and possibly distorted (beam spreading), by atmospheric turbulence. It induces strong fluctuations of the detected telecom signal, thus increasing the bit error rate. A steering mirror using a measurement from a beam coming from the satellite is used to pre-compensate the deflection. Because of the point-ahead angle between the downlink and the uplink, the turbulence effects experienced by both beams are slightly different, inducing an error in the correction.

This error is characterized as a function of the turbulence characteristics and of the terminal characteristics, such as the servo-loop bandwidth or the beam diameter, and is included in the link budget. From this result, it is possible to predict intensity fluctuations detected by the satellite, both statistically (mean intensity, scintillation index, probability of fade, etc.) and temporally (creation of time series from power spectral densities). The final objective is to optimize the different parameters of an optical ground station capable of mitigating the impact of atmospheric turbulence on the uplink in order to be compliant with the targeted capacity (1Terabit/s by 2025).

10096-7, Session 2

The fast QC-LDPC code for free space optical communication

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Free Space Optical Communication systems use the atmosphere as a propagation medium, so the atmospheric turbulence effects lead to multiplicative noise related with signal intensity. In order to suppress the signal fading induced by multiplicative noise, we introduce a fast Quasi-Cyclic (QC) Low-Density Parity-Check (LDPC) code. As a linear block code based on sparse matrix, the performances of QC-LDPC extremely near to the Shannon limit. Currently, the researches on LDPC code in Free Space Optical Communications mainly focused on Gauss-channel and Rayleigh-channel, whereas our LDPC code design over atmospheric turbulence channel which is not Gauss-channel or Rayleigh-channel is more close to the practical situation and it behaves more advanced performances. According to the characteristics of atmosphere channel, which is modeled as logarithmic-normal distribution and K-distribution, we design a special QC-LDPC code, and deduce the log-likelihood ratio (LLR). An irregular QC-LDPC code for Fast coding ,whose code rates are variable, is proposed in this paper. The proposed code achieves excellent performance of LDPC codes ,and can present the characteristics of high efficiency in low rate, stable in high rate and less number of iteration. The result of belief propagation (BP) decoding shows that the bit error rate (BER) obviously reduced as the Signal Noise Ratio (SNR) increased. So the LDPC channel coding technology can effectively improve the performance of FSO. At the same time, the bit error rate after decoding reduces with the increase of signal-to-noise ratio arbitrary, not having error limitation platform phenomenon with error rate slowing down.

10096-8, Session 2

Downlink receiver algorithms for deep space optical communications

Meera Srinivasan, Ryan Rogalin, Norman Lay, Andre Tkacenko, Matthew Shaw, Jet Propulsion Lab. (United States)

The goal of the Deep Space Optical Communications project at the Jet Propulsion Laboratory is to demonstrate laser communication links at ranges out to approximately 3 AU. In this paper, we discuss a downlink receiver concept capable of demodulating optical pulse-position modulated (PPM) waveforms with data rates varying from approximately 50 kbps up to 265 Mbps, using a range of PPM orders, slot widths, and code rates. The receiver operates on recorded timestamps corresponding to the times-of-arrival of photons detected by a photon-counting detector array followed by a commercial time-tagger. Algorithms are presented for slot, symbol, and frame synchronization as well as parameter estimation, de-interleaving, and decoding. Estimates of link performance are evaluated through Monte-Carlo simulation for an optical channel that includes optical losses, detector blocking, signal clock dynamics, and pointing-induced downlink fades. Based upon these simulation results, it is expected that link closure may be achieved with at least 3 dB of margin under a variety of relevant conditions.

10096-9, Session 2

Binary polarization-shift-keyed modulation for interplanetary CubeSat optical communications

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While pulse-position-modulation (PPM) is an established time-domain modulation scheme for long-haul free-space optical communication links, it does not scale adequately for CubeSat missions where SWaP requirements severely limit the laser power. To compensate, we have developed a novel modulation scheme in the polarization-domain that re-envisions high-photon-efficient laser communication for interplanetary CubeSat missions.

Our proposed low-SWaP laser transmitter is based on direct modulation of two gain-switched diode lasers and polarization multiplexing, such that the transmission signal is a periodic pulse train with data encoded in each pulse's polarization state (e.g. TE or TM polarization). In contrast to PPM, where the pulse arrival time is unknown, the periodicity of the pulse train here enables additional time-gating at the receiver as a highly effective technique for background noise rejection. This transmitter scheme was built with commercial components and demonstrated within an end-to-end link testbed with single-pixel WSi superconducting nanowire detectors as receivers for the two polarization channels. Background noise is injected to simulate various SNR regimes for direct-to-Earth links. We successfully demonstrate signal acquisition under extremely low SNR (i.e. -43.5 dB average signal power to average noise power ratio) at a 1-MHz symbol rate. Other system design constraints, such as the monolithic telescope design, optics and electronics design layout will be discussed.

10096-10, Session 2

Experimental demonstration of multi-aperture digital coherent combining over a 3.2-km free-space link *(Invited Paper)*

David J. Geisler, Timothy M. Yarnall, Curt M. Schieler, Mark L. Stevens, Bryan S. Robinson, Scott A. Hamilton, MIT Lincoln Lab. (United States)

The next generation free-space optical (FSO) communications infrastructure will need to support a wide variety of missions, including LEO-to-ground, GEO-to-ground, and deep-space-to-ground links. As a result of the limited size, weight, and power (SWaP) on space-borne assets, the ground terminals need to efficiently scale to large effective collection areas to support extremely long link distances or high data rates. In addition, versatile ground stations capable of supporting modulation format independence while delivering excellent sensitivity (i.e., photons-per-bit) provide a generalized ground station architecture that preserves backwards compatibility with legacy systems. Recent advances in integrated digital coherent receivers enable the lossless coherent combining of signals from several smaller apertures to act as a single large effective aperture.

In our previous work, we experimentally validated a next-generation ground station concept that relies on digital signal processing based coherent combining (i.e., full-field addition). Specifically, this involved a fiber-based laboratory setup that achieved a lossless combination of four received signals for a 6-dB sensitivity improvement over the performance of a single receiver. In this work, we experimentally demonstrate the coherent combining of signals received by four independent receive chains after propagation through free space. Here, each receive chain consists of a 40-mm aperture, a pre-amplified coherent receiver, and high-speed ADCs. Measured results show the effect of coherently combining an optical waveform after transmission through 1.6-km of atmosphere.

10096-11, Session 3

Temperature-stabilized, narrowband tunable fiber-Bragg gratings for matched-filter receiver

Jeffrey M. Roth, Joseph W. Kummer, Jeffrey R. Minch, Bryan G. Malinsky, Vincent Scalesse, MIT Lincoln Lab. (United States)

We report on a 1550-nm matched filter based on fiber Bragg gratings (FBGs) that is actively stabilized over temperature. The filter is constructed of a cascaded pair of athermally-packaged FBGs. The tandem FBG pair produces an aggregate 3-dB bandwidth of 3.9-GHz that is closely matched to a return-to-zero, 2.880- GHz differential-phase-shift-keyed optical waveform. The FBGs comprising the filter are controlled in wavelength using a custom-designed, pulse-width modulation (PWM) heater controller. The controllers allow tuning of the FBGs over temperature to compensate and cancel out native temperature dependence of the athermal FBG package. Two heaters are bonded to each FBG device, one on each end. One heater is a static offset that biases the FBG wavelength positively. The second heater is a PWM controller that actively moves the FBG wavelength negatively. A temperature sensor measures the FBGs' temperature, and a feed-forward control loop adjusts the PWM signal to hold the wavelength within a desired range. This stabilization technique reduces the device's native temperature dependence from approximately 0.65 nm/degreesC to 0.06 nm/C, improving the temperature stability by up to tenfold. The technique demonstrates that the FBGs can be held to ±1.5 nm (±188 MHz) of the target wavelength over a 0 to +50degreesC temperature range. The temperature-stabilized FBGs are integrated into a low-noise, optical pre-amplifier that operates over a wide temperature range for a laser communication system.

10096-12, Session 3

Power and photon-efficient WDM-scalable DPSK Lasercom transceivers

David O. Caplan, John J. Carney, Mark L. Stevens, MIT Lincoln Lab. (United States)

Compact, power-efficient, and scalable transceiver technologies are attractive for free-space optical (FSO) communications. Differential phase shift keying (DPSK) modulation has long been considered for FSO applications because it provides a good balance between performance, complexity, and size, weight, and power constraints - providing better sensitivity and lower nonlinear impairments than on off keying (OOK), and extending to higher data rates than pulse position modulation (PPM). For these reasons, DPSK is the high-speed modulation of choice for NASAs Laser Communications Relay Demonstration (LCRD) program, which plans to demonstrate operational laser communications using DPSK over a 40,000 km class link to a satellite in geosynchronous orbit. However, there is room for improvement in power-efficiency and scalability of existing DPSK transceiver designs, which presently leverage external modulator-based transmitters that can take several Watts of modulation drive power for a single channel. While wavelength division multiplexing (WDM) is a straightforward means of increasing data rate, the corresponding cost increase of modulation drive power for a multi-channel WDM transceiver may be prohibitive for many power-starved applications. In this paper, we investigate the use of directly modulated lasers (DMLs) for generating high-fidelity DPSK waveforms. This approach eliminates the need for an external data modulator, which shrinks the hardware footprint and has potential to significantly reduce modulation drive power requirements. We also show that low-drive power DMLDSPK transmitters are compatible with achieving near-theoretical communication performance at a 2.88 Gbps channel rate compatible with LCRD using a WDM-scalable design.

10096-13, Session 3

Optimization of rare-earth-doped amplifiers for space mission through a hardening-by-system strategy

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Rare-earth doped optical fibers (REDF, Er or Er/Yb-doped) are a key component in optical laser source (REDFS) and amplifiers (REDFA). The high performances of these fiber-based systems made them promising solutions as part of gyroscopes, telecommunication systems... However, REDFs are very sensitive to space radiations, their degradation limits their integration in space missions. To overcome this issue, several studies were carried out and some solutions at the component level were proposed such the Cerium co-doping or the hydrogen loading of the REDF by our group. More recently our group initiates an original coupled simulation/experiment approach to improve the REDFA performances under irradiation by acting at the system level and not only on the component itself. This procedure allows optimizing the properties of the amplifier (gain, noise figure) under irradiation through simulation, knowing from preliminary tests the REDF radiation response in terms of radiation induced attenuation (RIA).

Our simulation chain of the REDFA performances is based on a homemade C code; the optimization of the system is ensured using a PSO (Particle Swarm optimization) algorithm. Using some experimental inputs (such the RIA measurement and the spectroscopic features of the fiber) we

demonstrate its efficiency to reproduce the amplifier degradation when exposed to radiations in various experimental configurations. This was done by comparing the obtained simulation results to those of dedicated experiments performed on various REDFA architectures. Comparison reveals a good agreement between simulations and experimental data (with <10 % error). Finally, exploiting the validated codes, we optimize the REDFA in order to get the best performances during the space mission and not on-ground.

10096-14, Session 3

Design of a stabilized, compact gimbal for space-based free space optical communications (FSOC)

Andrew Cline, Jim J. McNally, Paul D. Shubert, Nicholas Jacka, Robert E. Pierson, Applied Technology Associates (United States)

Data transmits via optical communications through fibers at 10's of Terabits per second. Given the recent rapid explosion for bandwidth and competing demand for radio frequency (RF) spectrum allocations among differing interests, the need for space-based free space optical communications (FSOC) systems is ever increasing. FSOC systems offer advantages of higher data rates, smaller size and weight, narrower beam divergence, and lower power than RF systems. Lightweight, small form factor, and high performance two-axis gimbals are of strong interest for satellite FSOC applications. Small gimbal and optical terminal designs are important for widespread implementation of optical communications systems, in particular, for satellite-to-satellite cross links where the advantages of more secure communications links (Lower Probability of Intercept (LPI)/ Lower Probability of Detect (LPD)) are very important.

We developed design concepts for a small gimbal focusing on the use of commercial off-the-shelf (COTS) subsystems to establish their feasible implementation against the pointing stabilization, SWaP, and performance challenges. The design drivers for the gimbal were weight, the elevation and azimuth field of regards, the form factor envelope (1U Cube Sats), 100 ?rad pointing accuracy, and 10 degrees per second slew capability. Innovations required in this development included a continuous fiber passed through an Azimuth Fiber Wrap and Elevation Fiber Wrap, overcoming typical mechanical and stress related limitations encountered with fiber optic cable wraps. In this presentation, we describe the configuration trades and design of such a gimbal.

10096-15, Session 3

Radiation-resistant optical fiber amplifiers for satellite communications

Leontios Stampoulidis, James Edmunds, Marios Kechagias, Jihan Farzana, Gooch & Housego Systems Technology Group (United Kingdom); Gary Stevens, Gooch & Housego (Torquay) Ltd. (United Kingdom); Matthew Welch, Efstratios Kehayas, Gooch & Housego Systems Technology Group (United Kingdom)

Photonics has the potential of being the catalyst technology for developing next-generation high-throughput satellite communication networks. Optical fiber amplifiers are key building blocks in laser communication terminals and telecom photonic payloads. In this paper we present 1.55um optical fiber booster amplifiers and pre-amplifiers suitable for satellite to ground, inter-satellite links and flexible photonic payloads. We validate the designs in the relevant space environment by characterizing the performance against ionizing and non-ionizing radiation for fiber-optic and opto-electronic components respectively and report on functional performance of the amplifiers over temperature. Specifically, we present unit-level performance evaluation of polarization-maintaining booster optical amplifiers with saturated output powers of > >+19 dBm within the C-band, after ionizing radiation up to 100 krad TID. We also report on the development of a high-gain and low-noise pre-amplifier and present experimental data on signal gain and noise figure results up to 100 krad TID. The pre-amplifier can deliver at least 35 dB over the full C-band and >40dB around 1550 nm at 100krad TID. When noise management is employed, the typical gain value is increased to 50 dB and the amplifier delivers more than 40 dB gain across the complete C-band. The post-irradiation noise figure measured is in the range of 4 dB at 20 krad and increases to a maximum of 4.5 at 100 krad within the entire C-band.

10096-16, Session 3

Transmission and pump laser modules for space applications

John McDougall, Phil Henderson, Paul Naylor, Jason Elder, Adrian Norman, Gooch & Housego Systems Technology Group (United Kingdom); Ian Turner, Gooch & Housego, Boston (United States); Leontios Stampoulidis, Efstratios Kehayas, Gooch & Housego Systems Technology Group (United Kingdom)

We present progress on the design, development and space qualification of high-power Distributed Feedback (DFB) lasers and single- and multi-mode pump laser modules that can be used in diverse applications, such as laser telemetry, navigation and flexible photonic payload systems. The DFB module achieves >50% power consumption reduction compared to conventional terrestrial equivalent parts and generates 80mW of optical power ex-fiber. The module has a side mode suppression of >25dB with a linewidth and relative intensity noise of <1MHz and <-150dB/Hz respectively. In the context of pump laser modules, we present functional and environmental performance of (a) single-mode high-brightness and (b) multimode high-power lasers. The optoelectronic modules employ laser-welding technology, are fully hermetic and fiber-pigtailed utilizing glass to metal soldering. The single- and multi- mode pump laser modules are capable of generating >240mW at 976nm and 7W optical power at 915 nm respectively. The multi-mode lasers are integrated into 14-pin butterfly packages and the single mode lasers are integrated into 8-pin mini-DIL packages. Both modules are coolerless and include a back-facet photodiode and a thermistor for measuring optical power and temperature respectively. The functional performance of both modules is presented, including behaviour over temperature and post-irradiation performance following exposure to non-ionizing radiation (proton) for both types.

10096-18, Session 3

Superconducting nanowire single photon detector arrays for deep space optical communications *(Invited Paper)*

Matthew Shaw, Francesco Marsili, Andrew Beyer, Ryan Briggs, Jet Propulsion Lab. (United States); Jason Allmaras, California Institute of Technology (United States); William H. Farr, Jet Propulsion Lab. (United States)

The Deep Space Optical Communication (DSOC) project at the Jet Propulsion Laboratory aims to perform a bidirectional laser communication technology demonstration from deep space, at ranges from 0.1 - 3 AU. To support high data rates over such distances while keeping the mass and power on the spacecraft comparable to radio-frequency communication systems, extremely high-performance single photon detectors are required at the ground receiver. To this end, JPL has been developing 64-pixel tungsten silicide superconducting nanowire single photon detector (WSi SNSPD) arrays suitable for use in the DSOC ground terminal. To efficiently

couple to a 5-meter telescope aperture in the presence of atmospheric seeing, the arrays are free-space coupled and have a combined 320-micron diameter active area. The development is targeting 70% system detection efficiency at an operating wavelength of 1550 nm, 150 ps time resolution, a maximum count rate approaching 109 counts per second, a numerical aperture capable of supporting an f/1.2 beam, a background-limited dark count rate, and an operating temperature of 1 Kelvin. In this paper, we will present our progress toward these goals, both in terms of focal plane array development and cryogenic readout technology.

10096-19, Session 3

A luminescent detector for free-space optical communication

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Free-space optical communication holds the promise of high-throughput wireless communication channels for long distances as well as for short-range indoor applications. To fully benefit from the high data rates enabled by optical carriers, the light needs to be efficiently collected onto a fast photodetector, which requires complex pointing and tracking systems. Here, we show that fluorescent materials can be used to increase the active area of a photodiode by orders of magnitude while maintaining its short response time and increasing its field of view. Using commercially available materials, we demonstrate a detector with an active area of 126??cm2 achieving data rates up to 2.1 Gbps at an eye-safe intensity. We demonstrate a detector geometry with omnidirectional sensitivity and discuss the need for new materials tailored for communication applications.

10096-20, Session 4

Tutorial: Laser communication architectures for data delivery from low-Earth orbit *(Invited Paper)*

Bryan S. Robinson, MIT Lincoln Lab. (United States)

Data delivery from platforms in low-Earth orbit (LEO) to the ground can be challenging due to orbital geometry constraints that limit access to ground stations. Often, a space relay architecture is utilized, where data generated on the LEO platform is first relayed to another space platform (e.g. in geosynchronous orbit) which has direct view of a ground station. Such systems require relatively large terminals due to the long space-to-space link distances and are expensive to operate due to the need for a space-relay. Alternatively, data can be linked directly from a LEO platform to a ground station with relatively small terminals. However, such links are constrained by the short and infrequent times when a ground station is in view of the LEO platform and spectral constraints which can limit the data rate and power efficiency of radio-frequency links. Recent laser communication demonstrations have shown that both direct-to-Earth and space-to-space links can be achieved with small transmit and receive terminals. Moreover, laser communication links have fewer spectral constraints, enabling high-data-rate high-efficiency links. In this tutorial, we will discuss the impact of laser-communications on space-relay and direct-to-Earth architectures for delivering large volumes of data from LEO to ground.

10096-21, Session 5

Ultra-sonic motor for the actuators of space optical communications terminal

Tomohiro Araki, Yuta Kobayashi, Noritsugu Kawashima, Kazuaki Maniwa, Shingo Obara, Japan Aerospace Exploration Agency (Japan); Toru Zakoji, Akihiro Kubota, Tamagawa Seiki Co., Ltd. (Japan)

Main advantages of space optical communication technologies compared with RF communications are 1) Wide-bandwidth that enables much higher data rate and 2) Smaller antenna and hardware due to the ultra-short wavelength characteristics.

Cost and weight of each spacecraft has been decreasing year by year. Space optical communication technologies, that are under establishing, have been required to reduce cost and weight recently.

General rotational actuator of spacecraft are magnetic motors. However, it is difficult to reduce it's weight and cost dramatically since magnetic motors including iron core and metal coil. In addition, we do not have a flexibility of. magnetic motor's shape.

JAXA is interested in optical data relay including LEO-GEO optical communication. In this application, space optical communication equipment must equip rotational actuator as coarse pointing mechanism. Therefore, authors have focused on ultra-sonic motor (USM) for the equipment of space optical communication so that we will achieve lower cost, lower weight and more-flexible-shape actuator than magnetic motors.

In this presentation, authors propose applications of USM as actuators of space optical communications. USM has been widely used in our life and industry. Usage in industry including vacuum circumstance of semiconductor manufacturing process. So, authors estimated USM are able to apply for actuators of spacecraft.

At first, authors discuss advantages and disadvantages of USM compared to classic magnetic motors. Then, driving performance of USM under vacuum, high and low -temperature conditions are shown.

10096-22, Session 5

Simultaneous data communication and position sensing with an impact ionization engineered avalanche photodiode array for free space optical communication

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Photodetectors in free space optical communication systems perform two functions: reception of data communication signals and position sensing for pointing, tracking, and stabilization. Traditionally, the optical receive path in an FSO system is split into separate paths for data detection and position sensing. The need for separate paths is a consequence of conflicting performance criteria between position sensitive detectors (PSD) and data detectors. Combining the functionality of both detector types requires that the combinational sensor not only have the bandwidth to support high data rate communication but the active area and spatial discrimination to accommodate position sensing. In this paper we present a large area, concentric five element impact ionization engineered avalanche photodiode array rated for bandwidths beyond 1GHz with a measured carrier ionization ratio of less than 0.1 at moderate APD gains. The integration of this array as a combinational sensor in an FSO system is discussed along with the development of a pointing and stabilization algorithm.

10096-23, Session 5

Multi-segment tapered optical mirror for MEMS LiDAR application

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Laser Detecting and Ranging (LiDAR) systems are becoming more common especially in the robotic and autonomous car industry. Using MEMS scanning mirror enables high speed and compact LiDARs as well as low cost production. However, the MEMS mirrors usually have small aperture size that limits the amount of power collected by the system, where a collection lens is located after the scanner to focus the light on small area and low noise detector. The existing solutions to increase the power are increasing MEMS aperture by sacrificing the low cost feature and reliability/flatness of the mirror, collecting the light directly on a large-area detector without the MEMS and the lens while sacrificing the noise performance or using a collection lens with an expensive array of detectors and complex electronics. In this work, we present a novel solution that is cheap and simple based on avoid having the MEMS mirror in the path of the collected light and replacing the lens by a tapered optical mirror that couples large amount of power to the small area of the detector from the larger area of the tapered mirror input aperture. The expected improvement in the collected power is analyzed versus the tapering angle of the mirror. An improvement of about 20x is obtained for 10-degree tapering angle but limiting the acceptance angle of the LiDAR system to ±10 degrees. A multi-segment optical system is introduced to allowing for the optimization of the acceptance angle and the power improvement ratio. Using a 3-segment mirror, the expected improvement is about 15x with an acceptance angle of ±30 degrees. The design has been fabricated and tested experimentally showing good agreement with the theoretical expectations.

10096-24, Session 5

Design of stabilized platforms for deep space optical communications (DSOC)

Nicholas Jacka, Rick Walter, Darren R. Laughlin, Jim J. McNally, Applied Technology Associates (United States)

Numerous Deep Space Optical Communications (DSOC) demonstrations are planned by NASA to provide the basis for future implementation of optical communications links in planetary science missions and eventually manned missions to Mars. There is a need for a simple, robust precision optical stabilization concept for long-range free space optical communications applications suitable for optical apertures and masses larger than the current state of the art.

We developed a stabilization concept by exploiting the ultra-low noise and wide bandwidth of ATA-proprietary Magnetohydrodynamic (MHD) angular rate sensors and building on prior practices of flexure-based isolation. We detail a stabilization approach tailored for deep space optical communications, and present an innovative prototype design and test results. Our prototype system provides sub-micro radian stabilization for a deep space optical link such as NASA's integrated Radio frequency and Optical Communications (iROC) and NASA's DSOC programs. Initial test results and simulations suggest that >40 dB broadband jitter rejection is possible without placing unrealistic expectations on the control loop bandwidth and flexure isolation frequency. This approach offers a simple, robust method for platform stabilization without requiring a gravity offload apparatus for ground testing or launch locks to survive a typical launch environment. This paper reviews alternative stabilization concepts, their advantages and disadvantages, as well as, their applicability to various optical communications applications. We present results from testing that subjected the prototype system to realistic spacecraft base motion and confirmed predicted sub-micro radian stabilization performance with a realistic 20 cm aperture.

10096-26, Session 5

Design and experimental demonstration on improved high order grating for wide angle beam steering of liquid crystal optical phased array

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Interest in optical phased array (OPA) technology has greatly increased in recent years because of the advantages of beam agility with small size, low weight and power consumption. One of the most promising techniques is liquid crystal optical phased array (LC-OPA), which has several properties that are required for laser beam steering including maga-pixels, real-time programmable and low voltage. This LC beam steering technology can be used in various areas of information processing, laser lidar and free space laser communication. However, the main limitations associated with this device are the diffraction efficiency and the maximum angular range (less than 3°) due to the fringing field effect.

In this paper, device design and experimental demonstration on the method of improved high order grating (i-HOG) to realize wide-angle beam steering on liquid crystal optical phased array (LCOPA) is presented, and the numerical simulation was published before on Proc. SPIE. Meanwhile, the steering range of LC-OPA and the principle of i-HOG method are studied based on the periodic blazed grating model. The device operates with i-HOG method is based on a beam deflection from a deeper phase modulation. Theoretical analysis indicates that the diffraction order where the laser beam steered is determined by the phase reset order. By using 4ϖ phase reset order on a one-dimensional device, the steering angle is doubled as well as an acceptable diffraction efficiency up to 80%. Meanwhile, the comparison between 2ϖ and 4ϖ reset order on the steering performance including deflection angle and efficiency are made. These experimental results are presented to show the angular magnification of i-HOG method.

10096-27, Session 5

Laser guide stars for optical free-space communications

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The German Aerospace Center (DLR) and the European Southern Observatory (ESO) performed a measurement campaign together in April and July 2016 at Teide-Observatory (Tenerife), with the support of the European Space Agency (ESA), to investigate the use of laser guide stars (LGS) in ground to space optical communications.

Atmospheric turbulence causes strong signal fluctuations in the uplink, due to scintillation and beam wander. In space communications, the use of the downlink channel as reference for pointing and for pre-distortion adaptive optics is limited by the size of the isokinetic and isoplanatic angle in relation to the required point-ahead angle. Pointing and phase errors due to the decorrelation between downward and upward beam due to the point-ahead angle may have a severe impact on the required transmit power and the stability of the communications link.

LGSs provide a self-tailored reference to any optical ground-to-space link, independently of turbulence conditions and required point-ahead angle. In photon-starved links, typically in deep-space scenarios, LGSs allows dedicating all downlink received signal to communications purposes, increasing the available link margin.

The scope of the joint DLR-ESO measurement campaign was, first, to measure the absolute value of the beam wander (uplink-tilt) using a LGS, taking a natural star as a reference, and, second, to characterize the decrease of correlation between uplink-tilt and downlink-tilt with respect to the angular separation between both sources. This paper describes the experiments performed during the measurement campaign, providing an overview to the measured data and the first outcomes of the data post-processing.

10096-59, Session 5

Design, analysis, integration, and testing of a prototype coarse pointing assembly for laser communication

Eric D. Miller, Brian Parris, Facebook Inc. (United States); Michael DeSpenza, Graham C. Nelson, Ilya Gavrilyuk, Quartus Engineering Inc. (United States)

No Abstract Available

10096-28, Session 6

Small optical inter-satellite communication system for small and micro satellites
(Invited Paper)

Kyohei Iwamoto, Sony Corp. (Japan) and Japan Aerospace Exploration Agency (Japan); Takashi Nakao, Taiji Ito, Takeshi Sano, Tamotsu Ishii, Keiichi Shibata, Mitsuhiro Ueno, Shinji Ohta, Sony Corp. (Japan); Tomohiro Araki, Yuta Kobayashi, Hirotaka Sawada, Japan Aerospace Exploration Agency (Japan)

We are developing a small optical inter-satellite communication system that can be introduced into small and micro satellites. This system makes data system and operations of small and micro satellites in real-time. In this paper, we discuss fundamental functions and system design of this inter-satellite communication system.

Data communication, broadcasting and some applications are using real-time data with satellite systems. It is required steady connecting to ground systems. Some use data relay satellites on GEO, some use satellite interconnection with radio waves. Large and middle size satellites are introduced because of power consumption for long distance radio wave connection. In recent years, small and micro satellites became usable not only in academic studies but in business fields. They are premised on operating at LEO and have limited power budget that makes hard to introduce applications required real-time data. Free space optical communication is one of a promising approach to tackle with an issue of real-time data system with small and micro satellites.

We have assumed relaying data through LEO satellites to connect to ground systems. And distance of each satellite have 4500km long in a same orbit.

To make our system usable for small and micro satellites, miniature optical systems with high power laser, miniature actuator mechanism and control system for precious optical axis control to point which is coming from our optical disc technologies are introduced. These technologies make this system available with 1kg weight, 20cm cubic size, 15W power consumption and 20-30Mbps data link.

10096-29, Session 6

Design of low SWaP optical terminals for free space optical communications (FSOC)
(Invited Paper)

Paul D. Shubert, Jim J. McNally, Andrew Cline, Robert E. Pierson, Applied Technology Associates (United States)

Along with advantages in higher data rates, spectrum contention and security, free space optical communications (FSOC) can provide size, weight, and power (SWaP) advantages over radio frequency (RF) systems. With the significant maturation of components and technology for reliable, power efficient laser sources, detectors, fiber preamplifiers, encoding schemes, space-qualified sensors, beam stabilization, and pointing and tracking technologies, implementing FSOC systems has now become an affordable reality. The possibility of an "Internet-in-the-Sky" is now a reality. FSOC operates at 10,000 times the frequency of RF systems, resulting in very narrow beam divergence. This can provide more secure communications links that have lower probability of intercept and lower probability of detect (LPI)/LPD), and jam proof communications systems.

SWaP is always an issue in space systems and can be critical in applying free space optical communications to small satellite platforms. This presentation addresses the system design of small space-based free space optical terminals with Gigabits per second (Gbps) data rates. We define system architectures and requirements to ensure the terminals are capable of acquisition, establishment, and maintenance of a free space optical communications link. We use design trades, identification of blocking technologies, and performance analyses to evaluate the practical limitations to terminal size, weight, and power, and develop small terminal design concepts to establish their practicality and feasibility. To mitigate the disadvantages brought by SWaP limitations, we considered techniques such as modulation formats and capacity approaching encoding, and evaluate performance as a function of SWaP.

10096-31, Session 6

Discovery deep space optical communications transceiver

W. Thomas Roberts, Michael B. Borden, Jet Propulsion Lab. (United States)

NASA's 22 cm diameter Deep Space Optical Communications (DSOC) Transceiver is designed to provide a bi-directional optical link between a spacecraft in the inner solar system and an Earth-based optical ground station. This design, optimized for operation across a wide range of illumination conditions, is focused on minimizing blinding from stray light, and providing reliable, accurate attitude information to point its narrow communication beam accurately to the future location of the ground terminal. Though our transceiver will transmit in the 1550 nm waveband and receive in the 1064 nm waveband, the system design relies heavily on reflective optical elements, extending it flexibility to be modified for use at different wavebands. The design makes use of common path propagation among transmit, receive and pointing verification optical channels to maintain precise alignment among its components, and to naturally correct for element misalignment resulting from launch or thermal element perturbations. This paper presents the results of trade studies showing the evolution of the design, unique operational characteristics of the design, elements that help to maintain minimal stray light contamination, and concepts for adapting the design for use in different situations and conditions.

10096-32, Session 6

1.5U Cubesat lasercom terminal for multi-Gbps optical links from LEO

Shantanu Gupta, He Cao, Slava Litvinovitch, Kent Puffenberger, Michael M. Albert, Jeremy Young, Dave Pachowicz, Timothy Deely, Fibertek, Inc. (United States)

Commercial interest and acceptance of space optical communication is accelerated by the development of cost-effective, low size, weight & power (SWaP) space lasercom terminal. We report on the design, development and lab testing of a 1.5U-Cubesat lasercom terminal capable of multi-Gbit/sec optical downlink from slant ranges (<1,500 km) typical from LEO orbit.

The lasercom terminal uses a specially designed and manufactured, off-axis reflective afocal telescope with a 64-mm clear aperture, and a shared transmit/receive optical path. The field-of-view is >±0.15-deg, compatible with coarse-pointing of small-satellites and latest generation of CubeSat ADCS. A low-light sensitive focal-plane-array (FPA) sensor is used for image-processing based line-of-sight (LOS) stabilization of a 1-um ground optical beacon, along with a piezo-FSM actuator optimized for large angular range (>±1-deg) and closed-loop bandwidth ~50-Hz. A multi-point, two-stage passive isolation system provides immunity to launch vibration, and has >30-dB/decade of high-frequency damping beyond ~60-Hz. The overall system is designed for ~10-urad of LOS pointing stability, when subjected to typical satellite platform disturbance profiles. A 1.5-um fiber-laser transmitter is coupled to the telescope via a fused collimator providing a near diffraction limited beam. Above hardware fits in a 1U-CubeSat frame, and is optimized for operation over temperature range of 0-50 C. Integrated structural-thermal-optical performance analysis, fabrication and testing of key components has confirmed our design and performance predictions.

To complete the space lasercom terminal, a CubeSat form-factor1.5-um fiber-amplifier transmitter card, a high-speed optical transceiver card, and digital-modem/bus-interface cards are added, for total ~1.5U in volume. The host satellite provides initial coarse-pointing to the ground beacon and subsequent slew for tracking. Link budget supports >5-Gbit/sec downlink data rates to compact ground-station terminal (30-cm telescope) for ~2W of laser transmitter power, while allocating >11-dB of link margin for various penalties. Results of integrated testing of the lasercom terminal in a simulated lab environment will also be presented.

10096-33, Session 7

Progressing towards an operational optical data relay service

Frank F. Heine, Daniel Troendle, Tesat-Spacecom GmbH & Co. KG (Germany); Rolf Meyer, Michael Lutzer, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); Edoardo Benzi, Harald Hauschildt, European Space Research and Technology Ctr. (Netherlands); Christoph Rochow, Tesat-Spacecom GmbH & Co. KG (Germany); Matthias Motzigemba, Tesat-Spacecom GmbH & Co KG (Germany)

The European Data Relay System, EDRS, will provide quasi real time access to earth observation data created by low earth orbiting spacecrafts using Gbit laser communication links. Currently five EDRS compatible Laser Communication Terminals (LCT) are in orbit, three of them on earth observation spacecrafts (Sentinel 1A, Sentinel2A, Sentinel1B) and two geostationary systems on Alphasat and Eutelsat 9B, the host of the first EDRS data relay payload (EDRS-A). The paper will report on the recent progress on the in-orbit commissioning campaigns for the individual units.

10096-34, Session 7

Laser based bi-directional Gbit ground links with the Tesat transportable adaptive optical ground station *(Invited Paper)*

Frank F. Heine, Karen Saucke, Daniel Troendle, Tesat-Spacecom GmbH & Co. KG (Germany); Hermann Bischl, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); Dominique Elser, Christoph Marquardt, Max-Planck-Institut für die Physik des Lichts (Germany); Hennes Henninger, Rolf Meyer, Ines Richter, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); Zoran Sodnik, European Space Research and Technology Ctr. (Netherlands); Matthias Motzigemba, Tesat-Spacecom GmbH & Co KG (Germany)

Optical ground stations can be an alternative to radio frequency based transmit (forward) and receive (return) systems for data relay services and other applications including direct to earth optical communications from low earth orbit spacecrafts, deep space receivers, space based quantum key distribution systems and Tbit capacity feeder links to geostational spacecrafts.

The Tesat Transportable Adaptive Optical Ground Station is operational since September 2015 at the European Space Agency site in Tenerife, Spain.. This paper reports about the results of the 2016 experimental campaigns including the characterization of the optical channel from Tenerife for an optimized coding scheme, the performance of the T-AOGS under different atmospheric conditions and the first successful measurements of the suitability of the Alphasat LCT optical downlink performance for future continuous variable quantum key distribution systems.

10096-35, Session 7

Demonstration of free-space optical communication (FSOC) for long-range data links between balloons on Project Loon *(Invited Paper)*

Baris I. Erkmen, Todd Belt, Oliver Bowen, Devin R. Brinkley, Paul J. Csonka, Michael L. Eglington, Andrei Kazmierski, Edward Keyes, Nam-Hyong Kim, Bruce Moision, John Moody, Thanh Tu, William Vermeer, Google (United States)

Internet connectivity is limited and in some cases non-existent for a large number of the world's population. Project Loon aims to address this problem with a network of high-altitude balloons traveling in the stratosphere at approximately 20 km altitude. The balloons are navigated by taking advantage of the stratified wind layers at different altitudes, adjusting the balloon's altitude to catch winds in the desired direction. Data transfer is achieved by 1) transmitting signal from (to) an Internet-connected ground station located at our Telco partners' site; 2) hopping the signal across balloons between the ground station and the users' geographic area, and 3) finally beaming connectivity down (up) directly to (from) the end-users' phones or other LTE-enabled devices.

In this paper, we will summarize results from Project Loon's early-phase experimental flights of stratospheric inter-balloon links at 20 km altitude, demonstrating bidirectional, full duplex 130 Mbps throughput at distances in excess of 100 km over the course of several-day flights. The terminal utilizes a monostatic design, with dual wavelengths for communication and a dedicated wide-angle beacon for pointing, acquisition, and tracking. We will summarize the constraints on the terminal design, and the key design trades that led to our initial system. The paper's focus will be on assessments of link quality and the pointing performance from our flights. We will present link throughput performance at various distances, and also show pointing

stability results from different segments of flight. We will conclude with a brief discussion of our future roadmap to reaching operational capacity.

10096-37, Session 7

DLR's free space experimental laser terminal for optical aircraft downlinks

Christian Fuchs, Christopher Schmidt, Benjamin Rödiger, Amita Shrestha, Martin Brechtelsbauer, Julio Cesar Ramirez Molina, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); Jorge Pacheco, Veronika Gstaiger, Deutsches Zentrum fur Luft und Raumfahrt eV (Germany)

The German Aerospace Center's Institute of Communications and Navigation developed the Free Space Experimental Laser Terminal II and has been using it for optical downlink experiments since 2008. It has been developed for DLR's Dornier 228 aircraft and is capable of performing optical downlink as well as inter-plattform experiments. After more than 5 years of successful operation, it has been refurbished with up-to-date hardware and is now available for further aircraft-experiments. The system is a valuable resource for carrying out measurements of the atmospheric channel, for testing new developments, and of course to transmit data from the aircraft to a ground station with a very high data rate.

This paper will give an overview about the systems and describe the capabilities of the flexible platform. Furthermore, the use of the system in various projects over the past years, as e.g. for the measurement of atmospheric parameters and for quantum key distribution experiments, are described. Measurement results of a recent flight campaign will be presented. Finally, an outlook to future use of the system is given.

10096-45, Session PTue

Theoretical model and experimental verification on the PID tracking method using liquid crystal optical phased array

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Liquid crystal optical phased array (LC-OPA) has been considered with great potential on the non-mechanical laser deflector because it is fabricated using photolithographic patterning technology which has been well advanced by the electronics and display industry. As a vital application of LC-OPA, free space laser communication has demonstrated its merits on communication bandwidth. Before data communication, ATP (acquisition, tracking and pointing) process costs relatively long time to result in a bottle-neck of free space laser communication. Meanwhile, dynamic real time accurate tracking is sensitive to keep a stable communication link. The electro-optic medium liquid crystal with low driving voltage can be used as the laser beam deflector.

This paper presents a fast-track method using liquid crystal optical phased array as the beam deflector, CCD as a beacon light detector. PID (Proportion Integration Differentiation) loop algorithm is introduced as the controlling algorithm to generate the corresponding steering angle. To achieve the purpose of fast and accurate tracking, theoretical simulations and experimental demonstrations are presented that PID closed-loop control system can suppress random attitude vibration. Theoretical tracking accuracy is less than 6.5?rad. Experimental results show that after 10 adjustments, the system reaches the state of steady tracking, the tracking accuracy of less than12.6?rad.

10096-46, Session PTue

Indoor test of fog effect on wireless optical link

Abir Touati, Abderrazak Abdaoui, Farid Touati IV, Qatar Univ. (Qatar); Ammar Bouallegue, Ecole Nationale d'Ingénieurs de Tunis (Tunisia)

Free space optical communications (FSO) is considered as one of the most promising current research areas which is applied in various applications and research fields. FSO system operates in a high bandwidth allowing a high data rate compared to RF links. On the other hand, wireless optical communications suffer from various phenomena. In fact, FSO systems use a laser beam for signal transmission. In nature, the transmission in the visible and infrared range is affected by the fog which is considered as the most challenges of FSO transmissions. This is due to the fact that fog particles and the wavelengths in this range have the same order of magnitude. In order to characterize the attenuation caused by fog, several empirical models were developed such as Kim, Kruse, Al Naboulsi and Ijaz models. In this work, we are interested in identifying the model which fits better the experimental data. We made a comparison between the experimental measurements and the attenuation given by these different models. This research work was carried out in Qatar University laboratory. Hence, due to Qatar specific climate where the fog appearance is rare and unexpected, we designed an indoor atmospheric laboratory chamber with dimension of 480 x 28.5 x 28.5 cm^{3} where the fog is generated by a fog machine and injected through some holes in the chamber. These holes allow us to control the thickness of fog by ensuring the transition from dense to very light fog.

10096-48, Session PTue

Integration of Geographic Information System data for atmospheric turbulence modeling

Paul D. Shubert, John Garnham, Robert E. Pierson, Applied Technology Associates (United States)

Free space optical communications systems (FSOC) offer numerous advantages over radio frequency (RF) systems including 10X or better data rates, avoidance of spectrum contention issues, and very narrow beam divergence resulting in more concentrated power at the receiver thus reducing the transmit power requirements. For designers to accurately define the propagation characteristics of a FSOC terrestrial communications path, high fidelity models integrating the many physical phenomena contributing to the turbulence in the layers along the propagation path are needed. In this paper, we describe the integration of Geographic Information System Data into an atmospheric turbulence code.

Detailed geographic data, such as digital elevation models (DEM) and land use/land cover (LULC) information is incorporated into an atmospheric turbulence code to provide detailed modeling of the refractive index structure constant, Cn2, in the surface layer and convective boundary layer (CBL) along an optical path. Optical turbulence in these layers is important in the evaluation of terrestrial free space optical communications systems. Turbulence in these layers is driven by surface heating and decreases rapidly with optical path height above the terrain. Several authors have developed detailed models that estimate the Cn2 profile as a function of various surface and meteorological parameters. Implementation of these models requires the user to estimate the surface parameters, which may be variable along the path, for each specific application. Incorporation of geographic data into the models simplifies the inputs required and provides a more detailed and specific analysis of terrestrial FSOC.

10096-49, Session PTue

Uncertainty quantification of network availability for networks of optical ground stations

Inigo del Portillo, Marc Sanchez-Net, Bruce G. Cameron, Edward F. Crawley, Massachusetts Institute of Technology (United States)

Free space optical communications is envisioned as the next milestone in space communications, due to the higher data-rates achievable (an increase of 10 to 100 times with respect to current RF technology), and its lower size, mass, and power. The main drawback of this technology is the decrease in network availability as a result of link outages caused by cloud coverage. Site diversity has been proposed as a mitigation technique. During the last years, several studies have been conducted in order to determine the optimal location of the optical ground stations. These studies can be classified in two groups: those that use high-frequency historical cloud coverage data to estimate the availability of the network, and those that develop probabilistic models based on long-term averages. Different studies use different datasets to estimate the cloud conditions at different locations. However, no analyses have been conducted to quantify the uncertainty of the results when a) the inputs to the models come from different datasets, and b) the network availability is computed using different proposed methods.

This paper analyzes the differences in network availabilities when using different methods and datasets, and quantifies the uncertainty of the results. For that purpose, we first review the methods proposed in the literature, and the existing cloud coverage datasets (both based on satellite imagery and terrestrial observations). Next, we compare the results obtained from using different methods and datasets for several scenarios. Finally, we propose a new probabilistic global cloud coverage model that aggregates values from existing datasets and quantifies the uncertainty in the measure of cloud probability, and the corresponding analytical method to compute the availability of a network of multiple optical ground stations and the uncertainty associated with this value.

10096-50, Session PTue

Nighttime outdoor ambient lights for visible light car-to-car communication system

Chung Ghiu Lee, Chosun Univ. (Korea, Republic of); Jong-Young Kim, Daewoo Electronic Components Co. Ltd. (Korea, Republic of); Soeun Kim, Gwangju Institute of Science and Technology (Korea, Republic of)

Free-space optical (FSO) system includes an optical wireless communication (OWC) operating on visible wavelength range, so-called visible light communication (VLC). Among wireless technologies for intelligent transport system (ITS), VLC system is an option for physical link and is attractive due to employment of LED lamps in many car types and traffic signal lamps. Conventional research results have been focused on enhancing communication performance based on data rate and transmission distance, and recently, there have been gradual improvements. On the other hand, ambient light is known to affect the communication performance of VLC systems by increasing DC optical power level since the receiver detects visible wavelength. Such increased DC optical power should be understood in terms of wavelength and intensity. It can degrade the system performance.

Therefore, for applications of LED lights to outdoor communication systems e.g. car-to-car communications, the interferences from the ambient light should be investigated. We take an approach to measure the status of ambient light during night to understand the contribution of ambient light assuming the optical detector is the optical receiver of a VLC system installed on a car. The VLC system in this study assumes a link composed of a rear lamp in a front car as a communication transmitter (source) and a photo-receiver with an appropriate optical filter as a communication receiver (detector) at the height of front bumper in a car. Other light sources except lights from other cars as well as traffic sign lamps, billboards, are ignored.

The optical power distribution over color wavelengths are measured and analyzed for different physical situations. The geometry depends on types of light sources including traffic signals, head lamps of the approaching cars, outdoor LED billboards. The analyzed results contribute to understanding of the significant elements, which affects the VLC performance during night. The results will explain color-dependent interference from ambient light. The result will help to design VLC receiver circuitry for improved performance.

10096-51, Session PTue

Effect of the variation of refractive index on free space optical communications under Qatar climate

Abir Touati, Abderrazak Abdaoui, Farid Touati IV, Qatar Univ. (Qatar); Ammar Bouallegue, Ecole Nationale d'Ingénieurs de Tunis (Tunisia)

Despite its various features and benefits, free space optical communications (FSO) suffer from several phenomena such as absorption, scattering and turbulence. The turbulence is related to the weather factors such as temperature, humidity, pressure and wind velocity. Harsh climate can cause high turbulence inducing optical signal fading. For this reason, it is very interesting to study the effect of high turbulence on wireless optical links. In the literature, several existing models characterizing the strength of turbulence or the refractive index are employed. In this work, we studied the effect of Qatar harsh climate on the behavior of FSO transmissions. Qatar is characterized by a hot summer and moderate winter. The temperature in summer can easily exceed the 42 C while in winter the temperature doesn't fall below the 14 C. The experimental test was carried out at Qatar University (QU) and the system setup is composed of two FPGA boards and two FSO terminals installed at two different buildings separated by a distance of 600 m. Each terminal has the capacity of transmitting data at 1 Gb/s. The measurements are related to the atmospheric factors taken from a weather station installed at QU. The measurements were carried out during winter and summer 2015. We present a comparison between the behavior of FSO performance during summer and winter in term of packet ratio delivery (PDR). We notice an important difference between the behavior of FSO during summer and winter seasons. Furthermore, using the weather factors taken from the weather station, the refractive index is calculated based on the existing models then related to the PDR of FSO link.

10096-52, Session PTue

Atmospheric turbulence effects on the performance of the laser wireless power transfer system

Vitaliy V. Kapranov, Vjatcheslav Y. Tugaenko, Ivan S. Matsak, S.P. Korolev Rocket and Space Corp. Energia (Russian Federation); Natalia A. Suhareva, M.V. Lomonosov Moscow SU (Russian Federation); Arkadiy Blank, Lomonosov Moscow State University (Russian Federation)

Ground laser wireless power transfer (WPT) systems use a laser beam to send concentrated light through atmosphere to remote receiver that converts the light to electricity. Atmospheric turbulence has a significant impact on the laser beam propagating through the atmosphere over long distances. The operational efficiency of a receiver depends on the uniformity of illumination, while turbulence can results in intensity scintillation of laser

beam on receiver. Application of adaptive correction is necessary to control spreading and wandering of the laser beam.

In this paper we present system and techniques for laser WPT with adaptive correction. Control of position, wavefront tip and tilt is used for adaptive beam shaping and maximizing receiver efficiency. We describe results of a set of laser WPT system tests performed over a 1.5 km near-horizontal atmospheric path. Used optical system can create up to three beams (532 nm, 808 nm, 1064 nm) together. 1064 nm channel was used as a power beam and 808 nm for probe beam. So we have narrow power beam and wide probe beam simultaneously. Measuring of atmospheric-turbulence induced laser beam intensity scintillations for 808 nm beam at the special receiver was obtained to characterize turbulence.

Two important parameters for describing quality of atmosphere laser WPT system are used: overall efficiency and turbulence extension. The experimental results show that overall efficiency can be increased over than 5% by using of presented adaptive correction technique for both weak and strong turbulence conditions. Some criteria for choosing parameters of adaptive correction are given.

10096-53, Session PTue

Alignment and qualification of the GAIA telescope with a Shack-Hartmann sensor

Xavier Levecq, Guillaume Dovillaire, Imagine Optic SA (France); Dominique Pierot, Airbus Defence and Space (France)

Gaia is an ambitious ESA mission to chart a three-dimensional map of our Galaxy in the process reveal-ing its composition, formation and evolution. The payload design is characterized by a dual telescope concept (2 times 1.45 x 0.5m?), with a common structure and a common focal plane. Both telescopes are based on a three-mirror anastigmat (TMA) design. Both telescopes are aligned to have the exact same focal length (35m).

We will present the core technology of Imagine Optic: the Shack-Hartmann technique and how such a technology (included in the RFlex product) can be used to align large telescopes. Such a system can be easily calibrated on site. Once calibrated, an accuracy of ?/200 rms on the telescope is achievable. The Rflex sensor is small, light and not sensitive to vibrations or air turbulences.

It has been used to measure the WFE alternatively on both telescopes on their single but very large field (1m). The exit pupils of the telescopes are rectangular and are imaged on the measurement plane of the wavefront sensor to avoid pupil distorsion.

Legendre polynomials are used to characterize each measured wavefront map. CodeV models are used to predict the influence of each alignment actuator placed on the secondary aspherical mirror. By a minimization of a merit function taking into account several measurements into the field, the mirrors can be aligned by controlling the actuators.

On ground alignement using RFlex has contributed to telescope flight predictions better than 50 nm rms at 120K cryogenic operational temperature.

10096-54, Session PTue

Path profiles of Cn2 derived from radiometer temperature measurements and geometrical ray tracing

Brian E. Vyhnalek, NASA Glenn Research Ctr. (United States)

Atmospheric turbulence has significant impairments on the operation of Free-Space Optical (FSO) communication systems, in particular temporal and spatial intensity fluctuations at the receiving aperture resulting in power surges and fades, changes in angle of arrival, spatial coherence degradation, etc. The refractive index structure parameter Cn2 is a statistical measure of the strength of turbulence in the atmosphere and is highly dependent upon vertical height. Therefore to understand atmospheric turbulence effects on vertical FSO communication links such as space-to-ground links, it is necessary to specify Cn2 profiles along the atmospheric propagation path. To avoid the limitations on the applicability of classical approaches, propagation simulation through geometrical ray tracing is applied. This is achieved by considering the atmosphere along the optical propagation path as a spatial distribution of spherical bubbles with varying relative refractive index deviations representing turbulent eddies. The relative deviations of the refractive index are statistically determined from altitude-dependent and time-varying temperature fluctuations, as measured by a microwave profiling radiometer. For each representative atmosphere ray paths are analyzed using geometrical optics, which is particularly advantageous in situations of strong turbulence where there is severe wavefront distortion and discontinuity. The refractive index structure parameter is then determined as a function of height and time, and compared with accepted models and the results from wave theory.

10096-55, Session PTue

Effect of tropical climate on the propagation characteristics of terrestrial FSO links: a case study

Geetha Prakash, Nagarjuna College of Engineering & Technology (India); Raaghvam Nigam, PES Institute of Technology (India)

Free Space Optical (FSO) systems are being actively considered as viable options for seamless integration between backhaul optical fiber links and RF or copper links used for last mile connectivity. However, adverse atmospheric conditions can affect the performance and distance over which the link can operate reliably.

Propagation of optical waves through the atmosphere is affected by atmospheric turbulence, scattering off aerosols and atmospheric absorption. Atmospheric turbulence is a result of localized variations of temperature, humidity, and pressure in the atmosphere.Turbulence is by nature a random process, and as such may be described using statistical quantities. Atmospheric turbulence induced fading is one of the main impairments affecting Free Space Optics (FSO).

FSO systems can suffer outages in the presence of heavy fog, smog and haze. Many places in India see very heavy rainfall. We have studied the effects of rainfall on propagation characteristics in Dakshina Kannada district , Kar- nataka, India where Surathkal is located which is affected by heavy rainfall for about four to six months in a year. We observe that the attenuation during heavy rainfall is quite high and leads to extremely low levels of the received signal or complete erasure of the transmitted data. With the val- idation through simulation in this paper, on the use of Digital Fountain codes in FSO links, we suggest that if such codes are used in areas prone to rainfall, it would help in the recovery of dropped packets and would also improve the BER performance.

10096-57, Session PTue

Free space optics for high speed outdoor wireless communications

Armin Jooshesh, Islamic Azad Univ. Firozkoh Branch (Iran, Islamic Republic of); Afshin Jooshesh, Univ. of Victoria (Canada)

Free Space Optics (FSO), also called Free Space Photonics (FSP) or optical wireless, refers to the transmission of modulated visible or infrared (IR) beams through the atmosphere for broadband communications. FSO systems can function over distances of several kilometers as long as a line

of sight link exists between the source and destination. Optical wireless is ideal for very high bandwidth (up to 2.5 Gbps) data, voice, and multimedia communications.

Since FSO transceivers can transmit and receive through glass, it is possible to mount the system inside buildings, which eliminates the need to compete for roof space, simplifies wiring and cabling, and lowers maintenance costs. The only essential requirement is a line of sight link between the transmitter and receiver [1].

An FSO system is comprised of two terminals, each with an optical transceiver which consists of a transmitter (i.e., a laser source) and a light receiver (i.e., a photo-detector) to provide full duplex (bi-directional) communications. Each FSO terminal uses a high-power optical source plus an optical antenna that transmits light through the atmosphere to the receiver antenna. Light directors (i.e., optic lenses) are used for steering and directing the signals.

Optical communications follow electromagnetic propagation laws. Thus the path loss includes geometric spreading which is inversely proportional to the square of the distance. In addition, there absorption, diffraction and scattering losses due to atmospheric gas molecules and airborne particles [2]. These phenomena cannot be ignored in optical path loss models due to the relative size of optical wavelengths (800-1700 nm), airborne particles such as contaminants (dust, pollen, large bacteria), water droplets (1,000-100,000 nm) and, to a lesser extent, molecular atmospheric gases (~0.3 nm). Further, atmospheric turbulence consisting of moving eddies of varying refractive indices bends the optical communication path (according to Snell's law), so the incident beam appears to dance around the optical receiver. Even in clear conditions, local temperature gradients, pressure variations, and scattering by airborne particles produce a varying refractive index along the transmission path [3]. The major effects related to atmospheric turbulence include, beam wander, intensity fluctuation (or scintillation) and angle of arrival fluctuations [4].

10096-58, Session PTue

An experimental performance evaluation of the hybrid FSO/RF

Abir Touati, Qatar Univ (Qatar)

No Abstract Available

10096-60, Session PTue

Design method of off-axis two-mirror reflective optical antenna used in satellite laser communication system

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Satellite laser communication technology, whose carrier is laser, is a communication link with high speed and large -capacity, which is built between planets, between planet and the earth. For the satellite laser communication of point to point, optical antenna is the key point of the satellite laser communication system, which affects the link of laser directly, so the research of optical system design is of great significance. The off-axis reflective system has no obscuration, so that has higher efficiency of energy transferring for the satellite laser communication. However the traditional design methods in the off-axis system is gradually reaching its limitations. In this paper, a novel method is proposed to design the freeform off-axis reflective imaging systems. It introduces the differential equations depending on the principle of Fermat's principle and sine condition. The points on unknown surface will be calculated by the differential equations with the initial conditions, including the positions of imaging spots, the positions of starting aperture and the different incident field of views. After the surface fitting depending on the points calculated, the initial construction of off-axis reflective system will be provided and further optimized. In finally, according to the differential equations method, to design a multi-field-of-view (FOV) off-axis two mirrors optical system, in which the imaging position is defined, the field of view in y-axis are -7 o ~-8o, the MTF is above 0.4 at the 50lp/mm, and when the spot is at 15um, the energy concentration is greater than 85%. The design method of differential equations is not only simple and effective in computation, but also has a wide application prospect in the calculation of off-axis systems.

10096-501, Session Plen

Gravitational Wave Astronomy: News from the Dark Side of the Universe

Karsten Danzmann, Max Planck Institute for Gravitational Physics (Germany) and Leibniz Univ. Hannover (Germany)

So far, we have only been able to look at the universe and observe it with electromagnetic waves. But most of the universe is dark and will never be observable with light. Since September 2015 we can use a new sense and from now on we will be able to listen to the universe using gravitational waves with detectors on the ground and soon in deep space.

10096-38, Session 8

The C3PO Project: A laser communication system concept for small satellites

Benoît d'Humières, TEMATYS (France); Yann Gouy, Emilie Steck, Airbus Defence and Space (France); Crisanto Quintana Sanchez, Dominic O'Brien, Univ. of Oxford (United Kingdom); Fabian Sproll, Wolfgang Riede, Paul Wagner, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); Michael Salter, Qin Wang, Duncan Platt, Acreo Swedish ICT AB (Sweden); Aneta Michalkiewicz, Anna K. Debowska, Astri Polska Sp. z o.o. (Poland); Yoann P. Thueux, Airbus Defence and Space (United Kingdom); Daniel Hampf, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); Jerzy M. Krezel, Astri Polska Sp. z o.o. (Poland)

The satellite market is shifting towards smaller (micro and nano-satellites), lowered mass and increased performance platforms. Nanosatellites and picosatellites have been used for a number of new, innovative and unique payloads and missions. In the recent years, more than half of the pico- and nanosatellites were built with an educational purpose.

This trend requires new design, miniaturization, better ratio performance/power, and a reduction of onboard power consumption. In this context, disruptive technologies, such as Laser-optical communication systems, are opening new possibilities.

This paper presents the C3PO system, "advanced Concept for laser uplink/downlink CommuniCation with sPace Objects", and the first results of the development of its key technologies. The objective of the project is to create a communications system that uses a ground-based laser to interrogate a satellite, and an embedded modulated retro-reflector (MRR) to return modulated light back to the ground. The breakthrough in our communication system is that it frees up the satellite manufacturer from embedding a laser source on the satellite: simplifying the satellite design and avoiding the process of frequency allocation

This laser communication system is well-suited to small satellites, with the potential to provide a high data rate for very little on-board mass and low power consumption. The aim of the project is to achieve data rates of 1Gbit/s with a transmitter mass of less than 1kilogram.

C3PO aims to show that communications with LEO satellites using MRR based transceivers is feasible. In this paper results of the initial experiments presenting demonstration of technologies will be shown.

10096-39, Session 8

Optimization and throughput estimation of optical ground networks for LEO-downlinks, GEO-feeder links and GEO-relays

Christian Fuchs, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); Sylvain Poulenard, Airbus Defence and Space SAS (France); Nicolas Perlot, Fraunhofer-Institut für Nachrichtentechnik Heinrich-Hertz-Institut (Germany); Jérôme Riedi, Univ. des Sciences et Technologies de Lille (France); Josep Maria Perdigues Armengol, European Space Agency (Netherlands)

Optical satellite communications play an increasingly important role in a number of space applications. However, if the system concept includes optical links to the surface of the Earth, the limited availability due to clouds and other atmospheric impacts need to be considered to give a reliable estimate of the system performance. An OGS network is required for increasing the availability to acceptable figures.

In order to realistically estimate the performance and achievable throughput in various scenarios, a simulation tool has been developed under ESA contract. The tool is based on a database of 5 years of cloud data with global coverage and can thus easily simulate different optical ground station network topologies for LEO- and GEO-to-ground links can be simulated. Further parameters, like e.g. limited availability due to sun blinding and atmospheric turbulence, are considered as well.

This paper gives an overview about the simulation tool, the cloud database, as well as the theory behind the simulation scheme. Several scenarios have been investigated: LEO-to-ground links, GEO feeder links, and GEO relay links. The results of the optical ground station network optimization and throughput estimations will be presented. The implications of key technical parameters, as e.g. memory size aboard the satellite, will be discussed. Finally, potential system designs for LEO- and GEO-systems will be presented.

10096-40, Session 8

Weather impact on the availabilities of FSO space-to-ground links

Thierry Robin, Benoît d'Humières, TEMATYS (France)

Free-space optics (FSO) communication systems in space have been developed to overcome the data rate limitation of RF systems. In particular, links between satellites and satellites as well as ground stations and satellites, Unmanned Aerial Vehicles (UAVs) and other platforms flying stratospheric altitudes are of growing interest.

When dealing with ground-satellite FSO systems, it is necessary to have appropriate atmospheric propagation data. In fact, weather conditions influence the occurrence of clouds, turbulence, snow, rain, fog, haze, aerosol and dust that lead to the attenuation of the transmitted signal. Space-to-ground optical communications are adversely affected by these atmospheric phenomena and it is important to study the weather impact on the communication link.

In a first step, we analyze the capabilities and limitations of currently available meteorological data, satellite products and other databases with regards to predicting the availabilities of FSO space-to-ground links. Our study includes Copernicus, AERONET and MODIS datasets as well as reanalysis from ECMWF (European Centre for Medium-Range Weather Forecasts).

Then, we apply this analysis to prepare a dataset that we use to calculate the weather impact on the link budget of a typical ground station. We utilize a model evaluating the atmospheric attenuation including absorption and scattering due to aerosols and clouds, losses due to rain and fog, and intensity scintillation due to atmospheric turbulence.

Our calculations allow to obtain the statistics of the weather impact on the FSO space-to-ground link. We present a sample calculation with monthly statistics on attenuation due to absorption and scattering as well as attenuation due to atmospheric turbulence.

These types of statistics can be used to predict the availabilities of FSO space-to-ground links of a station or a network of stations. They can also be used to optimize the locations of the ground segment of FSO communications networks.

10096-41, Session 8

Digital optical feeder links system for broadband geostationary satellite

Sylvain Poulenard, Alexandre Mege, Bernard Roy, Airbus Defence and Space SAS (France); Josep Maria Perdigues Armengol, European Space Agency (Netherlands); Christian Fuchs, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); Nicolas Perlot, Fraunhofer-Institut für Nachrichtentechnik Heinrich-Hertz-Institut (Germany); Jérôme Riedi, Univ. des Sciences et Technologies de Lille (France); Péter Farkas, Fraunhofer-Institut für Nachrichtentechnik Heinrich-Hertz-Institut (Germany)

An optical link based on a multiplex of wavelengths at 1.55µm is foreseen to be a valuable alternative to the conventional radio-frequencies for the feeder link of the next-generation of high throughput geostationary satellite. The main satellite operator specifications for such link are an availability of 99.9% over the year, a capacity around one Terabits/s and to be bent-pipe.

Optical ground station networks connected to Terabit/s terrestrial fibers are proposed. The availability of the optical feeder link is simulated over 5 years based on a state-of-the-art cloud mask data bank and an atmospheric turbulence strength model. Yearly and seasonal optical feeder link availability are derived and discussed.

On-ground and on-board terminals are designed to be compliant with 10Gbit/s optical channel rate taking into account cirrus attenuation and adaptive optic systems to mitigate the impact of moderate to strong atmospheric turbulences on single mode fiber optical receivers. The forward and return transmission chains, concept and implementation, are described. These are based on a digital transparent on-off keying optical link with, digitalization of the DVB-S2 and DVB-RCS signals prior to the transmission, and an error correcting code.

Eventually, the satellite architecture is described taking into account optical and radiofrequency payloads as well as the interfaces between them.

10096-42, Session 8

High Speed optical links for UAV applications *(Invited Paper)*

Chien-Chung Chen, Matt Malfa, Andrew Grier, Harvard K. Harding, Kevin J. Quirk, Hamid Hemmati, Facebook Inc. (United States)

High speed optical backbone links between a fleet of UAVs is an integral part of the facebook connectivity architecture. To support the architecture, the optical terminals need to provide high throughput rates (in excess of tens of Gbps) while achieving low weight and power consumptions. The initial effort is to develop and demonstrate an optical terminal capable of meeting the data rate requirements and demonstrate its functions for both air-air and air-ground engagements. This paper will address the opto-mechanical design challenges and our implementation of our initial air-ground link demonstrations.

10096-43, Session 8

Data delivery performance of space-to-ground optical communication systems employing rate-constrained feedback protocols

Curt M. Schieler, Bryan S. Robinson, Don M. Boroson, MIT Lincoln Lab. (United States)

Space-based optical communication systems that transmit directly to Earth must provision for changing conditions such as dynamic power fluctuations that can occur due to atmospheric turbulence. One way of ensuring error-free communication in this environment is to introduce link-layer feedback protocols that use an Earth-to-Space uplink to request retransmission of erroneous or missing packets. In this paper, we consider near-Earth systems that use low-bandwidth uplinks to supply feedback. Relaxing the uplink signaling bandwidth can reduce the complexity of the space terminal, but it also decreases the efficacy of feedback schemes. We give analytical and simulated results for the downlink performance penalty of a system employing data rate-constrained automatic repeat request (ARQ) protocols. We find that the tradeoff is primarily influenced by the coherence time of the atmosphere.

10096-44, Session 8

Field demonstration of multi-rate, narrow-beam undersea optical communication with photon-counting and linear receivers in a turbid harbor

Hemonth G. Rao, Catherine E. DeVoe, Andrew S. Fletcher, Igor D. Gaschits, Farhad Hakimi, Scott A. Hamilton, Nicholas D. Hardy, John G. Ingwersen, Richard D. Kaminsky, Marvin S. Scheinbart, Timothy M. Yarnall, MIT Lincoln Lab. (United States)

We deployed a narrow-beam optical measurement and communication experiment over several days in the shallow, turbid water of Narragansett Bay, Rhode Island (USA). The experiment consisted primarily of a transmitter module and a receiver module mounted on a metal framework that could be lengthened or shortened. The communication wavelength was 515 nm. The experiment characterized light propagation characteristics, including images of the received beam over time. The experiment included manual beam steering. Images obtained during the steering process provided insight into future development of an automated steering procedure. Water transmissivity was also measured. Over time and tides, the optical extinction length varied between 0.66 m and 1.07 m. The transmitter's optical power was kept low at 0.25 mW. The receiver included a high-sensitivity photon-counting photomultiplier tube (PMT) and a high-speed linear avalanche photodiode (APD). Both links processed data continuously in real time. The PMT supported multiple channel rates, from 1.302 Mbaud to 10.416 Mbaud. It also included strong forward error correction (FEC) capable of operating at multiple code rates. The PMT link demonstrated near-theoretical channel performance at all data rates, error-free output after FEC, and robust operation during day and night. This link efficiently traded data rate for link loss. It demonstrated error-free performance for input powers as low as -84.1 dBm, or 18 extinction lengths. The APD receiver demonstrated a channel error rate of 1e-9 at 125 Mbaud. Furthermore, it demonstrated a channel error rate correctable by FEC at a link loss equivalent to 9 extinction lengths.

Conference 10097: High-Power Laser Materials Processing: Applications, Diagnostics, and Systems VI

Tuesday - Thursday 31–2 February 2017

Part of Proceedings of SPIE Vol. 10097 High-Power Laser Materials Processing: Applications, Diagnostics, and Systems VI

10097-1, Session 2

Latest results on solarization of optical glasses with pulsed laser radiation

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Femtosecond laser are growing tools for material processing and lithography. Femtosecond laser help to generate three dimensional structures in photoresists without using masks in micro lithography. This technology is of growing importance for the field of backend lithography or advanced packaging. Optical glasses used for beam shaping and inspection tools need to withstand high laser pulse energies.

Femtosecond laser radiation in the near UV wavelength range generates solarization effects in optical glasses. In this paper results are shown of femtosecond laser solarization experiments on a broad range of optical glasses from SCHOTT. The measurements have been performed by the Laser Zentrum Hannover in Germany. The results and their impact are discussed in comparison to traditional HOK-4 and UVA-B solarization measurements of the same materials. The target is to provide material selection guidance to the optical designer of beam shaping lens systems.

10097-2, Session 2

Impact of design-parameters on the optical performance of a high-power adaptive mirror

Wouter D. Koek, David Nijkerk, TNO Science and Industry (Netherlands); Jeroen A. Smeltink, Teun C. van den Dool, Erwin J. van Zwet, Gregor E. van Baars, TNO (Netherlands)

TNO has developed a High Power Adaptive Mirror (HPAM) concept to be used in the CO2 laser beam path of an Extreme Ultra-Violet light source for next-generation lithography. Because this element allows for extensive control of the shape, size and position of the focused high-power infrared radiation (wavelength 10.6 micron, powers up to 50kW) it can greatly assist the continuous endeavor to optimize the conversion-efficiency of laser produced plasmas.

To support the design of the water-cooled (piezo-)actuated surface sheet we have studied how diverse design-parameters affect the optical performance of a HPAM-equipped system. This paper reports on the outcomes and insights of these analyses.

For example, the high power beam may cause unwanted, and uncorrectable, thermally-induced inter-actuator surface deformations (so-called 'dimpling'). Using wavefront propagation, we studied the relation between the spatial frequency and amplitude of dimpling onto the quality of the top hat (QTH) spot profile that can be realized.

Furthermore we have analyzed the impact of the number of actuators (NoA) on QTH. We will show that there is not a simple smooth relation between NoA and QTH, but that there is a series of QTH 'plateaus'. This implies that a critical NoA must be realized to allow for 'next-level' QTH performance. The physical origin of these critical NoA's will be discussed.

Other research topics include the impact of actuator layout (Cartesian versus radial grid), and the relation between influence function and actuation noise / dynamic range requirements.

Furthermore we will discuss the (frequently underestimated) importance of defining proper metrics.

10097-3, Session 2

Fast adaptive laser shaping based on multiple laser incoherent combining

Lionel Garcia, Olivier Pinel, Pu Jian, Nicolas Barré, Lionel Jaffrès, Jean-François Morizur, Guillaume Labroille, CAILabs (France)

Multi-plane light conversion (MPLC) is an advanced light reshaping technique that enables complex light manipulation with few optical components. This technique is based on a passive, tailored and multi-reflective passive phase element achieving intrinsically lossless unitary transforms. The ability to control both amplitude and phase of several incident transverse modes permits complex and versatile transformations while the fully reflective and lossless design makes it compatible with high-power and high energy lasers.

We give a special focus to the multi-plane light conversion ability to achieve simultaneous reshaping and combining of several non-coherent laser sources and its applications to laser material processing. We present simulations and experimental results of a high-power, multiple beam shaper and combiner supporting up to ten incoherent kilowatt singlemode inputs. By achieving the transformation of several independent inputs into an optimal target base of modes, we create a tailored beam intensity profile. Two different types of output based are aimed:

- One targets the optimum beam quality (or minimal M? parameter) achievable with up to ten non-coherently combined beams.

- The other produces a tailored beam intensity profile which shape can be finely adapted simply by tuning the input lasers power.

In the numerous parameters of laser processes, it is well known that the laser beam intensity profile is one of the key factors: on demand, adaptable laser profile can significantly improve applications where the laser-matter interaction control is critical including selective laser welding or laser metal deposition additive manufacturing processes.

10097-4, Session 2

Beam shaping as an enabler for new applications

Yvonne Guertler, Max Kahmann, TRUMPF Laser- und Systemtechnik GmbH (Germany); David L. Havrilla, TRUMPF Inc. (United States)

For many years, laser beam shaping has enabled users to achieve optimized process results as well as manage challenging applications. The latest advancements in industrial lasers and processing optics have taken this a step further as users are able to adapt the beam shape to meet specific application requirements in a very flexible way.

TRUMPF has developed a wide range of experience in creating beam profiles at the work piece for optimized material processing. This technology is based on the physical model of wave optics and can be used with ultra short pulse lasers as well as multi-kW cw lasers. Bascically, the beam shape can be adapted in all three dimensions, which allows maximum flexibility. Besides adaption of intensity profile, even multi-spot geometries can be produced. This approach is very cost efficient, because a standard laser source and (in case of cw lasers) a standard fiber can be used without any special modifications.

Based on the innovative beam shaping technology, TRUMPF has developed new and optimized processes. Two of the most recent application developments using these techniques are cutting glass and synthetic sapphire with ultra-short pulse lasers, and enhanced brazing of hot dip zinc

coated steel for automotive applications. Both developments lead to more efficient and flexible production processes, enabled by laser technology, and open the door to new opportunities. They also indicate the potential of beam shaping techniques since they can be applied to both single-mode laser sources (TOP Cleave) and multi-mode laser sources (brazing).

10097-5, Session 3

Inline measurement for quality control from macro to micro laser applications

(Invited Paper)

Markus Kogel-Hollacher, Martin Schoenleber, Jochen Schulze, Precitec Optronik GmbH (Germany); Thibault Bautze, Matthias Strebel, Rüdiger Moser, Precitec GmbH & Co. KG (Germany)

The essential basis for a reliable and target-aimed process control is the understanding of the interaction between the laser beam and the treated material and this was gained by thorough research on the influence of the process input parameters on the interaction sub processes and on the treatment result. The main players con-ducting this research over the decades have been research facilities and institutes and this research is still in progress. Since the moment when it was possible to achieve the necessary power density to start the process of deep penetration welding, accompanied by a keyhole, there is hope - and need - to measure e.g. the depth of this vapor channel. In the decades in which the technology of deep penetration welding has been used, various approaches have been developed that allow a measurement of the depth of the keyhole. The aim of this contribution is to show a compact overview on the different approaches to monitor and/or control micro and macro laser welding processes and especially bring out those which successfully have been transferred from laboratory to serial production in the recent past and will be in the near future.

Laser materials processing in general offers several possibilities for process monitoring systems or process control but the complexity of the process itself, meaning the dependence of the processing result on several process input parameters, does not facilitate their use. As only continuous supervision of the manufacturing process can guarantee the high demands on the quality of the produced parts, process monitoring systems have become more and more standardized devices in laser applications. There is no doubt that the basis for reliable on-line process monitoring systems is the possibility to measure significant indicators, which demonstrates the instantaneous condition of the interaction zone and/or neighboring areas.

This contribution to the Photonics West 2017 LASE conference on the one hand will demonstrate an approach using chromatic coded line sensors for post-weld inspection, on the other hand will show a sensor, based on interferometric principle, which is capable to in-situ measure keyhole depth during deep penetration laser welding and further potential of this sensor approach.

10097-6, Session 3

Capillary depth measurement for process control

Wilrid Dubitzky, Friedhelm D. Dorsch, Patrick Haug, Jan-Patrick Hermani, Sven Plasswich, Lukas Effing, TRUMPF Laser- und Systemtechnik GmbH (Germany)

Optical coherence tomography (OCT) is a 3D imaging technique based on a low-coherence interferometer. The technique can be applied to laser welding applications measuring the capillary depth with close-loop control of laser power or feed rate. A controlled constant weld depth allows running applications closer to their process limits, thus increasing the output performance per production cycle. It is also expected that the online measurement of the weld depth reduces the number of necessary destructive sample inspections. An essential premise is a reliable weld depth measurement independent from influencing factors.

This work analyzes the influence of laser power, beam diameter, feed rate, and work piece material on the weld depth measured using the OCT technique. At typical powertrain laser welding parameters of 4 kW laser power, 5 m/min feed rate, and 200 μm laser spot size, it leads to acceptable results. If the parameter set is changed, realignment of the probe beam becomes necessary to avoid misinterpretation of the measurement signal. Still, there are physical limits of the OCT technique for keyhole depth measurement. The interferometer probe beam cannot hit the deepest point of extreme deep and narrow keyholes even at perfect alignment. At constant feed rate, this keyhole shape occurs at high laser power in combination with small laser spot size. Another limit is welding at low laser power density where a defined keyhole is not settling. At constant feed rate, this happens at low laser power combined with large laser spot size.

The above results obtained by using a fixed laser optic are compared to the corresponding results from a scanner optic.

10097-7, Session 3

Comprehensive analysis of the capillary depth in deep penetration laser welding

Florian Fetzer, Meiko Boley, Rudolf Weber, Thomas Graf, Institut für Strahlwerkzeuge, Univ. Stuttgart (Germany)

Laser welding is the state of the art joining technology in terms of productivity and thermal loads. In deep penetration laser welding the quality of the resultant welds depends on the dynamics of the capillary. These dynamic processes are of major influence on the controllability of the laser welding process and on the prevention of weld defects. The capillary dynamics was investigated by means of time- and space-resolved in-process X-ray imaging and optical coherent tomography. The X-ray diagnostics allows a measurement of the capillary geometry with frame rates of 1 kHz, while the optical coherence tomography enables the determination of the capillary depth with an acquisition rate of up to 70 kHz. These measurements were correlated to provide profound insight in the laser welding process. The measurements were correlated to evaluate the dynamic dependence of the capillary depth in dependence on the incident laser power. The measurements were performed for copper, aluminum and mild steel. The capillary depth resulting from different forms of laser power modulations, such as sinusoidal modulation or sawtooth waves was investigated. Thereby the response of the capillary depth to laser power changes can be determined. Additionally, the power range in which the capillary depth reacts almost linearly to the input laser power can be defined. Based on these measurements the changes of the capillary depth in deep penetration laser welding can be described by methods known from control theory. These analyses can be utilized to calibrate transient simulations of deep penetration laser welding and to identify the influence of material properties.

10097-8, Session 3

Modelling and control for laser based welding processes: modern methods of process control to improve quality of laser-based joining methods

Ralf-Kilian Zäh, ZeMA gGmbH (Germany); Benedik Mosbach, Jan Hollwich, ZeMA - Zentrum für Mechatronik und Automatisierungstechnik gGmbH (Germany); Benedikt Faupel, Hochschule für Technik und Wirtschaft des Saarlandes (htw saar) [University of Applied Sciences] (Germany)

To ensure the competitiveness of manufacturing companies need to optimize their manufacturing processes. Slight variations of process parameters and machine settings have effects on the product quality. It is necessary to keep the formation of welding seams within specified limits. Therefore, the quality of connection is ensured, by using post-process-methods or special in-process-methods. These in-process-systems achieve an evaluation which shows whether the weld seam is acceptable or not. Furthermore, in-process-systems use no feedback for changing the control variables.

The research group presents current results of Online-Controlling, Model-Predictive-Controlling, in laser welding processes to increase the product quality. To record the characteristics of the welding process, tested online methods are used during the process. Based on the measurement data, a state space model is ascertained, which includes all the control variables of the system. Depending on simulation tools the control system is designed for the model and integrated into an NI-Real-Time-System.

10097-9, Session 3

OpenLMD, multimodal monitoring and control of LMD processing

Jorge Rodríguez-Araújo, Antón García-Díaz, AIMEN Ctr. Tecnológico (Spain)

Laser Metal Deposition (LMD) is a promising additive manufacturing approach to fabrication of large metallic parts directly from 3D CAD models. However, it poses issues related to distortion and defect generation that require human intervention and machining operations to achieve the desired shape. Previous works on on-line monitoring and control of LMD have demonstrated improvement of process control (e.g. improved surface shape) and the capability to reduce the appearance of defects. Although these results address partial problems and have limited practical use, they point to on-line multimodal monitoring -especially image-based monitoring- as a key enabler of LMD processing automation.

This paper describes OpenLMD, a novel open-source solution to the orchestration and virtualization of a complete LMD processing robot cell, capable to easily integrate sensors and process equipment as necessary while keeping a common reference of time and spatial coordinates for data acquisition. Moreover, this solution may be easily extended to other laser processing applications (e.g. laser welding) that can benefit from on-line monitoring and control.

It is demonstrated in a robot cell acquiring images in different spectral bands. A CMOS sensor covering the visible and NIR range at 500Hz and an uncooled PbSe FPA covering the MWIR range at 1kHz image the melt pool coaxially. An CMOS sensor coupled to a laser stripe measures the 3D geometry off-axis. A novel control strategy based on multimodal monitoring of relevant variables (e.g. melt pool width, shape, texture dynamics, speed, thermal gradient, 3D shape) based on the proposed architecture is also described.

10097-503, Session Plen

Development of 250W EUV Light Source for HVM Lithography

Hakaru Mizoguchi, Gigaphoton Inc. (Japan)

We have been developing CO2-Sn-LPP EUV light source for HVM EUVL. We have reported engineering data from our resent test such around 118W average clean power, CE=3.7%, with 100kHz operation and other data 1). We have already finished preparation of higher average power CO2 laser more than 20kW at output power cooperate with Mitsubishi electric cooperation 2). Further improvements are underway, we will report the latest data. Also we will report the latest data of Pilot 250W EUV source system.

1) Hakaru Mizoguchi, et. al, Proc. SPIE 9048, (2014) [9048-12]

2) Yoichi Tanino et.al, EUV Symposium 2013, (Oct.6-10.2013, Toyama)

10097-10, Session 4

Laser beam welding with high power cw-laser at 515 nm and 1070 nm wave length *(Invited Paper)*

Jens Standfuss, Dirk Dittrich, Philipp Mohlau, Jens Liebscher, Fraunhofer IWS Dresden (Germany)

Laser beam welding of materials like copper, lightweight aluminum alloys with high magnesium content as well as aluminum pressure die casting is still a challenge. Caused by facts like:

- the high reflectivity,

- low viscosity of the meld pool,

- alloying elements with low evaporating temperature and

- dissolved gases,

spatter, pores and melt pool ejection can occur with reduced process stability and will lead to bad weld seam quality. On the other hand for potential joining applications in the field of electro mobility and lightweight design stable laser welding processes are required.

The use of high power cw-laser source with brilliant beam quality and different wave length in combination with a high-frequent 2D beam oscillation is a promising approach to overcome these limitations. The influence of different wavelengths (515 nm and 1070 nm) for lasers with comparable beam parameter product and power up to 1000 W @ 515 nm and up to 5000 W @ 1070 nm were investigated. A keyhole modulation using a 2D high frequent beam oscillation up to 4 kHz was used for an improved weld process. As a result high quality welds with reduced porosity and less spatters occurred. The potential of this technology will be discussed for several materials and industrial applications for welding of aluminum pressure die casting of automotive components will be presented.

10097-11, Session 4

Investigation of electroless Ni(P)/Pd/Au metallization for solder joining of optical assemblies using laser-based solderjet bumping

Thomas Burkhardt, Max Mäusezahl, Oliver de Vries, Jan Kinast, Christoph Damm, Erik Beckert, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

Solder joining is an all inorganic, adhesive free bonding technique for optical components and

support structures of advanced optical systems. We established laser-based Solderjet Bumping for mounting and joining of elements with highest accuracies and stability. It has been proven for optical assemblies operating under harsh environmental conditions, high energetic or ionizing radiation, and for vacuum operation. Spaceborne instrumentation experiencing such conditions and can benefit from inorganic joining to avoid adhesives and optical cements. The metallization of components, necessary to provide solder wetting, mainly relies on well-adhering layer systems provided by physical vapor deposition (PVD). We present the investigation of electroless Ni(P)/Pd/Au plating as a cost-efficient alternative under bump metallization of complex or large components unsuitable for commercially available PVD. The electroless Ni(P)/Pd/Au plating is characterized with respect to layer adherence, solderability, and bond strength using SnAg3Cu0.5 lead-free solder alloy.

10097-12, Session 4

Hot cracking during laser welding of steel: influence of the welding parameters and prevention of cracks

Marcel Schaefer, TRUMPF GmbH + Co. KG (Germany); Steffen Ke?ler, Philipp Scheible, Nicolai Speker, Thomas Harrer, TRUMPF Laser- und Systemtechnik GmbH (Germany)

In continuous wave keyhole-mode laser welding of high strength steel alloys hot cracking can occur. Hot crack susceptibility depends on several factors as described e.g. by Cross [1]. Thus, welding parameters as well as the alloy composition and weld fixturing interact in behalf of hot crack susceptibility. In this paper we investigate the dependency of crack formation on the laser power, the welding speed and the laser wavelength.

To prevent hot cracks there are contrary statements when focusing on laser welding parameters e.g. the line energy P/v. Pshennikov [2] found that a higher welding speed v decreases the hot crack susceptibility, but the opposite behavior was detected by Matic [3].

We show, that the dependence of the line energy onto the crack susceptibility is opposite in two cases: first, the laser power P was varied at constant feedrate v and second the feedrate v was varied at constant penetration depth PD. Furthermore, to investigate the influence of different beam qualities on the hot crack formation, the feedrate was varied but the focal diameter and the penetration depth were kept constant.

Moreover the laser wavelength is considered to influence the hot crack formation. In Gollnow [4] no hot cracks are detected in laser welds of mild steel when a fiber laser is used. On the contrary, when using a CO2 laser, hot cracks appear in the middle axis of the fusion zone. To investigate the influence of the laser wavelength on the crack formation, welding results of a TruDisk solid state laser and a TruFlow CO2 laser with the same beam parameter product of BPP=4 mm.mrad, the same focal diameter and adjusting to the same penetration depth of PD=4 mm are compared. Finally, some strategies to prevent hot cracking in partial penetration welds in steel alloys are presented.

10097-13, Session 4

Vacuum fiber-fiber coupler

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Research and development carried out by the ISF Welding and Joining Institute of RWTH Aachen University has proven that combining high power laser and low vacuum atmosphere provides a welding performance and quality, which is comparable to electron beam welding. The developed welding machines are still using a beam forming which takes place outside the vacuum and the focusing laser beam has to be introduced to the vacuum via a suitable window. This inflexible design spoils much of the flexibility of modern laser welding. With the target to bring a compact, lightweight flying optics with flexible laser transport fibers into vacuum chambers, a high power fiber-fiber coupler has been adapted by II-VI HIGHYAG that includes a reliable vacuum interface.

The vacuum-fiber-fiber coupler (V-FFC) is tested with up to 16 kW sustained laser power and the design is flexible in terms of a wide variety of laser fiber plug systems and vacuum flanges. All that is needed to implement the V-FFC towards an existing or planned vacuum chamber is an aperture of at least 100 mm (4 inch) diameter with any type of vacuum or pressure flange.

The V-FFC has a state-of-the-art safety interface which allows for fast fiber breakage detection for both fibers (as supported by fibers) by electric wire breakage and short circuit detection. Moreover, the System also provides connectors for cooling and electric signals for the laser beam optics inside the vacuum.

The V-FFC has all necessary adjustment options for coupling the laser radiation to the receiving fiber.

10097-14, Session 5

On the possibility of visualization of undersurface submicron-sized inhomogeneities via laser-induced incandescence of surface layers

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As one can easily ascertain by simple estimates, a nanosecond-scale laser pulse can overheat the thin surface layer of a light-absorbing material to a temperature of thousands Kelvins. Thermal emission of this laser-heated surface (laser-induced incandescence, LII) is easily observed in the visible spectral range by a photomultiplier. The local LII intensity of the laser-heated surface depends on the presence of undersurface structural inhomogeneities (voids, cracks, regions of local doping, etc.). In the present work, we perform computer simulations of the processes of transient laser heating of a surface layer with hidden submicron-sized voids located under the surface in order to assess the possibilities of their visualization via LII.

Calculations showed that undersurface microscopic inhomogeneities can significantly affect the local LII intensities of the laser-irradiated surface. The calculations were performed with the ordinary heat diffusion equation, assuming temperature-independence of material parameters as a first approximation. The value of laser power was adjusted to obtain local heating of the surface to a temperature of 2000...3000 K. For laser pulses of 20 ns duration, heat diffusion length was taken as 300 nm, hence typical values of the void diameter and of the void-to-surface distance in the calculations were chosen of the order of L. The intensity of LII was calculated with the using of Planck's blackbody emission law at a fixed wavelength of 500 nm.

As a result of the computer simulations performed, we can conclude that the undersurface local deviations of material parameters (heat conductivity, heat capacity) can be detected via LII with the resolution of the order of heat diffusion length.

10097-15, Session 5

Oxidation and sublimation of porous graphite during fiber laser irradiation

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Porous graphite plates, cylinders and cones with densities of 1.55-1.82 g/cm3 were irradiated by a 10 kW fiber laser at 0.075 –3.525 kW/cm2 for 120 s to study mass removal and crater formation. Surface temperatures reached steady state values as high as 3767 K. The total decrease in sample mass ranged from 0.06 to 6.29 g, with crater volumes of 0.52 - 838 mm3, and penetration times for 12.7 mm thick plates as short as 38 s. Minor contaminants in the graphite samples produced calcium and iron oxide to be re-deposited on the graphite surface. Significantly increased porosity of the sample is observed even outside of the laser-irradiated region. Total mass removed increases with deposited laser energy at a rate of 4.83 g/

MJ for medium extruded graphite with an apparent threshold of 0.15 MJ. Visible emission spectroscopy reveals C2 Swan and CN red, CN violet bands and Li, Na, and K 2P3/2,1/2 – 2S1/2 doublets. The reacting boundary layer is observed using a midwave imaging Fourier transform spectrometer (IFTS) at 2 cm-1 spectral resolution, 0.5 mm/pixel spatial resolution, and 0.75 Hz data cube rate. A two layer radiative transfer model was used to determine plume temperature, CO, and CO2 concentrations from spectral signatures. The new understanding of graphite combustion and sublimation during laser irradiation is vital to the more complex behavior of carbon composites.

10097-16, Session 5

Real-time monitoring and controlled selective ablation based on optical emission spectroscopy technique

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Short and ultra-short lasers are widely used for subtractive processes in modern advanced nano to microelectronics industry. i.e in manufacturing of data display units, interactive (touch) sensors, bio/ physical sensors– while at the same time connect to the internet things through a micro–millimetre–sized antennae. The integration of different components are only possible by precise and controlled processing. Laser subtractive processes require nanometre depth precision, micron lateral precision, minimal side wall thermal damage, minimal surface kerfs, no substrate damage and no contamination by nanoparticles. In this study, we optimize such processes by real time observations that detect layer removal and ablation mechanisms by optical emission based laser induced breakdown spectroscopy (LIBS). LIBS is a multi-elemental analytical technique, in which atomic and ionic characteristic emission lines are used to identify chemical composition of the target. This state of the art real time monitoring technique collect signals which originate from within the laser process interaction zone. Ultrashort laser pulses are used for the selective ablation of very thin layers, with precise stops at layer interfaces and minimal side-wall surface diffusion. This optical emission based technique is employed for real time monitoring in patterning, selective ablation and structuring of industrial materials like ITO, monolayer graphene and molybdenum, aluminum and molybdenum (MAM) based hetero-structures. Spatial resolution in the order of nm is achieved and experimental parameters (of laser, spectrometer and optics) are evaluated to optimize and apply it in industrial processing.

10097-17, Session 6

A cutting-edge solution for 1µm laser metal processing

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The recent 1µm-laser cutting market is dominated by fiber and disk lasers due to their excellent beam quality of below 4mm*mrad. Teradiode’s 4kW direct diode laser source achieves similar beam quality while having a different beam shape and shorter wavelengths which are known for higher absorption rates at the inclined front of the cutting keyhole. Research projects, such as the HALO Project, have additionally shown that polarized radiation and beams with Laguerre-Gaussian modes different from the typical LG00 lead to higher cutting speeds as well as to improved cut quality for ferrous and non-ferrous metals. Diode laser have the inherent property of not being sensible to back reflection which brings huge advantages in cutting high-reflective materials. The II-VI HIGHYAG laser cutting head BIMO-FSC offers the unique feature of machine controlled and continuous adjustment of both the focus diameter and the focus position. This feature is proven to be beneficial for cutting and piercing with high speed and low hole-diameters. In addition, the optics are designed for lowest focus shift.

As a leading laser processing head manufacturer, II-VI HIGHYAG qualified its BIMO-FSC MZ (M=magnification, Z=focus position) cutting head for Teradiode’s 4kW direct diode laser source to offer a cutting-edge solution for high-power laser cutting. Combining the magnification ability of the cutting head with this laser source, customers experience strong advantages in cutting metals in broad thickness ranges. Thicknesses up to 25mm mild steel can be cut with excellent edge quality easily.

Furthermore, a new optical setup equivalent to an axicon with a variable axicon angle is demonstrated which generates variable sized ring spots. The setup provides new degrees of freedom to tailor the energy distribution for even higher productivity and quality.

10097-18, Session 6

Adapting the axial focus in high-power laser processing machines within mm-range

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The High-Power Focus Mirror we present in this paper gives access to focus position adaption along 3.6 mm in high-power laser manufacturing. We developed and tested a new thermo-mechanical design for a unimorph deformable mirror that provides an extensive focal length range down to -2 m focal length. Moreover, the mirror’s unique thermal characteristics enable high-power applications up to 2 kW (1200 W/cm?) with stable optical beam quality as thermal lensing is successfully suppressed. Thus, the laser’s optical beam quality M? is stable over the entire actuation and thermal range.

We will describe the design and manufacturing process as well as the characterization of the High-Power Focus Mirror.

The mirror setup is based on a unimorph concept using a piezoelectric actuator and a thin glass substrate with a highly reflective multilayer coating. An integrated copper layer improves the heat dissipation. Providing maximum stroke as well as excellent dynamic properties, the deformable mirror substrate is mounted by our established compliant cylinders.

We investigated the incorporation of the High-Power Focus Mirror into a commercial laser-cutting system. We set up a laser-cutting test bench including a multimode laser source, the focus mirror, a commercial laser processing head, and measuring instruments. In this assembly we measured the achievable focus position range as well as the laser beam quality.

We demonstrated that with this setup, it is possible to address new, innovative high-power application fields in 3D laser processing such as laser cutting, welding, and structuring.

10097-19, Session 6

Ultrafast fiber beam delivery system technology and industrial application

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Flexible beam delivery of high power lasers has become a standard for most continuous wave applications. It also offers great advantages for

high power ultrafast lasers with pico- and femtosecond pulses which are now increasingly used in industrial applications. However, free space beam delivery is the standard in today's ultrafast processing machines as fiber beam delivery has not been available due to extremely high peak powers at a fibers end facet. During the last years we have developed a modular beam delivery system that suits industrial ultrafast lasers and can be integrated into existing processing machines. Using micro-structured hollow core fibers, the sealed laser light cable efficiently guides laser pulses of several 100 µJ over distances of up to 10 meters with excellent beam quality, while power, pulse duration and polarization are maintained. The beam guidance in a hollow core, which can be filled with air or other gases allows the transport of very high peak powers on the order of GW as more than 99% of the energy is confined in the hollow core. Hollow core fibers have particular characteristics that need to be considered during coupling and transmission and determine the application for material processing. Based on the analysis of hollow core fiber transmission we will discuss requirements for successful integration into industrial production and report on achievable performance under realistic operation with regard to efficiency of transmission, beam and polarization preservation in static and dynamic situations. Examples of demanding applications will be shown.

10097-20, Session 6

I-PFO: the new technology for simple and flexible implementation of high productive on-the-fly remote processes

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In summer this year TRUMPF will launch the I-PFO technology. This is a new programming and control concept for a simple and flexible implementation of laser based „On-The-Fly" remote processes.

The I-PFO (Intelligent Programmable Focusing Optics) knows its own position in the working area of an industrial robot as well as the location and orientation of processing points, e.g., weld seams on the work piece. On the basis of information on current robot movement, which it receives continuously, the I-PFO begins processing autonomously wherever geometrical and process related restrictions allow it.

For the first time it is possible to program or adopt complex remote processes in a fast and easy way by the "TeachIn" function via the robot teach pendant.

Additionally a module for 3D simulation is an option of the system. This software creates automatically the ideal remote process based on the part, fixture, production cell and required process parameters.

The I-PFO doesn't need additional hardware due to the fact that it runs on the controller within the scanner. Hence the minimum amount of modules (laser source, scanner and industrial robot) are sufficient to enable high productive remote processing.

Furthermore it works together with different types of industrial robots which allow highest flexibility at the production planning.

Finally one laser source can supply up to six I-PFOs, which guarantees the maximum beam-up time at the production line.

10097-21, Session 6

Diode lasers for direct application by utilizing a trepanning optic for remote oscillation welding of aluminum and copper

Haro Fritsche, Norbert Mueller, Fabio Ferrario, Sebastian Fetissow, Thomas Hagen, Ronny Steger, Andreas Grohe, Wolfgang Gries, DirectPhotonics Industries GmbH (Germany)

We report the first direct diode laser module joint with a trepanning optic for remote oscillation welding. The Trepanning optic consists in it's basic setup of 2 motors, one for changing the tilt of the quartz glass plate which results in the size of the the beam displacement and another motor for rotating that plate for generating the beam oscillation with up to 16.000 rpm.

This trepanning optic is here directly mounted to the collimated DirectProcess 900. This way the beam profile is remained rectangular, nearly flat top and has a Beam parameter product of 6 mm mrad without the power loss of fiber coupling. The laser was operated in cw mode.

The performance of the 500 W DirectProcess direct diode laser for oscillating welding by utilizing a novel trepanning optic is discussed for its application to aluminum/aluminum and aluminum/copper joints. Welding results were analyzed for but welds of aluminum samples with thicknesses up to 1.5 mm and with copper samples.

The trepanning optics for an oscillating beam enabled the DirectProcess 900 at the 500 W level to effectively weld aluminum as well as copper-aluminum joints.

The DirectProcess 900 C achieved very good welding quality for aluminum as well as thin copper-aluminum joints with comparable welding speeds as with fiber lasers in similar configurations. Still, the oscillation of the laser beam with a trepanning optic is more accurate and easier as similar welding pattern achieved by 2D-Scanners.

10097-22, Session 6

Concepts for laser beam parameter monitoring during industrial mass production

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In today's industrial mass production, lasers have become an established tool for a variety of processes. As with any other tool, mechanical or otherwise, the laser and its ancillary components are prone to wear and ageing. Monitoring of these ageing processes at full operating power of an industrial laser is challenging for a range of reasons. Not only the damage threshold of the measurement device itself, but also cycle time constraints in industrial processing are just two of these challenges.

Power measurement, focus spot size or full beam caustic measurements are being implemented in industrial laser systems. The scope of the measurement and the amount of data collected is limited by the above mentioned cycle time, which in some cases can only be a few seconds.

For successful integration of these measurement systems into automated production lines, the devices must be equipped with standardized communication interfaces, enabling a feedback loop from the measurement device to the laser processing systems.. If necessary these measurements can be performed before each cycle.

Power is determined with either static or dynamic calorimetry while camera and scanning systems are used for beam profile analysis. Power levels can be measured from 25W up to 20 kW, with focus spot sizes between 10µm and several millimeters. We will show, backed by relevant statistical data, that defects or contamination of the laser beam path can be detected with applied measurement systems, enabling a quality control chain to prevent process defects.

10097-23, Session 7

Enhancement of low pressure cold sprayed copper coating adhesion by laser texturing on aluminum substrates

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Low Pressure Cold Spray (LPCS) is an efficient, simple and cheap way to obtain metallic coatings on a large variety of substrates. The more sophisticated High Pressure Cold Spray (HPCS) requires much higher investments. In both cases a metallic powder (typically Copper or Aluminum) is accelerated in a gas stream through a convergent/divergent nozzle. Particles impact at supersonic velocities on substrate and bond with it through plastic deformation, creating a metallic coating. A particularity of the Cold Spray Technology is the possibility to obtain thick coatings (mm-range) and even build-up massive parts without thermal impact on the base material, whereas other thermal spray processes may be limited in thickness.

A common problem of LPCS is the low spraying yield and low bonding strength of coatings. The objective of this study was to combine LPCS with Laser textured substrates in order to reduce crack propagation at the coating/substrate interface and therefore enhance the adhesion of coatings. Laser texturing allows controlling exactly the geometry of the surface compared to grit-blasting process, which is currently used in industry to prepare surfaces before spraying. Laser texturing is free of environmental constraints (no use of solvents). It also avoids brittleness of the surface by grit inclusion and noise issues of the grit-blasting process.

Several texturation geometries were tested, mostly spaced holes at micrometric scale, done with nanosecond and picosecond sources. A significant enhancement of the bonding strength was obtained after an optimization of the texturation pattern for a substrate made of aluminum AW5083, with a copper based coating. The improvement was confirmed by comparison with coatings onto raw and grit-blasted substrates, allowing to obtain the same final quality of coating and deposition efficiency.

10097-24, Session 7

Analysis of hazardous substances released during CFRP laser processing

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Due to their outstanding mechanical properties, in particular their high specific strength parallel to the carbon fibers, carbon fiber reinforced plastics (CFRP) have a high potential regarding resource-efficient lightweight construction. Consequently, these composite materials are increasingly finding application in important industrial branches such as aircraft, automotive and wind energy industry. However, the processing of these materials is highly demanding. Mechanical processing methods such as milling or drilling are connected with notable tool wear. Thermal processing methods are critical as the two components matrix and reinforcement have widely differing thermophysical properties, possibly leading to damages of the composite structure in terms of pores or delamination. An emerging innovative method for processing of CFRP materials is the laser technology. As a thermal method, laser processing is related to the release of potentially hazardous, gaseous and particulate substances. Detailed knowledge of these process emissions is the basis to ensure the protection of man and the environment, according to the existing legal regulations. This knowledge will help to realize adequate protective measures and thus strengthen the development of CFRP laser processing.

In this work, the measurement methods used and exemplary results of the analysis of the exhaust air and the air at the workplace during different laser processes with CFRP materials are presented. The investigations have been performed in the course of different cooperative projects, funded by the German Ministry of Science and Education (BMBF) in the course of the funding initiative “Photonic Processes and Tools for Resource-Efficient Lightweight Construction”.

10097-25, Session 7

Significance of laser pre placed cladding in 3D metal printing by direct metal laser sintering

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Laser preplaced cladding of St-6, WC and Inconel powders is carried out using 1064 nm Pulsed Nd:YAG or 808 nm HPDL CW lasers. A special powder dispenser to deliver an uniform layer of powder and simultaneously compact the powder on coupon is based on roller flour mill design. A conical coaxial nozzle surrounding the square laser head of HPDL diode laser is specially developed. Laser processing parameters - power, scan rate, spot size and inert gas and powder carrier gas pressure are established for optimum performance. Analytical and numerical 3D models of preplaced cladding are formulated by lumped and finite difference methods of heat and mass transfer. A good correlation between experimental cladding conditions comparing with numerical simulation and analytical predictions are confirmed.

10097-26, Session 8

Laser anti-corrosion treatment of metal surfaces

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There was an active research of new ways to improve the surface properties of metals and to increase the corrosion resistance. One of the breakthrough methods to protect the material against corrosion is laser treatment. We used a CW fiber laser operating at 1064 nm with up to 18,4 W output power. Experimentally, the samples (steel plates) were irradiated by laser for 35 seconds. Surface treatment of metal was provided at a room temperature and a relative air humidity of 55%. The impact of laser radiation on the surface has contributed to a small change of its chemical composition. It forms protective fluoride coating on the metal surface. The laser radiation significantly increased the concentration of fluorine in the metal from 0.01 atom. % to 5.24 atom. %. The surface roughness of steel has changed from 3.66 ? to 2.66 ?. Protective coatings with best resistance to corrosion were obtained with laser power density in a range of 93.3 W/cm2 to 95.5 W/cm2.

10097-28, Session 8

193nm high power lasers for the wide bandgap material processing

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The material processing by DUV laser region has been required for wide band gap material and precise hole and groove in DUV region. It is still very hard to get high power solid-state lasers in this spectral region especially below 200nm. The rare-gas halide excimer lasers are only the solution, and now the time has come to examine the new applications of material processing with DUV excimer lasers.

We have developed three types of DUV excimer lasers. The first is an injection-locked 193nm excimer laser of 120W with an ultra-narrow spectrum below 0.3pm. The excimer lasers at 193nm as well as 248nm have been used in the semiconductor manufacturing for long years, and have field-proven stability and reliability. One of the important features will be the ability to support green operations while improving performance.

The second is a high power (>450W) 351nm and 248nm laser with free spectrum operation for the low temperature poly-silicon annealing.

The third is an 193nm "hybrid" laser, which is the combination of a solid-state seed laser and an excimer laser amplifier. High light-harvesting efficiency and high coherence of the hybrid laser has been achieved, which has M2 value of 1.6, and an average power of 110W with three-pass amplifications. An interference exposure test demonstrated the high beam quality. The high photon energy of 6.4eV at 193nm is expected to interact directly with the chemical bond of hard-machining materials, such as CFRP, diamond and reinforced glasses.

We will report the latest results of performance of 193nm high power DUV lasers and material processing.

10097-29, Session 8

Analyzing the effects of high repetition laser shock peening on corrosion resistance of magnesium using a specially designed dynamic test bench

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Magnesium has been considered as a promising replacement to conventional implants owing to its closeness to bone properties and a huge R&D is carried out aimed for its implementation. So far the major obstacle in using magnesium implants is its high corrosion rate. This paper analyzes the effects of High Repetition Laser Shock Peening (HRLSP) on corrosion rate of magnesium. Generally, the corrosion rate of Mg is validated using common conventional and static methods such as hydrogen evolution method, mass loss method and other electrochemical techniques. However, the authors feel the results from these methods may be misleading as the surrounding conditions to which the implant is subjected is not considered.

To test the effects of HRLSP on corrosion rate, the authors have developed a test bench capable to maintain the solution flow at 37.5°C and along with similar flow rates around implants as in human body. The pH change caused by the magnesium sample was recorded and corrosion rate was determined at the end from its mass difference. A dedicated PDMS fixture has been fabricated to house the sample. A complete elucidation regarding the design, fabrication and corrosion results of peened samples obtained using static method and dynamic test bench will be provided in the manuscript.

Corrosion tests were carried out on unpeened and samples peened with 0% overlap & 66% overlap. Corrosion rate of unpeened sample varied significantly under static and dynamic conditions while for peened samples corrosion rate was slightly higher under dynamic conditions.

10097-30, Session 8

Advances in laser technology for de-thorning of opuntia cactus

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The elimination of spines in feeding products as Opuntia cactus is currently carried out by manual-mechanic methods, causing strong losses, decrease in product life, and sanitary risks. Recently, was proposed a completely novel solution: to use the laser light in order to eliminate the spines. In this work, the author's shows recent advances in optimization of identification and ablation of thorns, in dependence on laser parameters as pulse duration, pulse energy and repetition rate. Using a pulse energy of 0.9 J and pulse duration of 180 microseconds, is possible to obtain the higher ablation rate per pulse without damage to the cortex of cactus.