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Conference 8959: Solid State Lasers XXIII: Technology and Devices

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Sunday - Tuesday 2 –4 February 2014

Part of Proceedings of SPIE Vol. 8959 Solid State Lasers XXIII: Technology and Devices

8959-1, Session 1

Single-crystal fiber optics: a review *(Invited Paper)*

James A. Harrington, Rutgers, The State Univ. of New Jersey (United States)

Single-crystal (SC) fiber optics made from oxide crystals such as sapphire and YAG have promising applications as both passive and active fibers. Most SC fibers such as sapphire are transmissive up to about 3 ?m and, therefore, are potentially excellent fibers for the transmission of high-power Er:YAG lasers operating near 3 ?m. As an active fiber, SC fibers grown from YAG and other garnets could provide an excellent alternative to conventional glass fiber lasers for the delivery of extremely high laser powers. In general, the optical and physical properties of SC fibers, including reduced non-linear effects such a stimulated Brillouin scattering (SBS) and high thermal conductivity, are often exceed those of glass fiber optics. The methods to grow SC oxide fibers, which include laser heated pedestal growth (LHPG), will be reviewed along with their optical and laser properties.

8959-2, Session 1

Coilable single crystals fibers of doped-YAG for high power fiber laser applications *(Invited Paper)*

Gisele Maxwell, Bennett Ponting, Nazila Soleimani, Eminet Gebremichael, Shasta Crystals (United States)

Single crystal fibers can both guide laser light and match the efficiencies of bulk crystals, which makes them ideal candidates for high-power fiber laser applications. This work focuses on the growth of a coilable fiber with a core of dopant. Scattering losses, dopant profile characterization and lasing experiments are presented.

8959-3, Session 1

Cladded single crystal fiber for high power lasers *(Invited Paper)*

Brandon Shaw, U.S. Naval Research Lab. (United States)

No Abstract Available

8959-4, Session 1

Yb:YAG single crystal fiber image amplifier *(Invited Paper)*

Peng Wan, Jian Liu, Lih-Mei Yang, Shuang Bai, PolarOnyx, Inc. (United States)

In the talk, Yb:YAG single crystal fiber is used for the first time to amplify week image signal. It was longitudinally pumped by a fiber-coupled laser diode with a maximum power of 66W at 940 nm. The image amplifier provided low noise and high gain amplification. Its amplification of ultrafast pulses will also be addressed.

8959-5, Session 2

Double clad YAG crystalline fiber waveguides for diode pumped high power lasing *(Invited Paper)*

Xiaodong Mu, Stephanie Meissner, Helmuth E. Meissner, Onyx Optics Inc. (United States); Anthony W. Yu, NASA Goddard Space Flight Ctr. (United States)

Large mode area single mode rare-earth doped YAG crystalline fiber waveguides have been prepared with adhesive-free bonding technology. Analyses indicate that high efficiency single-mode and single-frequency lasing up to tens of kilowatts becomes feasible due to high thermal conductivity and low Brillouin scattering. Preliminary laser results will be presented.

8959-7, Session 3

Increased efficiency of Er:YAG lasers at 1645 nm using narrow bandwidth diode lasers and dual-wavelength resonant pumping

Haro Fritsche, Oliver Lux, Casey Schuett, Technische Univ. Berlin (Germany); Stefan W. Heinemann, Marcus Dziedzina, Wolfgang Gries, DirectPhotonics Industries GmbH (Germany); Hans Joachim Eichler, Technische Univ. Berlin (Germany)

Compact high power lasers operating in the eye-safe spectral region around 1.6 µm find growing interest in the fields of free-space communication, telemetry and lidar applications. Resonantly pumped Er:YAG lasers emitting at 1645 nm which are pumped by diode lasers operating in the range from 1455 nm and 1570 nm are characterized by a high quantum efficiency. Since the pumping process involves different narrowband Stark sub-levels of the laser transition 4I13/2 ? 4I15/2, frequency stable and narrow bandwidth pump modules are required. We developed several cw as well as Q-switched Er:YAG lasers pumped both by fiber-coupled broadband pump diodes provided by LIMO as well as by wavelength-stabilized diode laser modules provided by DirectPhotonics. The latter feature narrowband emission at 1532 nm with linewidth of only 0.18 nm, whereas the broadband diodes emit at 1455 nm with linewidth of about 5-6 nm. While only 1 W cw output power is obtained using the broadband diodes, 2.5 W is achieved at the same pump power employing the wavelength-stabilized modules. This corresponds to a slope efficiency of 68% and an optical efficiency of more than 25%. Utilization of a Pockels cell enables pulsed operation at a repetition rate of 125 Hz with pulse energy of about 6.6 mJ and pulse duration of 60 ns. Moreover, implementation of an etalon provides frequency-stable and narrowband output of the Er:YAG laser. Finally, we demonstrate the first dual-wavelength pumped Er:YAG lasers realized by both single- and dual-side pumped configurations, resulting in further enhancement of the optical efficiency.

8959-8, Session 3

High-brightness monolithic diode-pumped Er:YAG laser system at 2.94 µm with 400W peak power

Maximilian Harlander, Arne Heinrich, Clemens Hagen, Bernhard Nussbaumer, Pantec Engineering AG (Liechtenstein)

Diode pumped Er:YAG laser systems are highly interesting for the steadily growing field of medical laser applications due to their stability and ruggedness. The emitted 2.94 µm light coincides with a major water absorption line enabling soft and hard tissue cutting. The required pulse energies and powers for cutting hard tissue have long been a challenge for diode pumped laser systems. We present a newly developed 30 W diode pumped laser module with pulse energies up to 150 mJ. The laser is operated in quasi continuous wave (qcw) mode with repetition rates usually ranging from 100 to 1000 Hz and pulse durations up to 250 µs.

To achieve these high powers the pump power dependent thermal lensing of Er:YAG has to be well understood to allow the optical laser cavity to be kept stable. Modelling the thermal lens with FEM algorithms beyond the standard ABCD matrix formalisms allowed a simulation of the lasers behaviour under high power operation. With this model the pump energies, and thus the thermal load on the Er:YAG crystal, can be calculated to predict the point at which the strength of the thermal lens is big enough to stabilize different cavity designs and the laser starts to emit. These predictions have been verified by measuring these threshold energies for two different cavity designs for different operational parameters. With these findings the laser cavities can be designed to meet different specifications to attribute a higher importance to power or beam quality.

8959-9, Session 3

Diode-pumped and passively Q-switched Er:YAG laser emitting at 1617 nm

Adrien Aubourg, Lab. Charles Fabry (France); Julien Didierjean, Nicolas Aubry, FiberCryst (France); François Balembois, Patrick Georges, Lab. Charles Fabry (France)

Er:YAG solid-state lasers are good candidates for applications requiring kilometer range propagation in the atmosphere, because it emits in the eye safe and free of water absorption wavelength region (1617 nm or 1645 nm). The long storage lifetime of erbium allows to produce energetic pulses in Q-switched operation.

Such cavities can be fiber-laser pumped or resonantly diode-pumped. The latter has an interesting potential for compact and low power consumption rangefinders, but provides highly divergent beams. We use Er:YAG single crystal fiber of 450 µm and 750 µm of diameter to confine the pump beam via total internal reflections, hence improving density of population inversion, higher gain and better output performances.

Numerical raytracings are done to evaluate the pump power inside the crystals. Simulation and measurement of gains inside both crystals diameters are compared. Passive Q-switched operation with a Cr:ZnSe saturable absorber points better population inversion densities with a 450 µm diameter crystal.

Indeed, with this diameter, emission at 1617 nm occurs whatever the initial transmission of the saturable absorber, and better performances in term of mean power are observed.

With a 750 µm diameter crystal, 150 µJ, 40 ns, 1617 nm pulses are measured at 400 Hz (Tinit = 80%)

With a 450 µm diameter crystal, 44 µJ, 56 ns, 1617 nm pulses are measured at 3 kHz. (Tinit = 85%)

8959-10, Session 3

Ho:YAG laser resonantly-pumped by a 1126-nm Yb-fiber laser

Igor V. Melnikov, National Research Univ. of Electronic Technology (Russian Federation); Alexei Lagutchev, Purdue Univ. (United States); Evgeny G. Gerasimov, VOSPI Ctr. (Russian Federation); Andrey A. Machnev, Pavel B. Novozhylov, National Research Univ. of Electronic Technology (Russian Federation)

Fiber-laser pumped Ho-lasers that operate around 2000 nm have proven to be a robust and reliable tool for effective medical and material-processing applications. Although capabilities of those lasers for the mid-IR generation have also been demonstrated, the demand for a highly precise and compact remote-spectroscopy tool prompts towards their further miniaturization along with narrow line while gaining high pulse energy repetition rate, and, what is more, high efficiency.

In this Report, we describe a small footprint (75x75 mm) room-temperature Ho-laser that is resonantly pumped by an Yb-fiber laser. The cw and pulsed operation of this laser are studied when the wavelength of the Yb-fiber laser that, in turn, is made of the 20-m piece of a GTWave fiber, is red-shifted to 1126 nm. The cw laser demonstrates 10.7 W of average output power while end-pumped by the 35-W 1126-nm fiber laser.Making use of an AO switch yields the average power at approximately the same level but with 40-ns pulsewidth and 80 kHz repetition rate.

8959-11, Session 3

Ultra-high-gain 2-µm amplifiers: single-frequency or broadband

Alex Y. Dergachev, Q-Peak Inc. (United States)

There is a rapidly increasing interest in the development of fieldable laser sources and laser-based instruments operating in 2-um spectral range for a variety of applications.

One of the most versatile schemes in the laser system development is the master oscillator-power amplifier architecture which allows to utilize a variety of seed sources: diode lasers, bulk or fiber oscillators. Such low-power seed sources are much easier to set to operate in the desired pulsewidth/ repetition rate/ bandwidth parameter space shifting the primary effort to the development of compact, reliable, high-gain amplifier schemes.

Typically fiber amplifiers are considered as the preferred option when gain of more than 20 dB is required. However, despite the ability to generate high average power (>>100 W), fiber amplifiers are prone to fundamental limitations on peak energy/power density due to deleterious non-linear effects as well as optical damage.

Bulk Ho-laser technology provides a unique combination of features such as high gain, broad bandwidth, immunity to non-linear effects and optical damage (almost).

To amplify low-power, CW or ns-pulsewidth, seed oscillator we developed a compact, single-stage, high-gain, 2-µm Ho:YLF amplifier which can operate with the gain of up to 45 dB with the seed power input as low as 0.1 mW. Same amplifier design was applied to amplify directly-modulated, CW seed sources allowing generation of mJ-level pulses.

The second example is the demonstration of Ho:YLF regenerative amplifier schemes which allows to amplify a mode-locked seed source to a mJ-level pulse energy with the gain of ~60 dB.

8959-12, Session 3

Mid-infrared diamond Raman laser with tuneable output

Alexander Sabella, Defence Science and Technology Organisation (Australia) and Macquarie Univ. (Australia); James Piper, Richard P. Mildren, Macquarie Univ. (Australia)

Compact solid state lasers in the mid-infrared and beyond are the subject of intense interest for many sensing and defence applications. Raman conversion provides a method for mid-infrared generation using relatively mature pump laser technologies operating closer to the near-infrared. To date, investigations into Raman generation of wavelengths longer than 2?m have been limited to only a few materials such as silicon and barium tungstate [1,2]. Recently, diamond has proven to be an excellent UV to near-infrared Raman laser material with potential for generating infrared output across a broad spectrum outside its multiphonon absorption band (4-6?m) [3]. Here we report a diamond Raman laser with tuneable operation from 3.50 to 3.78?m, which to the authors' knowledge is the longest wavelength obtained from a crystalline Raman laser.

An 8mm uncoated diamond crystal was placed within an external cavity and was pumped by a tuneable KTP OPO. Up to 70?J Stokes output was obtained with a slope efficiency of 10%. Multiphonon absorption at the Stokes wavelength was the main factor limiting performance. The effect of seeding on the Raman threshold was also investigated by exploiting the useful coincidence that for a Stokes output of 3.705?m the frequency difference between the OPO signal (2.480?m) and idler (1.864?m) was equal to the Raman frequency of diamond and thus resulted in resonantly enhanced four-wave-mixing. This reduced the threshold by a factor of two to 100?J.

The experimental results combined with numerical modelling offer guidelines for optimising laser performance in the mid-infrared and for designing diamond Raman lasers operating beyond 6?m.

[1] Jalali, B., et al., (2006), Prospects for Mid IR silicon Raman lasers, IEEE J. Sel. Top. Quant. 12, (6)

[2] Basiev, T., et al., (2006), Stimulated Raman scattering in mid IR spectral range 2.31–2.75–3.7?m in BaWO4 crystal under 1.9 and 1.56?m pumping, Laser Phys. Lett. 3, (1)

[3] Mildren, R., et al., (2013), Diamond Raman Laser Design and Performance, In: Mildren, R., Rabeau, J. Ed. Optical Engineering of Diamond, Wiley, pp. 239-276

8959-13, Session 4

Comparison of Er:YAG and Er:Y2O3 for lasing at near-3-micron wavelength

John Vetrovec, Drew A. Copeland, Amardeep S. Litt, Aqwest, LLC (United States)

We present comparisons of predicted performance and designs for near-3-micron Er:YAG and Er:Y2O3 lasers. The lasers use edge-pumped disk architecture [1, 2] with composite poly-crystalline (ceramic) laser disks. Concepts for laser oscillators and amplifiers operating in a quantum-defect-limited regime at a high-average power of several hundred watts and producing near-diffraction-limited beam quality are discussed. Challenges of thermal management of the laser disks in these high-heat fraction systems are addressed. This work also discusses approaches for mitigating amplified spontaneous emission by selective doping of the laser disk. Applications for these 3-µm lasers range from remote optical sensing to directed infrared countermeasures to remote laser generation of acoustics in water.

1. J. Vetrovec et al., "Progress in the development of solid-state disk laser," SPIE vol. 5332 pp. 235-243 (2004)

2. J. Vetrovec et al., "Initial Testing of Edge-Pumped Yb:YAG Disk Laser with Multi-Passed Extraction," SPIE vol. 8235 (2012)

8959-14, Session 4

Polycrystaline Cr:ZnSe laser pumped by efficient Tm:YLF laser

Lukasz F. Gorajek, Jan K. Jabczynski, Military Univ. of Technology (Poland)

We have demonstrated efficient generation of diode pumped Tm:YLF laser end-pumped by 25-W a fiber coupled laser diode bar. The incident pump density exceeded above 5 times the saturation pump density, thus the drawbacks of quasi-three-level scheme have been mitigated. We have obtained the best output characteristics (slope and maximum power) for out-coupling losses of 30% evidencing the high roundtrip gain for maximum pump power. Above 5 W of output power was demonstrated for 25-W pumping laser for elongated 120-mm cavity. For the free-running and Q-switching regimes the output spectrum was centered at 1908-nm with linewidth less than 15 nm. In the experiments on active Q-switching up to 5.5 mJ output energy was demonstrated limited by damage of laser elements. Near 0.5 MW peak power with the pulse durations of 11 ns was achieved for 20-Hz repetition rate with 10% duty cycle of pumping regime. The divergence angle was about 3.5 mrad and estimated parameter M2 < 1.15

We have demonstrated mid-infrared generation at 2488 nm with linewidth about 60 nm in free-running regime in polycrystalline Cr:ZnSe active medium. Output energy was 3 mJ from 80 mJ incident pump power. However, the slope efficiency was relatively low (4%) indicating need of further optimization of laser oscillator. High peak power of Tm:YLF laser can be decreased below damage threshold of Cr:ZnSe crystal by elongating pulse duration by means of increasing of modulation frequency or altering focusing optics.

8959-15, Session 4

Spectroscopy and mid-IR lasing of Cr2+ ions in ZnSe/ZnS crystals under visible excitation

Jeremy M. Peppers, Tetyana Konak, Dmitry V. Martyshkin, Vladimir V. Fedorov, Sergey B. Mirov, The Univ. of Alabama at Birmingham (United States)

Recent efforts have demonstrated efficient Cr2+:II-VI chalcogenide (e.g. ZnSe, ZnS) broadly tunable (1.9-3.3?m) lasers under direct intra-shell Cr2+ optical excitation. We report on the spectroscopic study of Cr2+:ZnSe/ZnS under visible excitation into the charge transfer band of Cr2+ ions. Polycrystalline samples prepared by thermal diffusion method were studied. Middle-infrared (mid-IR) photo-luminescence (PL) of Cr2+ ions was compared under direct 1532nm (5T2?5E) excitation and under 532nm excitation into charge transfer band. The quantum yield of Cr:ZnSe mid-IR luminescence under green excitation was estimated as close to 100% at room temperature. To estimate Cr excitation rate via charge transfer band, mid-IR PL kinetic measurements were performed with the use of 532nm picosecond pumping. Mid-IR PL kinetics of Cr:ZnSe under green excitation exhibit a relatively slow growth reaching a peak at ~5-8?s. PL kinetics in Cr:ZnS reveal shorter measured rise time (<1?s) limited by the response time of the detector. This rise of the PL intensity for 532nm excitation implies that 5E population continues to grow after the excitation pulse due to slow relaxation processes from higher-lying excited levels of Cr2+ to the upper laser level 5E. At the same time the excited level is pumped at a rate faster than it is depleted and, hence, it is reasonable to expect that the population of the 5E level could be inverted. For laser experiments we used 5ns radiation from BBO based optical parametric oscillator tunable over 450-700nm. Cr:ZnSe lasing at 2.5?m induced by 2+?1+?2+ ionization transitions of chromium under visible excitation was achieved.

8959-16, Session 4

Single-frequency operation of a resonantly pumped 1.645um Er:YAG Q-switched laser

Ran Wang, Qing Ye, Chunqing Gao, Beijing Institute of Technology (China); Yan Zheng, Mingwei GAO, School of Opto-Electronics, Beijing Institute of Technology (China)

Resonantly pumped Er:YAG lasers operating at 1.645 um have important applications in measuring the methane (CH4) which is one important greenhouse gas influencing the climate change. In this paper a resonantly pumped 1.645 um injection-seeded single frequency Er:YAG Q-switched laser is reported. The pump source was a 1.532 um Er-Yb fiber laser with a maximum output power of 20W. Firstly we studied the single frequency continuous-wave (CW) operation in resonantly pumped Er:YAG lasers.

Different techniques were investigated to get 1.645 um single frequency laser output. The maximum single frequency laser output was obtained from a monolithic Er:YAG non-planar ring oscillator (NPRO) developed by ourselves. Up to 10 W single frequency 1.645 um single frequency laser was obtained from the resonantly pumped Er:YAG NPRO, with a slope efficiency of 60% and a linewidth of 18.6 kHz, respectively. Then the pump beam was divided into two parts, one is for pumping the CW master laser and the other is for pumping the slave laser. The slave laser was a resonantly pumped AO Q-switched Er:YAG laser with a U-shaped resonator. By using a 0.25 at.% Er:YAG crystal we obtained 5.4 mJ Q-switched pulse at a pulse repetition rate of 1kHz. The single frequency master laser was injection-seeded into the Q-switched slave laser by using the Ramp-Hold-Fire technique. Finally we obtained 1.645 um single frequency Q-switched laser output with a pulse repetition rate of 200Hz, pulse width of 336ns and pulse energy of 4.75mJ, respectively.

8959-17, Session 5

Feasibility and performance study for a space-borne 1645 nm OPO for French-German satellite mission MERLIN

Marie J. Livrozet, Florian Elsen, Jochen Wüppen, Jens Löhring, Fraunhofer-Institut für Lasertechnik (Germany); Christian Büdenbender, Andreas Fix, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); Bernd Jungbluth, Hans-Dieter Hoffmann, Fraunhofer-Institut für Lasertechnik (Germany)

We present theoretical and experimental analyses of a pulsed 1645 nm OPO conducted to prove the feasibility of such a device for a space borne laser transmitter for IPDA LIDAR. The investigation is part of the French-German satellite mission MERLIN (Methane Remote Sensing Lidar Mission). As an effective greenhouse gas methane plays an important role for the global climate.

The architecture of the OPO is based on an optical concept from DLR IPA in Oberpfaffenhofen, consisting of two KTA crystals in a four-mirror-cavity. One of the cavity mirrors is piezo-driven to provide single frequency operation of the OPO. By means of numerical simulations we studied the performance and alignment tolerances of such a setup with KTP and KTA and investigated means to optimize the optical design in terms of higher efficiency and lower fluence on the optical components. For the experimental testing of the OPO we used the INNOSlab based ESA pre-development model ATLAS as pump laser at 1064 nm. At a pulse frequency of 25 Hz this MOPA delivers a pump energy up to 45 mJ with a beam quality factor of about M2 = 1.3. With KTP as nonlinear crystal the OPO obtained 9.2 mJ pulse energy at 1645 nm from 31.5 mJ of the pump and a pump pulse duration of 42 ns. This corresponds to a quantum conversion efficiency of 45%. After shortening the pump pulse down to 24 ns a similar OPO performance could be obtained by adapting the pump beam radius.

8959-18, Session 5

In-space performance of the Mercury Laser Altimeter (MLA) laser transmitter

Anthony W. Yu, Xiaoli Sun, Steven X. Li, NASA Goddard Space Flight Ctr. (United States)

The Mercury Laser Altimeter (MLA) instrument was launched on board of the MESSENGER spacecraft on August 3, 2003. MLA maps the Mercury's topographic landforms and other surface characteristics using a diode pumped solid state laser transmitter and a photon-counting receiver that measures the round-trip time of individual laser pulses. The data will also be used to track the planet's slight, forced libration – a wobble about its spin axis – which will tell researchers about the state of Mercury's core. The laser was first turned on in January 2008 and has been operating nominally in a regular basis since insertion into the Mercury orbit in 2011, MLA has gathered volumes of exciting science data. In this paper, we will review the laser transmitter performance and evaluate the extended operation of solid state lasers for space applications.

8959-19, Session 5

Self-Raman Nd:YVO4 laser and electro-optic technology for space-based sodium lidar instrument

Michael A. Krainak, Anthony W. Yu, Diego Janches, Sarah L. Jones, Branimir Blagojevic, NASA Goddard Space Flight Ctr. (United States); Jeffrey R Chen, NASA Goddard Space Flight Ctr (United States)

We are developing a laser and electro-optic technology to remotely measure Sodium (Na) by adapting existing lidar technology with space flight heritage. The developed instrumentation will serve as the core for the planning of an Heliophysics mission targeted to study the composition and dynamics of Earth's mesosphere based on a spaceborne lidar that will measure the mesospheric Na layer.

We present performance results from our diode-pumped tunable Q-switched self-Raman c-cut Nd:VO4 laser with intra-cavity frequency doubling that produces multi-watt 589 nm wavelength output. The c-cut Nd:VO4 laser has a fundamental wavelength that is tunable from 1063-1067 nm. A CW External Cavity diode laser is used as a injection seeder to provide single-frequency grating tunable output around 1066 nm. The injection-seeded self-Raman shifted Nd:VO4 laser is tuned across the sodium vapor D2 line at 589 nm.

We will review technologies that provide strong leverage for the sodium lidar laser system with strong heritage from the Ice Cloud and Land Elevation Satellite-2 (ICESat-2) Advanced Topographic Laser Altimeter System (ATLAS). These include a space-qualified frequency-doubled 9W @ 532 nm wavelength Nd:VO4 laser, a tandem interference filter temperature-stabilized fused-silica-etalon receiver and high-bandwidth photon-counting detectors.

8959-20, Session 5

INNOSLAB-based single-frequency MOPA for airborne lidar detection of CO2 and methane

Jens Löhring, Jörg Luttmann, Raphael Kasemann, Michael Schlösser, Jürgen Klein, Hans-Dieter Hoffmann, Fraunhofer-Institut für Lasertechnik (Germany); Axel Amediek, Christian Büdenbender, Andreas Fix, Martin Wirth, Mathieu Quatrevalet, Gerhard Ehret, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany)

We present the design and performance of two independent pulsed single frequency Nd:YAG based MOPA (master oscillator power amplifier) systems which were specifically developed as pump laser sources for the DLR's (Deutsche Zentrum für Luft- und Raumfahrt) CHARM-F (CO2 and CH4 Atmospheric Remote Monitoring – Flugzeug) system. CHARM-F is an airborne IPDA lidar for simultaneous and independent measurement of the column weighted-average dry-air mixing ratios of atmospheric carbon dioxide and methane, designed to be flown on board the German research aircraft HALO. Single frequency nanosecond pulses with pulse energies of about 10 mJ and 30 mJ are required at 1645 nm and 1572 nm wavelength for the measurement of CH4 and CO2, respectively. These application wavelengths are generated in optical parametrical oscillators (OPO) and amplifiers (OPA) out of the pump beam. Pulse pairs at a repetition rate of 50 Hz and a temporal separation of a few hundred µs are required.

Both pump laser sources comprise a stable linear Q-switched resonator which is injection seeded and actively stabilized with the Ramp&Fire-method. Both oscillators generate 8 mJ pulse energy at about 30 ns pulse duration. In both systems the beam is amplified in one INNOSLAB-based amplifier stage to about 85 mJ. The pulse energy of the CO2 system is additionally boosted to 150 mJ in a second amplifier stage. A compact double-sided optical assembly on a monolithic structured baseplate was developed as well as a rugged supply rack including controllers, diode drivers and a chiller according the appropriate requirements of flight hardware.

8959-21, Session 6

Narrow linewidth 257 nm nanosecond laser source based on hybrid MOPA

Xavier Délen, Loic Deyra, Lab. Charles Fabry (France); Aurelien Benoit, EOLITE Systems (France); Marc Hanna, François Balembois, Lab. Charles Fabry (France); Benjamin Cocquelin, Damien Sangla, François Salin, EOLITE Systems (France); Julien Didierjean, FiberCryst (France); Patrick Georges, Lab. Charles Fabry (France)

High average power UV laser sources with narrow linewidth are increasingly needed for applications like spectroscopy and remote sensing. In this work, we present such a laser based on hybrid MOPA architecture. A distributed feedback laser diode is amplified in an Yb-doped fiber preamplifier and modulated by an acousto-optic modulator (AOM) to deliver 15-150 ns pulses at 330 Hz. This signal is amplified in two stages of single mode Yb-doped fiber before going through a second AOM which further decreases the repetition rate and limits the amount of ASE. The beam is then further amplified in a large mode area (LMA) fiber. This amplifier stage is able to deliver 7 kW peak power for 15 ns pulses (35 MHz linewidth), limited by Stimulated Brillouin Scatering (SBS). To increase further the output power, a double pass Yb:YAG SCF amplifier is used. A maximum average power of 22.5 W is reached with 15 ns at 30 kHz. It gives a peak power over 50 kW which is 7 times higher than at SBS threshold for the LMA fiber. The beam quality at the output of the SCF is diffraction-limited, with M?<1.1. Frequency conversion to 257 nm is performed using two successive second-harmonic generation (SHG) stages. Up to 3.2 W is achieved at 257 nm with linewidth of 40 MHz and pulse duration of 15 ns. This result is an unprecedented value to our knowledge for a single frequency laser at 257 nm without using nonlinear conversion in resonant cavities.

8959-22, Session 6

High-power UV from a thin-disk laser system

Sven M. Joosten, Ronald Busch, Stefan Marzenell, TRUMPF Laser Marking Systems AG (Switzerland); Dirk H. Sutter, TRUMPF Laser GmbH & Co. KG (Germany); Carsten Ziolek, TRUMPF Laser Marking Systems AG (Switzerland)

The demand for laser systems for marking and micromachining using high power UV has created a significant growth of lasers in manufacturing. To further support this growth advanced and cost-efficient technologies are required. By using a laser system based on thin disk technology with cavity dumping very short pulses below 10ns are possible. In addition the pulse width is independent from the chosen pulse repetition rate. This is in contrast to conventional q-switched lasers. The combination of high average power and short pulses leads to high peak powers, e.g. more than 20kW at 100kHz. These are available even at high repetition rates up to 250kHz and enable high quality and high speed marking and micromachining. Using the field proven disk technology allows easy scaling to even higher power using innovative techniques. In this presentation we will present high contrast and high throughput marking applications as well as high precision and high throughput micromachining applications. The emphasis will be on the optimized marking and micromachining parameters as scan speed, laser peak power, repetition rate to minimize unwanted effects like overheating and maximize quality and throughput. The overall throughput can be further optimized using multiple beam lines with separate scan heads as well as advanced controlling software to distribute the marking content.

8959-23, Session 6

>220W output power at 355nm from a Q-switched diode-pumped solid-state laser

Young Key Kwon, Nerijus Slavinskis, Nick Hay, Aleksej M. Rodin, Powerlase Photonics Ltd. (United Kingdom)

Over 220W of average power has been achieved at UV wavelength of 355nm from a diode-pumped acousto-optically Q-switched Nd:YAG laser using intracavity second harmonic generation and sum frequency mixing in a nested sub-cavity design. In accordance with optimization conducted by numerical modeling, the experimental data proves significant enhancement of intracavity nonlinear conversion efficiency. The laser layout developed comprises two identical cavities delivering output pulses of 65ns duration and 11mJ energy at repetition rate 10kHz. A single output beam with smooth Gaussian transverse intensity distribution and over 22mJ of total pulse energy is formed by polarization multiplexing these two cavities. Synchronization of the emitted pulses with variable overlap permits flexible tuning within a wide range of temporal envelope and effective pulse duration. Pump diodes with long operational lifetime incorporated into side-pumped Nd:YAG gain modules together with other field-replaceable modules ensure considerable cost of ownership reduction and uptime improvement for a range of industrial material processing applications such as flat panel patterning, solar cell processing, semiconductor annealing and laser lift off. Moreover, the architecture of the diode-pumped solid-state UV-laser is readily scalable to higher output powers by utilizing geometric multiplexing. As result, the total achievable output power from solid-state lasers with high up-time and UV wavelength enables the cost effective replacement of high average power excimer lasers in industrial applications.

8959-24, Session 6

180W at 1kHz, 532nm SHG from LBO crystals using high average power Nd:YAG laser

Yoshinori Tamaoki, Yoshinori Kato, Koichi Iyama, Toshiyuki Kawashima, Hamamatsu Photonics K.K. (Japan); Noriaki Miyanaga, Osaka Univ. (Japan)

We have developed high average power MOPA laser system with SHG unit on the table top size (3 x 1.5m). This MOPA laser system is consisted of Q-switch oscillator, pre-amplifier, main-amplifier and SHG unit. At the wavelength 1064nm has been obtained the max average output power of 715W. And for some reason from a specification of laser processing, the SHG output beam is required to be in random polarization. However we have separated this beam to the longitudinal wave and the transversal wave. Because the each polarized beams have been focused on the SHG crystal type-1 LBO. The average power at the wavelength of 532nm has been obtained 89W and 91W at the each polarized beams. And then the each polarized beams have been combined at the wavelength of 532nm. Therefore we have achieved the random polarization beam at the wavelength of 532nm.We have achieved the average power 180W at the wavelength 532nm, the pulse width of about 100ns, the frequency of 1kHz. And the power efficiency of the SHG from the wavelength of 1064nm to 532nm was obtained about 25.6%.

8959-25, Session 6

Multi-kW IR and green nanosecond thin-disk lasers

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Thin-disk lasers with multi-kW output power in continuous-wave operation are widely used for industrial materials processing due to their excellent beam quality, high efficiency, and high reliability with low investment and operation costs.

We present our latest laboratory results for thin-disk lasers in continuous-wave operation with high output power and high brightness. Additionally, we highlight the development of nanosecond thin-disk lasers with multi-kW average output power. We show that in pulsed laser systems almost the same average power and beam quality as in cw systems can be realized. Utilizing the cavity-dumping principle for pulse generation we demonstrated multi-kW average output power with pulse energies exceeding 150 mJ. The laser generates pulses with a pulse duration of 20 ns which is almost independent of the power level and the repetition rate. The beam parameter product was measured to be better than 4.5 mmmrad (M? < 15).

Deploying intracavity frequency conversion the efficient generation of cw and pulsed laser output in the green spectral range is investigated. Results for a q-switched thin-disk laser with an average power exceeding 1 kW and a pulse duration between 100 ns and 300 ns are presented.

8959-26, Session 6

High-energy picosecond light source based on cryogenically conduction cooled Yb-doped laser amplifier

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Within HiLASE project, we are developing a laser system based on Yb-doped materials, which is going to deliver the output energy of 1J with the repetition rate of 120Hz and the pulse duration of 1-2ps. The laser system consists of a seed mode-locked fiber laser and two amplifier stages, namely, an Yb:YAG thin disk regenerative amplifier as a main amplifier and a cryogenically cooled single slab as a booster amplifier. We have obtained the output energy of 45mJ from the regenerative amplifier at the repetition rate of 1kHz. In case of the booster amplifier, we decided to adopt a conduction cooling method by using a closed-loop cryostat to build a compact and cost-effective system. We have evaluated the temperature dependence of gain bandwidth of the Yb:YAG crystal . The 3 at.% Yb:YAG crystal with the thickness of 3mm was mounted on the cryostat and pumped by a fiber-coupled laser diode. A supperluminescent diode was employed as broadband probe source. We found that the gain bandwidth was approximately 1.2nm at 120K which is still enough to obtain the 1-2ps pulses. Also, we have modeled a temperature distribution of Yb:YAG slab mounted on a cryogenic crystal holder cooling down to 100K. By adding a sapphire substrate between the crystal and the heatsink as a transparent heat spreader, we found that the temperature of pumped area can be reduced from 400K to 192K. However, a large temperature gradient in the crystal still existed. Improvement of crystal holder and experimental results will be presented.

8959-27, Session 7

400W Nd:YAG composite ceramic thin-disc laser in 10ns pulse at 167kHz

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We are developing a high-repetition and high-average-power Nd:YAG laser amplifier pumped by fiber coupled LDs in order to apply to laser machining of a carbon composite material (CFRP: Carbon Fiber Reinforced Plastic). The prototype amplifier of kW-class amplifier for CFRP processing was produced. Gain media are 6 thin discs on a non-doped ceramic YAG block. Each thin disc is 22mm x 30mm x 0.5mm thick. Nd concentration is 1at%. The amplifier is pumped by 4 fiber coupled LDs. Each LD can deliver 1kW at 808nm. Input laser is injected and ejected after amplification by dichroic mirrors. Moreover, measurement of wave-front distortion and a small-signal-gain was performed. As a result of measuring wave-front distortion, the component of wave-front distortion of the amplifier became clear, and we considered the wave-front compensation method about each component. Main component is defocus. Peak-to-Valley value is 19? at 1kW pumping. It can be compensated by lens system. Higher order components are ?2? at 1kW pumping. It can be compensated by deformable mirror. From the measurement result of the small-signal-gain, we had known that gain loss was by the temperature difference on Nd:YAG and seed laser of a broad spectrum causes. As a result of amplification test of seed laser of a narrow spectrum by 1kW LD pumping, small-signal-gain was 3.1. Next, we performed amplification test. As a result, we obtained the output of 404W at 2.8kW pump power and input of 164W.

8959-28, Session 7

Development of high-purity single-crystal diamond for optical components in thin-disk systems

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Microwave assisted chemical vapour deposited bulk diamond products have been used in a range of high power laser systems due to low absorption across a range of wavelengths and exceptional thermal properties. However the applications of polycrystalline products has frequently been limited to applications at longer wavelengths or thermal uses outside of the optical path due to the birefringence and scatter that are intrinsic properties of the polycrystalline material.

Several grades of single crystal diamond have been developed that overcome many of the limitations of the polycrystalline material, with low absorption and low birefringence grades for demanding optical applications. We will present new data characterising performance across infra-red and visible wavelengths with absorption coefficient measured by laser calorimetry at a range of wavelengths from 1064 nm to 452 nm. We will also discuss the results on ultra-low absorption development materials with absorption approaching those expected for intrinsic diamond. An additional challenge for optical applications is strain induced birefringence caused by extended defects propagating from defects in seed crystals. We will show results for recently developed low birefringence material, and discuss development work to produce ultra-low birefringence grades with birefringence below 10-6.

Finally we will discuss processing and polishing techniques for diamond that will facilitate its use in optics. Due to its exceptional hardness it is challenging to achieve good surfaces on diamond parts. We will show data on processing that can now achieve atomically smooth surfaces and are achieving improving flatness on parts, with high degrees of parallelism.

8959-29, Session 7

50-mJ, 1-kHz Yb:YAG thin-disk regenerative amplifier with 969-nm pulsed pumping

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Thin-disk lasers can serve as a powerful tool for many industrial and scientific applications, such as EUV plasma source for lithography. We are developing a 100-mJ Yb:YAG thin-disk regenerative amplifier operating at 1-kHz repetition rate pumped at 969-nm in pulsed regime and delivering 1-2ps pulses. Recently we achieved nearly 50-mJ of output energy with good beam quality (M2<1.2) and stable beam-pointing (<4μrad).

Achieving high-energy output at high-repetition rate requires a careful design to prevent any optically induced damage. For this reason, we adopted a large mode size on the thin-disk, which is pumped by a high-intensity laser diodes providing sufficient gain since Yb:YAG is a quasi-three state laser. Nevertheless, combination of high-intensity pumping at large mode diameter causes large thermal load of the thin-disk and may result in the thin-disk deformations leading to increased optical phase distortion and mode-matching issues as well as increased ASE (amplified spontaneous emission) causing degeneration of amplification. Special care needs to be taken into account when designing a laser cavity to make it resistant to changes of the thin-disk radius of curvature.

In order to compensate these detrimental factors, we applied pulsed pumping with wavelength-stabilized laser diodes at zero-phonon-line (969-nm) resulting in suppression of thermal loading of the thin-disk. Moreover, the pump pulse width shorter than the life time of Yb:YAG can reduce the ASE. Details of experimental results regarding the 50-mJ output and the results of a dual-head thin-disk regenerative amplifier aiming at the target energy of 100-mJ will be presented.

8959-30, Session 7

Green sub-ps laser exceeding 400 W of average power

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We present the world's first laser at 515 nm with sub-picosecond pulses and an average power exceeding 400 W. To realize this beam source we utilize an Yb:YAG-based infrared laser consisting of a fiber MOPA system as a seed source, a rod-type pre-amplifier and two Innoslab power amplifier stages. The infrared system delivers up to 930 W of average power at repetition rates between 10 and 50 MHz and with pulse durations below 800 fs. The beam quality in the infrared is M? = 1.1 and 1.5 in fast and slow axis. As a frequency doubler we chose a Type-I critically phase-matched LBO crystal in a single-pass configuration. To preserve the infrared beam quality and pulse duration, the conversion was carefully modeled using numerical calculations. These take dispersion-related and thermal effects into account, thus enabling us to provide precise predictions of the properties of the frequency-doubled beam.

To be able to model the influence of thermal dephasing correctly and to choose appropriate crystals accordingly, we performed extensive absorption measurements of all crystals used for conversion experiments. These measurements provide the input data for the thermal FEM analysis and calculation. We used a Photothermal Commonpath Interferometer (PCI) to obtain space-resolved absorption data in the bulk and at the surfaces of the LBO crystals. The absorption was measured at 1030 nm as well as at 515 nm in order to take into account the different absorption behavior at both occurring wavelengths.

8959-31, Session 7

Near fundamental mode high-power thin-disk laser *(Invited Paper)*

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We report on our latest results of near fundamental mode operation of Yb-doped thin-disk lasers. 4 kW of continuous wave output power at M?<1.4 has been achieved by using one disk only. To the best of our knowledge this is the highest cw output power ever extracted from a single disk resonator design aiming for fundamental mode beam quality. Furthermore, a promising optical-to-optical efficiency of up to 56% at peak power has been achieved by pumping at 969 nm. Besides zero phonon line pumping, standard resonator components of our TruDisk thin-disk laser product series have been used such as the laser disk, and the pump optics which allows for 44 passes of the pump light through the laser crystal. It should be noticed that neither aberration correction methods nor a vacuum resonator design have been necessary to achieve this result.

8959-32, Session 8

200W output power at 10ps from a scalable Z-slab Nd:YAG laser

Young Key Kwon, Simon P. Chard, Nick Hay, Aleksej M. Rodin, Powerlase Photonics Ltd. (United Kingdom)

We present the results of numerical and experimental optimization of modular multiple pass zig-zag slab amplifier incorporated into the picosecond laser producing more than 200W of average output power. The new Z-slab™ architecture has been developed by Powerlase representing the zig-zag bounce edge pumped slab Nd:YAG amplifier. The Z-slab™ is employed for efficient amplification of sub-10ps pulses from passively mode-locked seed laser of 5W average power at a wavelength of 1064nm with variable repetition rate from 10kHz to 1MHz. We attained the maximum average output power while minimising pulse width broadening and maintaining the high beam quality of the injected picosecond laser beam. Thermal distortions in Z-slab™ have been suppressed significantly by using efficient pumping from 885nm CW diode pump modules with fast axis collimation optics and a face cooling geometry. The amplified laser beam propagated through the thin conductively cooled Nd:YAG slab in a zig-zag bounce path between the cooled faces, and an average power over 200W has been achieved experimentally at the output of the modular multi-stage Z-slab amplifiers with a high beam quality M2<1.5. The high pulse energy and high average power with programmable burst mode of operation can provide significant improvement for the high throughput and cost effective materials processing.

8959-34, Session 8

High-average power diode-pumped Nd:glass laser amplifiers

Jay Doster, Faming Xu, Ryan Feeler, Northrop Grumman Cutting Edge Optronics (United States)

Side pumped rod geometry laser amplifiers using Nd doped glass materials have had limited average power performance due to thermal loading from flash lamp pumping. Utilizing diode laser pump sources, the thermal load can be reduced 2-3 times, thus allowing an increase in average power output. The demand for high average power, petawatt laser systems requires higher repetition rate front end systems with Nd doped phosphate and silicate glasses. Using the commercial of the shelf version of the REA laser amplifiers, a glass based REA laser amplifier is discussed. Characterization of small signal gain, stored energy, gain uniformity, and birefringence effects are presented. The laser amplifier is operated in a resonator and high average power results are presented.

8959-35, Session 8

Front-end for ELI-Beamlines' 100J cryogenically-cooled Yb:YAG multi-slab amplifier with temporal pulse shaping capability

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We present the front-end for the ELI-Beamlines L2 cryogenically cooled Yb:YAG multi-slab 100 J amplifier. The output of the front end has strict requirements on pulse spatial profile (square flattop), pulse energy (> 80 mJ, 10 Hz), and control over the shape and duration of the temporal profile. The front-end consists of three parts: a fiber-based seed pulse generator, an Yb:YAG regenerative amplifier, and an Yb:YAG multipass amplifier with spatial pulse shaping. The seed pulse generator is a compact fiber-based solution consisting of a CW oscillator, fiber amplifier, and a fiber Mach-Zender amplitude modulator to "cut out" the pulse train. The baseline is actively stabilized to maintain a pulse contrast level of 40 dB. Pulse contrast is enhanced further with ultra-fast Pockels cells and acousto-optic modulators. The 100 J amplifier is intended to pump OPCPA, so the amplifier output must be flat in time and have a 2 ns duration. To achieve this despite significant gain saturation in the power amplifier, we pre-shape pulses with 200ps resolution. To prevent hotspots on the gain medium and optics in the high power amplifier, the pulse has a high quality wavefront and is shaped into a square via a serrated aperture. The various stages of amplification and methods for baseline stabilization and temporal waveform control are discussed in detail. General performance of the front-end is also discussed.

8959-36, Session 8

High-pulse-energy mode-locked picosecond oscillator

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We report on a high-pulse-energy solid-state picosecond Nd:YVO4 oscillator with cavity-dumping. The laser is end-pumped by an 808 nm laser diode and passively mode-locked with a semiconductor saturable absorption mirror (SESAM). In pure cw-mode-locking, this laser produced 2.5W of average power at a pulse repetition rate of 40 MHz and pulse duration around 12 ps. A cavity dumping technique using an intra-cavity BBO electro-optic crystal, supplied with bidirectional voltage, was adopted, which effectively improved the cavity-dumped rate. Tunable high repetition rate from 100 kHz to 1 MHz was achieved. With electro-optic cavity dumper working at 900 KHz repetition rate, we achieved average power 530 mW, corresponding to a pulse energy of 590 nJ. The laser includes a 5 mm long, a-cut, 5% doped Nd:YVO4 crystal with a 5-degree angle at one end face. Laser radiation is coupled out from the crystal end face with a 5-degree angle, without insertion of a thin-film polarizer (TFP), thus simplifying the laser structure. This picosecond laser system has the advantages of compact structure and high stability, providing a good oscillator for regenerative amplifiers.

8959-37, Session 9

High single-pulse energy, passively Q-switched Nd:YAG laser for defence applications

Marc W. Smillie, Mark Silver, Stephen T. Lee, Trevor J. Cook, Thales Optronics Ltd. (United Kingdom)

Q-switched high-peak-power lasers at 1-micron have been used extensively in military products for many decades, with applications including rangefinders and laser target designators. Passive Q-switching of Nd:YAG, combined with diode end-pumped laser geometries, are particularly attractive due to their compact and rugged design and superior temperature performance and efficiency. We present a passively Q-switched, diode end-pumped, 1μm Nd:YAG laser with a single pulse energy in excess of 40mJ. To our knowledge, this is the highest single pulse energy reported for a passively Q-switched end-pumped laser. We achieved this with a novel pump scheme, which uses an engineered diffuser to create the necessary uniform gain distribution for efficient passive Q-switching. The system consists of a 3kW, 808nm, diode-laser stack pump source, and a set of collimating optics, with the engineered diffuser, to homogenise and condense the pump beam into the end of a 20mm diameter Nd:YAG laser rod. Q-switching is achieved with a Cr:YAG saturable absorber within a plane-plane cavity. The 40mJ value was achieved despite a pump coupling efficiency of only 55%, hence we believe higher energies are achievable. The beam parameter product and pulse width were measured to be 12mm mRad and 18ns, respectively, which are consistent with those required for the applications. We have investigated the pulse-to-pulse timing jitter of our system, which has been previously cited as the main drawback when implementing passive Q-switching for designation applications. We also present our work to identify the mechanisms behind, and our attempts to reduce, the pulse timing jitter.

8959-38, Session 9

Compact nanosecond pulsed single stage Yb-doped fiber amplifier

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High power pulsed fiber lasers and amplifiers are usually based on free-space coupled large mode area (LMA) Yb-doped fibers or all-fiber designs by using diode seed lasers and multiple amplifying stages. Our aim in this work is to reduce the complexity (and cost) of the MOPA system and demonstrate a compact, single-stage, all-fiber, hybrid solid state laser (SSL)/fiber amplifier for amplification of nanosecond pulses. The key component is a custom made ring-cavity SSL at 1064nm, which can be designed to provide nanosecond pulses with energies in the sub-mJ range and with high average powers (> 1W). The seed laser operates in single frequency, has an ultra-low noise, low timing jitter, excellent beam quality, a pulse width of 10ns and with repetition rates up to 20kHz. A fiber pigtailed version of the SSL with repetition rates up to 100kHz is under development. The seed laser is coupled to a custom

made 20/125um pump/signal combiner and further spliced to a short piece (0.7-1.0m) of highly Yb-doped gain fiber (~10dB/m at 920nm). Results so far show stable operation with peak powers up to 13kW and pulse energies up to 140uJ for ~2uJ input pulses (~18dB gain). A PER of 13dB could be measured with the non-PM combiner. A 20/125um PM version of the pump/signal combiner is planned, which would allow for higher PER and the development of a compact and stable, linearly polarized, high power nanosecond pulsed MOPA. Single-pass, extra-cavity frequency conversion to the visible- and UV range will also be demonstrated.

8959-39, Session 9

A 1 Joule, 10ns, 110Hz, 1064nm laser using standard components

Jay Doster, Faming Xu, Ryan Feeler, Northrop Grumman Cutting Edge Optronics (United States)

A 1J, 110W laser system is described. This laser is constructed from standard commercial laser amplifiers and packaged in an industrial housing. By utilizing standard components, the time for delivery and overall cost of the system is greatly reduced when compared to custom laser systems. Characterization of the laser performance is presented including beam profile, output energy, long term and short term stability. A discussion of harmonic conversion to 532nm and 355nm, laser seeding, and higher energy experiments is also presented.

8959-81, Session 9

Highly-efficient, optically synchronized thin-disk amplifier for pumping OPCPA at high repetition rates between 100-300 kHz

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We report on a highly efficient thin-disk regenerative amplifier seeded by the infrared edge of a Ti:Sapphire oscillator. The amplifier is optically synchronized to the broadband oscillator and thus ideally suited for pumping high power, few-cycle parametric amplification stages.

The thin-disk amplifier is based on a modified commercial TruMicro 5080. To prevent nonlinear pulse distortions, a CPA concept is implemented consisting of a fiber Bragg grating (FBG) with a stretching ratio of ~65 ps/nm. The FBG is tailored to match the higher order dispersion terms of the compressor, resulting in nearly Fourier-limited pulse durations of 1.3 ps. The reflection grating-based compressor exceeds an efficiency of 95 % leading to compressed average output powers of more than 200 W between 100 and 300 kHz. Thus the system reaches an overall optical-to-optical efficiency over 50 %. This infrared output is consequently frequency-doubled with efficiencies > 70 % yielding to more than 140 W of average green output power, to serve as a pump source for an infrared OPCPA. In combination with the ps-pulse duration, the excellent beam quality (M2<1.15) and long term stability (<0.5 % (rms) over >10 hours), the system is a unique pump source for high repetition rate and high power OPCPA systems. Assuming even a moderate conversion factor in the range of ~15 %, few-cycle laser pulses with output powers of more than 20 W and pulse energies up to 200 ?J are in reach with this technology.

8959-40, Session 10

Near- infrared, mode-locked waveguide lasers with multi-GHz repetition rates

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Ultrafast lasers with multi-GHz repetition rates have a range of important applications in optical frequency metrology, non-linear microscopy, optical sampling and for the calibration of astronomical spectrographs. Solid-state waveguide lasers offer various advantages like a low-threshold operation, high laser efficiency, low mode-locking threshold and the possibility for the realization of compact and integrated systems.

We have fabricated low-loss, ion-exchanged channel waveguides in a phosphate-glass doped with Yb3+ and Er3+/Yb3+ for operation around 1 micron and 1.5 micron, respectively. Using the Yb3+:phosphate glass waveguide, mode-locking was achieved at a wavelength of 1052 nm with a repetition rate of 4.9 GHz and a pulse duration of 800 fs at an output power of 80 mW. A commercially available quantum well semiconductor saturable absorber mirror (SESAM) with a modulation depth of 0.4% was employed for passive mode-locking. Using shorter cavity lengths, repetition rates of 10.4 GHz, 12 GHz and 15.2 GHz were achieved with pulse durations in the range of 750-830 fs.

Mode-locking around 1.5 micron was achieved in the Er3+,Yb3+ co-doped phosphate glass waveguides by using a novel SESAM based on a quantum dot in well (DWELL) structure. Stable, self-starting mode-locked operation was observed at a repetition rate of 4.8 GHz with a pulse width of 2.5 ps and an output power of 9 mW. Using a shorter device length, a repetition rate of 6.8 GHz was achieved, with a pulse-width of 5.4 ps and an output power of 30 mW. The repetition rate was tuned by more than 1 MHz by varying the pump power. This simple technique could offer a way for on-chip stabilization of the repetition frequency from a monolithic waveguide-based laser system.

8959-41, Session 10

28 W, 217-fs regenerative bulk amplifier based on Yb:CAlGdO4

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Yb:CaAlGdO4 (Yb:CALGO) is a very promising material for high power ultrashort pulse generation, due to its broad emission bandwidth and good thermal properties. Here we report, to the best of our knowledge, the highest power and shorter pulses ever demonstrated from a Yb:CALGO-based regenerative amplifier.

The system layout consists of a Yb:CALGO oscillator seeding a Yb:CALGO regenerative amplifier followed by a folded grating compressor. The Yb:CALGO oscillator provides approximately 650 mW output power in a 63 MHz repetition rate train of 92-fs long pulses. The related spectrum is 12.5 nm wide Full Width Half Maximum (FWHM) and centered around 1050 nm. Average output powers as high as 36 W at

500 kHz are achieved out of the regenerative amplifier while pumping with 116 W at approximately 980 nm. A small roll-over in the regenerative output power trend is observed at maximum pump power. This is mostly due to a drift of the diode emitted wavelength, away from the maximum crystal absorption peak. After compression, we obtained 28 W in a train of 217-fs long pulses, corresponding to an energy higher than 50 μJ per pulse and a peak power above 0.25 GW. The pulse spectrum is centered at 1046 nm and is approximately 11 nm wide, corresponding to a time bandwidth product of 0.69. The beam quality factor stays below M2=1.15 up to the maximum output power level, confirming the outstanding thermal performances of the Yb:CALGO material. Experiments on further power up-scaling are in progress.

8959-42, Session 10

Megawatt peak power level sub-100 fs Yb:KGW oscillator

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High peak power associated with femtosecond pulses is a unique feature that makes ultrafast lasers indispensable for many technologies such as nonlinear microscopy, micromachining, and tissue manipulation. The peak power of ultrashort pulses can be scaled by increasing their pulse energy or by decreasing the pulse duration. The former is usually achieved through amplification or cavity-dumping technologies, but requires complicated configurations and additional pulse compression systems. An alternative and much simpler strategy is to use extended-cavity oscillators, where the high-energy and therefore high-peak-power pulses can be delivered directly from the oscillator. However, as a pulse shaping mechanism, SESAM (semiconductor saturable absorber) mode-locking suffers from multipulse instabilities at high pulse energies. Introduction of a large amount of negative dispersion can prevent the instabilities albeit at the expense of largely increased pulse duration. In contrast, the Kerr-lens mode-locking (KLM) can offer fast-saturable-absorber like action, resulting in a dramatic reduction of pulse duration. In this work, we report on an extended-cavity Yb:KGW KLM oscillator which produced sub-100 fs pulses with MW peak power. In the original 36 MHz oscillator, 78 fs pulses were delivered with 50 nJ of pulse energy and 0.65 MW of peak power. As the cavity was extended to 18 MHz, we obtained 85 fs pulses with up to 83 nJ of pulse energy, corresponding to a peak power as high as 1 MW. This is the highest peak power reported to date from the Yb-ion extended-cavity oscillators.

8959-43, Session 10

Femtosecond Innoslab amplifier with 300W average power and pulse energies in the mJ-regime

Torsten G. Mans, Roswitha Graf, Jan Dolkemeyer, Claus Schnitzler, AMPHOS GmbH (Germany)

Applications in attosecond science, free-electron-laser beam facilities or spectroscopy on surfaces (e.g. ARPES) require high pulse-power and/or few-cycle laser sources. One successful way to generate such pulses at high repetition rates/high average powers is the OPCPA-technique. This technique in turn requires pump lasers with millijoules of pulse energies at high repetition rates.

In order to build such a pump laser a laser chain consisting of a 5W-seed-laser, a 500W-InnoSlab-amplifier and a grating compressor has been setup. The repetition rate of the seed source can be varied with a pulse picker from 1MHz down to 100kHz. It delivers stretched pulses of ~30ps. These pulses are inserted into the Yb:YAG InnoSlab amplifier stage. At a repetition rate of 200kHz more than 2mJ pulse energy is extracted from a multi-pass InnoSlab-stage. Differential slope efficiency of the InnoSlab-stage is 57%. After a Faraday Isolator and cylindrical telescopes the radiation is inserted into a grating compressor. Beam qualities have been measured to be M2<1.5 in both directions. Efficiency of the compressor has been determined to be >65%. Compression to <1ps could be achieved resulting in average pulse powers exceeding 1GW.

The laser system is ideally suited for direct or frequency-doubled pumping of an OPCPA-amplifier-stage with the potential of a further increase of pulse power by a factor of 10. Also parallelization of processes with e.g. diffractive optical elements in materials processing is a potential field of application.

8959-44, Session 10

Jitter-compensated Yb:YAG thin-disc laser as a pump for the broadband OPCPA front-end of the ELI-Beamlines system

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The main advantage of picosecond high power Yb:YAG thin disc lasers is that relatively high energies in the kHz repetition rate range can be easily accessed. There are a number of arguments in favor of using these lasers as a pump source for broadband OPCPA, one of them being higher temporal contrast of parametrically amplified pulses as virtually no noise is generated and amplified outside the pump pulse. Additionally, less stretching is required and the recompression of amplified broadband pulses down to sub-10 fs can be done solely by means of the chirped mirrors. However, when pump pulses are in the range of few picoseconds, any variation in pulse delay in the regenerative amplifier will have a large impact on OPCPA performance. This is particularly pronounced in the case of high numbers of roundtrips and long amplifier cavities, therefore pre-compensation for optical path changes is required. In our work we demonstrate a novel design of a jitter stabilization system and investigate the performance of two OPCPA stages pumped by a jitter-compensated thin-disc Yb:YAG laser. The proposed scheme employs a cross-correlation setup with two perpendicularly oriented nonlinear crystals. A small fraction of the OPCPA seed signal is being locked between cross-polarized and delayed replicas of a pump pulse. The feedback signal for the delay compensation stage is acquired by coupling the polarization-separated parts of the parametrically amplified seed into two channels of a balanced photodiode. The advantage of our setup is that it is completely standalone and independent of OPCPA performance or laser pulse energy variation.

8959-45, Session 11

Picosecond DPSS laser technology for OPCPA pumping

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Over the last decade, the method optical parametric chirped-pulse amplification (OPCPA) has been established to generate high energetic few-cycle pulses with sub-10-fs in the visible from table-top systems. This method requires a highly stable pump laser with picosecond pulse duration, high peak power and good beam profile. Our here presented picosecond, diode-pumped solid-state (DPSS) laser is well suited for OPCPA pumping. Several laser technologies have been employed to pump OPCPA systems and we show how our DPSS system compares in performance to other approaches.

High pulse energy and high average powers DPSS laser systems based on Nd:YAG rods are utilized for many applications ranging from material processing, such as laser cutting, welding, marking and modification, to pumping of laser materials, such as Ti:sapphire. In a master oscillator power amplifier (MOPA) configuration, DPSS systems can provide high average power and high pulse energies with good beam quality. Typically, these systems employ nanosecond pulses in commercially available and compact setups typically generating up to MW-level peak powers. We present the design and experimental challenges of a DPSS amplifier system to amplify picosecond pulses. Our system is seeded by a sub-5-fs Ti:sapphire oscillator and a fiber-based pre-amplifier. Further, our system consists of consecutive DPSS amplification stages with increasing aperture to support multi-10-MW peak power, high pulse energy and high average power. We discuss our implemented solutions to mitigate thermal effects and present the obtained performance of the picosecond pulse amplification.

8959-46, Session 11

All-fiber concept for ultrashort pulses from a passively Q-switched Nd:YVO4 microchip laser

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We present an all-fiber concept for ultrashort pulses from a passively Q-switched microchip laser (MCL). The combination of nonlinear compression and spectral filtering of self-phase modulated (SPM) pulse spectra leads to pedestal-free pulses with a shifted emission wavelength.

In a proof-of-principle experiment a Nd:YVO4-based passively Q-switched MCL is used emitting 100 ps long pulses at 1064 nm. These pulses are launched into an all-fiber system, which reduces the pulse duration in three steps. In the first step, the MCL pulses are amplified and SPM-broadened on the forward path toward a chirped fiber-Bragg-grating (CFBG). The CFBG compresses the pulses down to several picoseconds and reflects them back to a 1030/1064 nm WDM, which acts as narrow filter. In the next step, the compressed pulses on the way between the CFBG and WDM experience a wide SPM broadening due to their short duration and high peak power. Therefore, the outer spectral components of these pulses reach the transmission window of the WDM and are coupled out at the 1030 nm port. In the fiber tap of the 1030 nm port the propagation of these spectrally filtered and temporally shortened pulses results in an additional SPM broadening. In the third step, this chirp is removed with a subsequent hollow-core fiber leading to pedestal-free 170 fs long pulses at ~1030 nm. The shifted emission wavelength is advantageous for subsequent power amplification in Yb-doped materials. Such a compact fiber-based seed source might become a promising alternative to conventional mode-locked lasers, especially for industrial applications.

8959-47, Session 11

Femtosecond Cr:ZnS laser at 2.35 µm mode-locked by carbon nanotubes

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Single-wall carbon-nanotubes (CNT) have been shown to be an efficient saturable absorber material for laser mode-locking. They have been implemented in solid-state, fiber, semiconductor and waveguide lasers, and the mode-locked emission was obtained in the wavelength range from 0.78 to 2 µm.

We report the Cr:ZnS laser mode-locked by a CNT-based saturable absorber. The laser was built using an astigmatically-compensated cavity with 250 MHz pulse repetition rate. The single-wall CNT-based films offer short absorption recovery times (<1 ps) and reasonable modulation depth. An interesting property is their capability to mode-lock lasers at the extended spectral range due to their broadband absorption ranging between 1 and well beyond 2 µm. The CNT-based SA was deposited onto a surface of a protected silver mirror and used as a cavity high-reflector mirror. The cavity mode was focused on a surface of SA to a 60 µm spot. A specially designed chirped mirror compensated the intracavity GDD.

Laser pulses with duration of 105 fs were obtained at 2.37 µm wavelength with the spectral bandwidth of about 60 nm. With 1.8% OC transmission the output power was limited to 65 mW, that corresponded to the pulse energy of 0.25 nJ. From the mode-locking threshold we estimated the saturation fluence to be about 20 µJ/cm2. The laser was not self-starting, probably due to the insufficient modulation depth. However, once started by tilting the cavity mirror, it exhibited stable operation for several hours.

We believe that we demonstrated the longest-wavelength mid-IR CNT-mode-locked laser.

8959-48, Session 11

High-power directly diode-pumped femtosecond Yb:KGW lasers with optimized parameters

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High-average-power, high-repetition-rate Yb:KGW lasers with pulse duration from nanoseconds down to hundred femtoseconds are increasingly used for material processing and other applications. We present dual crystal Yb:KGW lasers capable to operate as Q-switched oscillator with output power up to 23 W and pulse length of 20 ns and regenerative amplifier with output power up to 20 W and pulse duration below 200 fs after compression of chirped pulses. Both lasers have excellent beam quality with beam parameter M2<1.2. In this paper , we will show aspects of the design and performance optimization of Yb:KGW laser systems.

8959-49, Session 11

Compact thin-disk picosecond regenerative amplifier at 1 kHz with VBG compressor

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The OPCPA for the high repetition rate beamline at ELI-Beamlines is pumped by regenerative amplifiers, which have a high beam quality and <2 ps output pulse durations. We report on the progress in the development of an Yb:YAG thin-disk amplifier, which delivers frequency doubled pulses for a 3 stage OPCPA. Our design includes a CFBG (chirped fiber Bragg grating, 50 ps/nm) followed by a VBG (volume Bragg grating, 170 ps/nm) forming a very compact and highly stable stretcher. Pulses are then amplified to more than 20 mJ in a diode pumped thin-disk regenerative amplifier. The diodes are wavelength stabilized for pumping into the zero-phonon line. The amplifier cavity is designed to introduce a very low B-integral due to the BBO Pockels cell and the air inside the cavity. Amplified pulses return to the same VBG from the opposite direction perfectly compensating for the GDD introduced by this grating originally. At the same time, pulses are still partially stretched so the self-phase modulation in the grating is avoided. That allows us to

use a standard sized VBG with highly energetic pulses. A residual chirp is compressed in a grating compressor, which is very short in comparison to other systems with similar pulse energies and increases the stability of the system. After the compression, the less than 1.7 ps-long pulses are frequency doubled to 515 nm in a LBO nonlinear crystal with high conversion efficiency. The whole setup is very compact and fits into a box 1200x600 mm2 large including the regenerative amplifier, grating compressor, and SHG.

8959-50, Session 12

Modeling of a CW Nd:YVO4 laser longitudinally pumped by high power VCSEL modules at 808 nm

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Recent progress in high power vertical-cavity surface-emitting lasers (VCSEL) and their unique features make them a good alternative to edge emitting laser diodes for longitudinal pumping of solid-state laser gain media. In comparison with edge emitting laser diodes, VCSELs have low threshold current, wavelength stability with temperature variation, low fabrication cost and circular beam shape. Stability of wavelength with temperature variation results in a simplified cooling system of laser pumps as well as increased laser reliability when operating at high temperatures.

On the other hand, among the variety of Nd-ion based gain media, crystals of Nd:YVO4 have relatively high absorption cross section and narrow absorption line width at 808 nm. Therefore, narrow emission bandwidth and wavelength stability of VCSELs against changes in temperature make them an attractive optical pump source for longitudinal excitation of Nd:YVO4 lasers at 808 nm.

In our numerical model, commercially available 6W and 15W VCSEL modules were studied as the pump sources for a CW Nd:YVO4 laser. To the best of our knowledge, this is the first time that VCSELs were considered and analysed for longitudinal pumping of a CW laser. For each case the optimum output couplers were determined. Next, the calculations of slope efficiency, maximum output power and optical-to-optical efficiency were carried out. For example, for a 6W VCSEL, the maximum output power reached 2.5W with a slope efficiency of 48% using a 10 % output coupler. In this case the optical-to-optical efficiency was found to be 42%. For a 15W VCSEL, using a similar output coupler, the maximum output power of 6W was reached with a slope efficiency of 47% and optical-to-optical efficiency of 40%. Our results indicate that VCSELs can serve as efficient pump sources of the CW Nd:YVO4 lasers. A comparison with pumping of a Nd:YAG crystal will be also presented.

8959-51, Session 12

Resonator free Er-Yb laser based on photo-thermo-refractive (PTR) glass

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Photo-thermo-refractive (PTR) glass became more popular in different laser applications, such as bandwidth narrowing, angle and spectral selecting, increasing laser contrast and etc. Recent research in PTR composition allowed to improve its holographic characteristics. Spectral selectivity of holograms achieved on this material is 5A. Also this glass is totally transparent in the close IR range 800-3000 ?m.

In this work authors propose to integrate laser inside the photo-thermo-refracting glass by doping it with Er and Yb ions. Such experiments already were made in our university but only changes in holographic characteristic were investigated. At this work authors researching luminescent characteristic of doped PTR glass. Key goal is to achieve laser generation on this material. Since the process of forming refractive index variations inside media connected with ion changes inside media and crystal growing it may inflict some problems with Er-Yb ions location. Recording process consists of two parts. First is UV expose with Kimmon 325 nm laser and second is thermal treatment. At first experiments include only doped glass without any holograms on it, that will show at what parameters laser generation on this material will be possible. On this step for generation used external mirrors. Second step in research is to achieve laser generation on same media where holograms are recorded. This part include recording on edges and on whole media to check the difference in Er-Yb luminescence connected with ligand changes. And the last step of this research is to record the holograms in such way which will allow to get rid of external resonator mirrors and achieve laser generation only in inner reflecting holograms. This problem is complicated with hologram recording process, since we need to record 2 reflecting holograms on the edges of material with proper phase shift between grating periods.

Achieving laser generation on inner reflecting holograms of photo-thermo-refractive glass give us two main advantages. First of all, this solution will allow reducing any losses in radiation connected with bypassing resonators in common lasers. And second, integration laser inside photo-thermo-refracting glass will allow adjusting output wavelength with high accuracy, at the moment up to 5A.

8959-52, Session 12

Single-frequency, fully integrated, miniature DPSS laser based on monolithic resonator

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We present a single frequency, stable, narrow linewidth, miniature laser sources operating at 532 nm (or 1064 nm) based on a monolithic resonators. Such resonators utilize birefringent filters formed by YVO4 beam displacer and KTP or YVO4 crystals to force single frequency operation at 532 nm or 1064 nm, respectively. In both configurations Nd:YVO4 gain crystal is used. The resonators dimensions are 1x1x10.5 mm3 and 1x1x8.5 mm3 for green and infrared configurations, respectively. Presented laser devices, with total dimensions of 40x52x120 mm3, are fully equipped with driving electronics, pump diode, optical and mechanical components. The highly integrated (36x15x65 mm3) low noise driving electronics with implemented digital PID controller was designed. It provides pump current and resonator temperature stability of ±30 µA@650 mA and ±0,003°C, respectively. The laser parameters can be set and monitored via the USB interface by external application. The developed laser construction is universal. Hence, the other wavelengths can be obtained only by replacing the monolithic resonator. The optical output powers in single frequency regime was at the level of 42 mW@532 nm and 0.5 W@1064 nm with the long-term fluctuations of ±0.85%. The linewidth and the passive frequency stability under the free running conditions were FWHM< 100 kHz and 3x10-9@1 s integration time, respectively. The total electrical power supply consumption of laser module was only 4 W. Presented compact, single frequency laser operating at 532 nm and 1064 nm may be used as an excellent source for laser vibrometry, interferometry or seed laser for fiber amplifiers.

8959-53, Session 12

Broadly tunable, longitudinally diode-pumped Alexandrite laser

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We present design and first performance data of a broadly tunable Alexandrite laser longitudinally pumped by a newly developed high brightness single emitter diode laser module in the red spectral range. Replacing the flash lamps usually used for pumping of Alexandrite will increase the efficiency and maintenance interval of the laser.

The pump module is designed as an optical stack of seven single emitter laser diodes. An opto-mechanical concept for the tight overlay of the radiation using a minimal number of optical components for collimation, e.g. a FAC and a SAC lens, and focusing was selected. The module provides optical output power of more than 14 W (peak pulse output in the focus) with a beam quality of M2=41 in the fast axis and M2=39 in the slow axis. The Alexandrite crystal is pumped from one end with a repetition rate of 35 Hz and 200µs long pump pulses. The temperature of the laser crystal can be tuned between 30 °C and 190 °C using a thermostat.

The diode pumped Alexandrite laser reaches a maximum optical-optical efficiency of 17.8 % and a slope efficiency of more than 30 % in fundamental-mode operation (M2 < 1.10). Conducting a Findlay-Clay analysis with four different output couplers the round-trip loss of the cavity is determined to be around 1 %. The wavelength is tunable between 755 and 788 nm via crystal temperature or between 745 and 805 nm via an additional Brewster prism.

8959-54, Session 12

Novel design of compact solid state resonators by way of volume Bragg gratings

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Volume Bragg gratings (VBGs) recorded in photo-thermo refractive glass (PTR) have high stability, and high laser damage threshold, allowing for many applications to the design of high power lasers. Gratings recorded in the transmitting geometry (TBG) have narrow angular selectivity, and can be used as a spatial filter in a resonator. Such gratings have previously been useful for improving the brightness of high power diodes. As the gratings have narrow angular selectivity, losses for higher order modes in the resonator no longer depend on the cavity length, allowing for the construction of short cavities with large mode areas. In this paper, we explore the design of short 1 cm cavities using a pair of sequential TBGs oriented in perpendicular planes as a spatial filter and no aperture in the cavity. The M2 parameter as a function of pump size and angular selectivity of the TBG are explored, using pump diameters ranging from 800 µm to 3 mm and angular selectivity ranging from 11 mrad to 1 mrad. M2 data of the TBG resonator is compared to a 1cm unstable, multimode resonator. Efficiency of the TBG cavity is compared to a stable, single mode hemispherical resonator. An M2 parameter of 1.05 is reported for an 800 µm pump diameter, a 6.2 mrad TBG, and a 1 cm long cavity.

8959-55, Session 13

100W Nd:YAG rotating cavity laser

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Many different approaches have been proposed to overcome performance limiting thermal effects found in solid state lasers. We make use of an intra-cavity rotating periscope to translate a collinear pump beam and laser mode across the gain medium. The back surface of the gain medium has a high-reflectance coating, for both the lasing and pump wavelengths, and thus acts as an active mirror. We call this arrangement the Rotating Cavity Laser, or RCL.

As the time scales associated with stimulated emission and heat flow are very different, the motion provided by the periscope effectively separates the optical and thermal processes in space. This is similar to the approach taken by quasi-CW lasers, which separates the two processes in time, and thus allows the RCL to provide a CW output whilst maintaining the thermal management ability of a quasi-CW laser.

Using motion for thermal management imparts a number of advantages, for example the potential to utilise high pump densities and thus smaller pumped regions than those found in thin disk lasers. Energy stored in the gain medium is therefore less susceptible to extraction via ASE, allowing the generation of high energy pulses at high repetition rates. Furthermore, this approach provides a simplified heat sinking arrangement when compared to other motion based thermal management techniques, such as the Rotary Disk Laser which depends on a moving gain medium.

We will be presenting the latest performance results for our RCL with CW power levels exceeding 100W from a single "end-pumped" Nd:YAG polycrystalline sample.

8959-56, Session 13

Development of Nd,Cr co-doped laser materials for solar-pumped lasers

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Sunlight is well known as an important source of clean energy. One way to use solar energy is to convert it to laser energy. Since electrical power is not required for such a laser, this next-generation technology offers great promise for the future. However, since the conversion efficiency from solar energy to laser energy is only a few percent, such lasers are not yet in practical use. To improve the efficiency of solar-pumped lasers, the selection of a suitable crystal is the most important factor. Large and broad absorption from the ultraviolet to visible region and high thermal conductivity to allow high-energy pumping are required for the crystal of solar-pumped lasers. In this work, Nd3+,Cr3+-codoped YVO4 and CaYAlO4 crystals were grown for the first time to the best of our knowledge. Nd:YVO4 is a laser crystal with a large emission cross section. We found a strong and wide absorption band in the ultraviolet region upon the addition of Cr ions. Furthermore, the absorption cross section of Nd,Cr:CaYAlO4 around 400 nm was more than 70 times that of Nd,Cr:YAG crystals. We also measured the fluorescence spectra of these crystals. Fluorescence at 1 ?m was observed by pumping at 400 nm. This indicates that energy transfer from Cr to Nd occurred effectively. The above results suggest that these crystals have potential for use in efficient solar-pumped lasers. We are currently developing a solar-pumped laser system using these crystals. We believe that solar-pumped lasers will become an important tool for renewable energy generation.

8959-57, Session 13

Yb:CaGdAlO4 laser under high pumping power: high performances and singularities

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Diode-pumped high-power lasers based on Yb-doped materials have raised an intense interest in the laser community since few years now. Among them Yb-doped CaGdAlO4 crystal (Yb:CALGO) is now recognized to exhibit exceptional and interesting properties for high-power and ultra-short pulse lasers. In fact, by combining both broad emission bandwidth and good thermal properties, it permits

to demonstrate ultra-short pulses [1,2] and high power [3-5]. Very recently this crystal has also been integrated in a thin-disk geometry [6] demonstrating in cw up to 150 W (multimode) and 50 W (single-mode) and up to 30 W in femtosecond regime. These experiments clearly demonstrate the interests of Yb:CALGO in classical bulk or thin-disk configurations for high power lasers.

When pumping Yb:CALGO at very strong pump power (typically >100 W), strong thermal astigmatism limiting the power due to spatial mode degradation may be observed which may creates some fundamental limitations. Indeed, very few thermal parameters are known for Yb:CALGO. In this paper, thermal properties are reported in order to explain some singularities such as spatial mode stabilization by passive polarization switching. We observe an unique spatial mode switching in Yb:CALGO laser when pumped in the multi-hundred watts of power. This permits to automatically stabilize to a TEM00 mode from highly spatial-multimode regime. This stabilization is achievable thanks to a polarization mode switching allowed by the particular spectroscopic and thermal properties of Yb:CALGO.

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8959-58, Session 13

Antireflective surface structures on optics for high-energy lasers

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The traditional approach using antireflective coatings on optics for multi-KW high energy lasers to reduce Fresnel losses has limitations due to optical damage under high power irradiation as well as delamination in operational environments. New methods have recently been developed for fabrication of antireflective surface structures (ARSS) on optics to reduce reflection losses that provide a more robust solution by using surface structures fabricated directly into the actual surface of the optics, without the need for coating with extraneous materials. We will present recent results that demonstrate superior ARSS performance on a wide variety of infrared optics for use in the near- to mid-infrared spectral region, including fused silica windows and lenses, laser gain media including YAG crystals and ceramics, and spinel ceramic windows, which have been successfully patterned with ARSS using reactive ion etching and/or photolithography. Reflection losses as low as 0.02% have been measured for fused silica windows with ARSS at 1.06 microns. Laser damage thresholds have been measured for substrates with ARSS and compared with uncoated and AR coated samples. Thresholds as high as 100 J/cm2 have been demonstrated in fused silica with ARSS using a 1.06 µm pulsed laser. In general, ARSS substrates show much higher laser damage thresholds than those of traditional AR coated substrates and similar to those of the bulk. Results for scale-up of the process for large size windows will also be presented. These remarkable results have direct applications for optics for high energy laser systems for which robust optical performance is required.

8959-59, Session 14

Insights into the anisotropic optical properties of monoclinic Yb-doped borate laser crystals

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Monoclinic borate crystals are relevant matrices for rare earth doping, and also promising candidates for high-power laser applications thanks to their large transparency domain and high optical breakdown threshold. We developed a family of high optical quality Yb-doped crystals of Li6(Yx,Gd1-x)(BO3)3 grown by Chockralzki method under congruent melting, with x = 0, 0.25, 0.5 and 0.75. Such crystal family allows efficient solid-state laser diode pumping with low quantum defect and limited thermal loading, large spectral emissions relevant for future ultrashort pulsed laser applications [1-3].

Since the Yb-doped laser crystals show monoclinic P21/c low symmetry, they belong to the bi-axial class. Therefore, the spectroscopic properties of the Yb3+ active ion are significantly affected by such environment, leading to strong anisotropic optical properties. We report on absorption and emission spectra and the associated cross-sections in polarized light, for different propagation directions, leading to a first insight of the anisotropy of such laser crystals. Moreover, we demonstrated polarization dependence of laser amplification at 1030 nm under diode pumping at 972 nm, achieving positive gain values. These observations confirmed the need of polarized light characterizations with these low-symmetry crystals, for each considered property at play during laser experiments. Finally, laser oscillation was obtained with slope efficiency up to 32%.

Recently, remarkable methodological and theoretical progress occurred with monoclinic crystals, providing an enlarged and brand-new description of optical anisotropies in monoclinic crystals [4]. This suggests that the optimal orientation of these crystals for an optimal exploitation of laser properties is still to be foreseen.

8959-60, Session 14

Optic axis dispersion in double tungstate crystals and laser operation at 2 µm

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Conical refraction knows a recent regain of interest for beam shaping or in laser gain media. This revival is mainly due to the availability of sufficiency long biaxial crystals with good optical quality that are needed to obtain this effect. However, biaxial crystals are anisotropic and

consequently their properties strongly depend on the orientation. In order to well describe those crystals the tensor properties are needed. To well define those tensors, measurements should be carried out in several known orientations. We will present the investigation on Nd-doped and undoped KGW and also Ho-doped KYW, on the optic axis orientation. The dispersion of the optic axis has been measured from 400 nm up to 1.58 µm. To obtain absolute values of the orientation X-rays diffraction measurements were carried out, and using the Laue method absolute values of the orientation of the optic axes can be deduced. The variation of the angle is more than 2° between the blue and the infrared. These measurements show that the refractive index tensor, given in literature, is not precise enough to predict the orientation of the optic axes in double tungstate crystals. Furthermore, the dispersion for doped and undoped crystals looks similar in all crystals. Over the investigated spectral domain, we do also not observe a rotation of the index ellipsoid along the crystallographic b-axis, which means the dispersion occurs only in one plane. These results are of great interest for groups working on conical refraction, especially when using this effect at several wavelengths.

8959-61, Session 14

Abnormal beam-profile behavior in the Nd:YAG ceramic regenerative amplifier

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Amplified spontaneous emission (ASE) can be detrimental to the performance of high-gain amplifiers. Temporal contrast, spectral bandwidth, and beam profile of the output pulse can be affected. The abnormal beam-profile behavior in the Nd:YAG ceramic regenerative amplifier (regen) has been investigated.

The Nd:YAG regen contained a 2%-doped 8 x 8 x 10-mm Nd:YAG ceramic active element that was pumped by a fiber-coupled 808-nm pump diode. The regen was seeded by a pulse-shaping system that produced subnanojoule, 2-ns FWHM pulses at 1064 nm. The 1-mm pump fiber core was 2:1 re-imaged into the regen active element. The regen had a 123-cm linear folded resonator with flat and 5-m concave spherical end mirrors. Several pump pulse widths (150, 250, and 350 us) were used to maximize output energy. The output beam profile was very sensitive to regen resonator misalignment. In the case of the 350-us pulse, slight misalignment caused beam disintegration while beam centroid stayed on the resonator axis. When aligned, the regen produced a Gaussian-like pulse with the flattened top.

The resonator length was changed to 165 cm. The output energy stayed the same (6 mJ), while the beam profile became Gaussian. Simulations showed that the beam size inside the active element is similar for both resonator lengths—0.91 mm and 0.94 mm, correspondingly.

After switching back to the 123-cm-long regen resonator with the flat-top output beam profile, the pump re-imaging optics were changed to a 1:1 imaging ratio. This caused an immediate change from the flat-top beam to the Gaussian one without any changes in the resonator. This beam behavior suggests the presence of ASE and regen amplification competition that can be avoided by careful attention not only to resonator parameters, but to pump geometry as well.

8959-62, Session 14

Spectroscopic characterization and energy transfer process in cobalt and cobalt-iron co-doped ZnSe/ZnS crystals

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Cobalt doped II-VI wide band semiconductors (e.g. ZnSe, ZnS, CdSe) are promising media for infrared (IR) laser applications. They could be utilized as effective passive Q-switches for cavities of Alexandrite as well as Nd and Er lasers operating over 0.7-0.8, 1.3-1.6, and ~2.8 ?m spectral ranges. We report spectroscopic characterization of Co:ZnSe and Co:ZnS crystals. Absorption cross-sections were measured for 4A2(F) ? 4T1(P), 4A2(F) ? 4T1(F), and 4A2(F) ? 4T2(F) transitions with maximum absorption at 768(726), 1615(1500), 2690(2740) nm for ZnSe(ZnS) crystals, respectively. The calculated absorption cross-sections of the above transitions were estimated to be 64(56)?1019, 7.5(7.8)?1019, and 0.52(0.49)?1019 cm2 for ZnSe(ZnS) crystal hosts. In addition to the above applications the cobalt ions could be utilized for excitation of Fe2+ ions via resonance energy transfer process. Tunable room temperature lasing of Fe2+ doped binary and ternary chalcogenides has been successfully demonstrated over 3.5-6 ?m spectral range. However, II-VI lasers based on Fe2+ active ions don't feature convenient commercially available pump sources (e.g. some Fe doped crystal hosts require pump wavelengths longer than 3 ?m). Therefore, the process of energy transfer from Co2+ to Fe2+ ions could enable utilization of commercially available visible and near-infrared pump sources. We report a spectroscopic characterization of iron-cobalt co-doped ZnS and ZnSe crystals over 14-300K temperature range. Mid-IR laser oscillation at 3.9 ?m(3.6 ?m) via energy transfer in the Co:Fe:ZnSe (Co:Fe:ZnS) co-doped crystals was demonstrated under cobalt excitation at 4A2(F) ? 4T1(P) (~0.7?m) and 4A2(F) ? 4T1(F) (~1.56 ?m) transitions.

8959-63, Session 14

Spectroscopic characterization of Fe2+-doped II-VI ternary and quaternary mid-IR laser active powders

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We report on spectroscopic characterization of laser active powders based on iron doped II-VI ternary and quaternary semiconductors for mid-IR laser applications. Iron doped Cd1-xMnxTe, Cd1xMnxS, Cd1-xMnxSe, Cd0.5Mn0.5S0.5Se0.5, Cd1-xZnxTe compounds with x=0.5-0.25, were prepared by using thermo diffusion technique. The starting binary powders were mixed in the appropriate molar ratios, sealed in evacuated (10-3 Torr) quartz ampoules, and annealed at 800-1000oC for several days. Samples composition, integrity, and grain size were characterized by micro-Raman and X-ray diffraction and revealed a variation of the crystal field parameters depending on powder composition. Fe2+ photoluminescence was characterized by spectral band position (normalized with respect to the detection platform spectral sensitivity) and lifetime at different temperatures, enabling calculation of the absorption and emission cross-sections. Practical utility of the developed powders was demonstrated by a room temperature random lasing of iron doped Cd0.5Zn0.5Te powders over 5620-6020 nm spectral range pumped by a 2.94 m radiation of a Q-switched Er:YAG laser. It was demonstrated that laser active Fe2+ doped ternary and quaternary II-VI materials can be produced by simple annealing of the commercially available binary powders omitting expensive and complicated crystal growth processes. Variation of composition, type and amount of the second cation in ternary II-VI materials results in effective shift of PL band of Fe2+ ions towards shorter or longer wavelength. Major spectroscopic characteristics of Fe2+ doped II-VI ternary and quaternary compounds were obtained and their practical utility for mid-IR lasing demonstrated.

8959-64, Session 14

Spectroscopic characterization of laser properties: isolating the best methods for accurate measurements and calculations

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Solid state laser designers utilize calculated and measured laser properties provided by materials manufacturers for systems modeling. Thus, the accuracy of the data provided is of critical importance in generating best estimates of a system performance. Over the years, SCHOTT has developed expertise is measurement methodologies for providing the most accurate information possible to the laser manufacturers. This paper outlines the best methods for spectroscopic characterization of the three most commonly utilized active ions in glass; Er, Yb, and Nd.

The material related properties that drive laser performance in a given system are the emission bandwidth, emission cross section, the radiative/fluorescence lifetime, and the nonlinear refractive index. In some cases, the exact wavelength at which the peak of the emission manifold falls at is also of significance. The Judd-Ofelt (JO) analysis is the most commonly employed method for extracting emission cross-sections and radiative lifetimes from measured absorption and emission curves. In the case of Er3+ and Yb3+; a simplification of the J-O method, McCumber analysis, or the reciprocity method maybe used for calculating the necessary laser properties.

For this paper, we identify the best methods that should be utilized for the obtaining the true laser properties of active ions in glass hosts. Using round robin studies at universities and the reference data published by LLNL, we show that instrument conditions can have significant impact on measurements and related calculations. We present methods for calibrated fluorescence measurements of laser emission. Moreover, we also analyze the possible correlations of the calculated Omega parameters to the laser properties obtained.

8959-65, Session 14

Simulation of birefringence in laser crystals

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Thermal lensing effects and birefringence in laser crystals strongly influence beam quality of high power solid state lasers. The thermal lensing effect is based on the temperature dependence of the refractive index and the deformation of end faces of a laser crystal. Furthermore, the structure of laser crystals leads to a polarization dependent variation of the refractive index, which is resulted from the photoelastic effect and the temperature induced stress in laser crystals. This polarization effect leads to birefringence. Consequently, radially and azimuthally polarized light propagate through Nd:YAG laser amplifiers with different radius, which reduces beam quality. This effect has a significant influence on high power laser amplifiers. An accurate analysis of the effect is required, to compensate this polarization effect. We developed a simulation tool, which is based on ray tracing of pump light and a 3-dimensional finite element analysis of the temperature, deformation and stress of the crystal. The photoelastic effects are calculated by the cut direction of the crystal, the stress in crystal and the photoelastic constants of the crystal. Simulation results show that such a finite element analysis leads to a more realistic calculation of birefringence effect than analytic calculations, which are based on plane stress or plain strain approximation. Simulation results are presented for different crystal and pumping configurations. For example, we show that birefringence is not radially symmetric for a 111-cut Nd:YAG crystal, even though the pumping configuration is radially symmetric.

8959-66, Session 14

Spectroscopic properties of Pr-doped PbCl2 for eye-safe 1.6µm laser applications

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The development of new gain media for eye-safe laser applications continues to be an active area of research. Most efforts have been focused on bulk solid-state gain media using the well known 1.5um transition of Er3+ ions doped into oxide host materials (e.g. Er: YAG, Er: Y2O3). A new eye-safe laser transition at ~1.65um was recently reported from Pr3+ doped into the low-phonon energy host RbPb2Cl5 [1]. In this work, results of the purification, crystal, and IR spectroscopy of Pr3+ doped PbCl2 are presented. PbCl2 is non-hygroscopic and has a low maximum phonon energy (~180 cm-1), which enables efficient emission in the infrared (IR) spectral region. Commercial PbCl2 was purified through a combination of zone-refinement and chlorination of the melt. The dopant PrCl3 was added to the purified PbCl2 and molten under bubbling of HCl gas. The crystal growth of Pr: PbCl2 was performed using horizontal Bridgman technique. The resulting Pr3+ doped PbCl2 crystal exhibited strong IR absorption bands in the 1.4-1.6 µm region, which allow for resonant pumping using commercial diode lasers. Pumping at ~1.45µm resulted in a broad IR emission band at ~1.63µm (75nm @ FWHM) assigned to the 3F3 ? 3H4 transition. Decay time studies revealed an average lifetime of ~170 µs at room-temperature, which increased to ~340 µs at 40 K. Results of temperature dependent absorption and emission studies as well as an analysis of the 1.6µm emission cross-section will be discussed at the conference.

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8959-67, Session PTue

Optical path difference of slanted edge diode-pumped Yb:YAG/YAG thin-disk laser

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The main disadvantage of ytterbium-doped material is its quasi-three level nature. This effect has a critical influence on the pump light distribution and the absorption efficiency inside the active medium which reduced the beam quality. Otherwise, one of the significant features of thin disk laser is its good beam quality factor. In this work, we present a novel edge-pumped Yb:YAG /YAG thin disk laser with slanted faces of 30(degree) , consists of a 0.2-mm-thick Yb:YAG crystal as a gain medium and a 1.3-mm-thick un-doped YAG crystal bonded on the gain medium and pumped by four non-symmetric hollow ducts . we calculate the distribution of the absorbed pump power within the crystal using Monte-Carlo-ray tracing and taking into account changes of absorption caused by crystal temperature. The second step consists of the calculation of the temperature within the crystal .By using the method of Reciprocity we found an optimal Yb-ions-concentration of 15% with maximum absorption efficiency of 76%. In addition, the numerical simulation of the output power is performed for different Yb(3+)-concentrations and different transmittance of the output coupler. Finally, we calculate the consequence of Optical Path Difference experimentally and compare with our numerical simulation. In experimental, we used a He-Ne laser as a source light that reflected rays on the surface of the disk are focused on the CCD by an optical relay telescope system. The value of the OPD inside the crystal increased from -918.35 mm to -2684.34 mm in the output power range of 18.6W to 160W.

8959-68, Session PTue

Solid funnel for diode-pumped high power Nd:YAG slab amplifier

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Recently, a cw laser using end-pumped slab amplifier reported record-high power with high beam quality. Each end of the slab amplifier was pumped by a set of high power diode stacks. Diverging diode beam in fast axis was collimated by micro-lens array and the collimated beam was focused by cylindrical lenses to an end face of the Nd:YAG slab. Slight misalignment or vibration of the focusing lens can results in accidental optical damage of the slab amplifier caused by absorption of scattered pump beam. The pump beam distribution in the slab is also affected by the misalignment. A solid funnel which guides focused pump diode beam to the slab is devised to reduce the effect of misalignment. The curved entrance surface of the solid funnel collimates the focused pump diode beam and internal reflections from slanted side surfaces mix the collimated pump beam in the funnel. The pump beam is transferred to the slab and then propagates through the thin slab by internal reflection. Mixing of the beam leads to uniform pump beam distribution in the Nd:YAG slab. The effect of misalignment of the focusing lens was investigated by simulating the change of absorbed pump beam distribution caused by shift of the cylindrical lens in several directions. The pump distribution in the slab and the total diode power absorbed in the slab were less affected by the lens position shift compared with the case of without using the funnel. As beam quality of amplified beam is affected by the pump beam distribution in the slab amplifier, the devised solid funnel can be useful in obtaining high power laser beam with high beam quality.

8959-69, Session PTue

DPSS MOPA laser system generating 300 mJ with one nanosecond pulse

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This report presents a diode-pumped solid state (DPSS) high peak power laser with output energy of 300 mJ, operating frequency of 300 Hz and pulse width of less than one nanosecond. The laser system consists of a master oscillator power amplifier (MOPA) configuration with the output energy of one millijoule from the oscillator, the energy of 12 to 15 millijoules from the pre-amplifier and the energy of 300 mJ from the power amplifier. The transversal mode is very close to the single mode with M2 less than 1.5 and the lasing wavelength is 1064 nm. The laser system is well packaged in a compact footprint of 2x3 square feet.

8959-70, Session PTue

A high-peak power, low-jitter, single-frequency, eyesafe laser: a concept design

Frank F. Wu, Irvine Photonic Systems (United States)

This report presents a new approach of using the cavity entrapped and amplified CW seeding signal to injection seed into the slave cavity to effectively suppress the side modes to realize the single frequency laser operation. The advantage of the realized regime is that in stable laser operation there is no need to adjust the slave cavity length to match the seeded light longitudinal mode in traditional seeding configurations. It is found that the slave laser frequency follows exactly to the injected seeded laser longitudinal mode which provides an effective method for frequency tuning, frequency control and locking. By applying this configuration, a high peak power, low jitter, single frequency eyesafe laser oscillator with output energy of near tens to more than 100 mJ can be realized, with a pulse width of tens of nanoseconds and near single transversal mode

8959-71, Session PTue

Self-adaptive, passively Q-switched, diode-side-pumped Nd:YAG slab laser

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Our approach utilizes a novel, closed-loop, reciprocal resonator concept for a diode-side-pumped Nd:YAG slab. The gain medium creates the phase-conjugated element operating in transmission as well as in reflection modes. In such a case we have dealt with dynamic out-coupling losses dependent on gain gratings parameters. We have shown that such a laser offers 30% efficiency and near diffraction limited output in free running regime. The aim of this work was to examine and compare such a laser concept for free running and Q-switching regimes.

In preliminary experiments the free-running regime was characterized in short (150-mm long) linear cavity with flat output coupler of 50% transmission. We obtained multimode output beam with parameter M2 ~10 and up to 350 mJ with 41.8% slope efficiency.

In self-adaptive, closed-loop laser scheme, up to 250 mJ of energy with 33.1% slope efficiency were achieved. It was shown that due to self-cleaning effect of phase conjugation the near diffraction limited output with parameter M2 < 1.3 was obtained. The observed asymmetry of beam was caused by an asymmetry of gain and temperature distributions in active medium.

For the Q-switching experiments we have exploited the passive Q-switches consisted of the stack of AR coated Cr:YAG crystals.

The linearly polarized beam with excellent pointing stability and relatively low energetic jitter was observed as a rule. 120-mJ energy of series consisting of 5 pulses was achieved.

The examination of spatial beam profile evidenced the almost diffraction limited output beam with parameter M2 < 1.1.

8959-72, Session PTue

Multiline possibility of Nd:YAlO3 laser in spectral range 1.3-1.5 μm

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The goal of our research was investigation of diode pumped Nd:YAlO3 (Nd:YAP) laser tuning possibility in spectral range of general interest 1.3 – 1.5 um. The laser radiation generation in this region is very required for many applications in medicine, atmospheric physics, and spectroscopy due to high absorption of this radiation in liquid water and water vapors. We use 1.0 at. % doped Nd:YAP active medium 5x8 mm in dimensions. As a pumping source, a fibre-coupled 808 nm laser-diode was utilized.

Two particular Nd:YAP laser resonators (one for 1.3 um spectral region and the second one for 1.4 um spectral range) consisted of a flat pump mirror and a curved output coupler were designed and constructed. The laser line selection was realized by the single 1.5 mm thick quartz plate placed at the Brewster angle between the output coupler and laser active medium. The six single emission lines were reached within the desired spectral range (1340 nm, 1341 nm, 1342 nm, 1403 nm, 1408 nm, 1433 nm). Moreover, the system generated in dual frequency regime for some line combination was possible to realized. The respective output laser

characteristics in terms of output power, beam spatial structure, and temporal profile were also recorded.

The results obtained provide a great potencial for wide variety of application in medicine and industry requiring laser operation in spectral range 1.3 – 1.5 um.

8959-73, Session PTue

Spectroscopic and lasing properties of Pr:YAlO3 material at cryogenic temperature

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One of the most attractive oxide laser material for Pr3+-ions is the YAlO3 which combines its good thermal and mechanical properties with nature birefringent character. Moreover, in comparison with the most prominent Pr-doped fluoride crystals, Pr:YAP exhibits positive value of the temperature coefficient dn/dT allowing to simply employ a microchip laser geometry which is in general very attractive because of its compactness, high efficiency and good beam quality. So, this provide a great potential for realizing compact and efficient laser sources suitable for various applications in industry (color-display and data storage technology), spectroscopy, fluorescence microscopy, and medicine.

In this contribution, spectroscopic properties of cryogenically cooled Pr:YAlO3 material in terms of fluorescence lifetime, and polarization-resolved absorption and emission spectra are reported, for the first time to our best knowledge. Moreover, first green laser emission obtained from Pr:YAlO3 crystal is demonstrated. The proposal of laser property investigation at cryo-temperature originated from our last results concerning the markedly improvement of the Pr:YAlO3 laser input-output properties while decreasing the crystal temperature, even within the temperature range 10–35°C realized by water cooling.

In our experiment, 1.1 at. % doped Pr:YAlO3 active medium mounted on a liquid-nitrogen-cooled copper finger in the vacuum chamber of the cryostat was used. To minimize resonator losses, microchip geometry realized by cavity mirrors directly deposited on the crystal faces was proposed. Using 1W GaN laser diode pumping, 37 mW of continuous-wave output power at 548 nm wavelength at 80 K crystal temperature was obtained.

8959-74, Session PTue

Measurement of thermal effects in solid-state laser gain medium by digital holography

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In high power diode pumped solid-state lasers, thermal effects in the laser medium are important factors limiting the power scaling and beam quality. Besides total pump power, pump structure, such as pump geometry, cooling scheme, laser crystal shape and dimension all affect the result of thermal effects. The theoretical modelling and calculations may only conclude approximate results with the consideration of parts of factors.

This paper introduces a new technique of measuring Nd:YAG rod thermal lensing by digital holography (DH). Both dynamic and steady state can be measured by this method. The digitally recorded hologram can reveal each part of the thermal effects in the crystal, and detailed variations of thermal effects can be mapped out through digital reconstructions of the captured holograms. It can help to study the uniformity of the pump distribution in the gain medium, find “hot” spots which may result in potential crystal crack. Moreover, an integrated thermal lensing can be accurately determined. DH is an informative tool to understand thermal effects and provide a guidance for laser cavity design and simulations.

8959-75, Session PTue

Zero-phonon-line pumped 100-kHz Yb:YAG thin disk regenerative amplifier

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Laser-induced plasma generated by high energy and high repetition rate few picosecond pulse is required for the efficient generation of mid-infrared and extreme ultraviolet light for medical and industrial applications. We are developing an Yb:YAG thin disk regenerative amplifier with 500-W average power, and have obtained 50-W output at repetition rate of 100-kHz with nearly diffraction limited beam profile. We compared the output characteristics of amplifier pumped at 940-nm and 969-nm, and found that the zero-phonon-line, corresponding to 969-nm in case of Yb:YAG, pumping can achieve the higher output due to the less heat effect in both statically and dynamically.

Generally, the maximum pump power of thin disk is limited by the melting point of bonding material to the heatsink and the thermally induced stress inside the thin disk. We monitored the surface temperature distribution of thin disk under the lasing and the non-lasing conditions by using a compact thermal camera. We found that the surface temperature of non-lasing thin disk pumped at 969-nm was less than half that pumped at 940-nm. Although the power of both diode was same in 250-W, the temperature difference between the lasing and the non-lasing condition pumped at 969-nm was only few degrees, whereas the temperature difference pumped at 940-nm was more than 50-C. We also measured the thermally induced thin disk deformations by using a Hartmann-Shack wavefront camera in both 940-nm pumping and 969-nm pumping. Thermally induced effects of thin disk in both pump wavelengths will be discussed in the presentation.

8959-76, Session PTue

Operation of multi-passed Yb:YAG laser with edge-pumped disks

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We report on testing of a Yb:YAG laser using two disk-type gain elements and multi-passing architecture. The disks are edge-pumped [1], thus allowing for reduced doping of crystals with laser ions, which translates to lower lasing threshold in Yb:YAG material. In addition, edge-pumping uniquely enables tailoring of gain profile by varying the arrangement of pump diodes. Thermal management of the disk is provided by a novel microchannel heat sink offering 1) ultra-low thermal resistance, 2) uniform extraction of waste heat from the disk, and 3) unparalleled dimensional stability (critical for low optical distortions).

This work presents results of testing the laser with two Yb:YAG laser disks and relay optics configured for power extraction with up to 40 passes through the disks [2]. Data from testing the laser each as an oscillator and as a pulse amplifier is presented. This work was in part

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8959-77, Session PTue

Diode pumped tunable lasers based on Tm:CaF2 and Tm:Ho:CaF2 ceramics

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The Tm:CaF2 (4 % of TmF3) and Tm:Ho:CaF2 (2 % of TmF3, 0.3 % of HoF3) ceramics, prepared using hot pressing, and hot formation technique had been used as an active medium of diode pumped mid-infrared tunable laser. A fibre (core diameter 400 um, NA=0.22) coupled laser diode (LIMO, HLU30F400-790) was used to longitudinal pumping. The laser diode was operating in the pulsed regime (6 ms pulse length, 10 Hz repetition rate) at wavelength 786 nm. The duty-cycle 6 % ensures a low thermal load even under the maximum pumping power amplitude 25 W (ceramics samples were only air-cooled). The 80 mm long semi-hemispherical laser resonator consisted of a flat pumping mirror (HR @ 1.85-2.15 um, HT @ 0.78 um) and a curved (r=150 mm) output coupler with a reflectivity of 98 % @ 1.85-2.0 um for Tm:CaF2 laser or 99.5 % @ 2.0-2.15 um for Ho:Tm:CaF2. Tuning of the laser was accomplished by using a birefringent filter (single 1.5 mm thick quartz plate) placed inside the optical resonator at the Brewster angle. The obtained Tm:CaF2 tunability ranged from 1892 to 1992 nm (the maximum output energy 1.8 mJ was reached at 1952 nm for absorbed pumping energy 78 mJ). In case of Tm:Ho:CaF2 laser tunability from 2016 to 2111 nm was reached (the maximum output energy 1.5 mJ was reached at 2083 nm for absorbed pumping energy 53 mJ). Both these material are good candidates for a future investigation of high energy, ultra-short, laser pulse generation.

8959-78, Session PTue

Gain-switched Fe:ZnMgSe laser oscillation under cryogenic temperature

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The bulk Bridgman-grown Fe:ZnMgSe crystals with the various concentrations of Mg was investigated from the spectroscopic and laser properties at cryogenic temperature. The pumping was provided by a Q-switched Er:YAG laser at the wavelength of 2.94 um, energy 5 mJ in 300 ns pulse, repetition rate 1 Hz. Q-switched operation was achieved by the Brewster angle cut LiNbO3 Pockels cell placed between the rear mirror and the Er:YAG laser active medium. The pump radiation was directed into the Fe:ZnMgSe crystal placed inside the LN dewar. The 55 mm long hemi-spherical cavity was formed by a dichroic pumping mirror (T = 78 % @ 2.94 um and R = 100% @ 4.5 um) and a concave output coupler (R = 95 % @ 4.5 um, r = 500 mm). The strong dependence of generated output energy on temperature was observed for both samples. The maximum output Fe:Zn1-xMgxSe laser energy was 220 uJ and 180 uJ (for Mg concentration x=0.19 and x=0.37, respectively) at Q-switched pumping at 80K. The more important is the central emission wavelength of 4.5 um and 4.7 um (for Mg concentration x=0.19 and x=0.37, respectively) at 80 K. The emission wavelength increased to 4.7 um and 4.9 um at 250K (for Mg concentration x=0.19 and x=0.37, respectively). This results show the possibility of longer wavelengths generation in comparison with previously studied Fe:ZnSe active medium. Fluorescence spectra and lifetime of Fe:ZnMgSe in the range from 250K down to 80K were also measured.

8959-79, Session PTue

Spectroscopic studies of Er3+ emission in co-doped phosphate glasses

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Erbium-doped bulk glasses are of high interest to many applications in the defense and medical fields. Current active use of these materials are in amplifiers for optical fiber communications, fiber lasers, LIDAR, and Q-switched, microchip lasers for laser range finding and in bulk solid state lasers. The dominant laser transition for the Er3+ ion is of a three-level nature, from the 4I13/2 metastable manifold to the ground-state manifold, 4I15/2. The transition between these two manifolds is influenced by the local fields generated in the host materials leading to emission wavelengths that may peak somewhere in the 1.53?m – 1.6?m region. Moreover, the three level nature of the transition necessitates high population inversion densities resulting in high pump thresholds and relatively low efficiencies. The Er3+ laser performance in materials, especially in glass, can be enhanced by co-doping with large amounts of Yb3+, thus enabling laser diode pumping of Yb3+near 980 nm. Here, absorption by the Yb 2F5/2 state transfers energy to the 4I11/2 state of Er3+, giving rise to sensitized emission with significant reduction in the absorption length of the gain medium. Aside from Yb, Cr and Ce doping is also used in glasses in order to enhance laser performance.

For the development of future eye-safe laser products, the study reported herein focused on examining the complex interactions between Cr, Ce, Yb and Er. A series of glasses were prepared with varying levels of these dopants. Two different phosphate glasses were utilized as the host glass matrix for the studies completed. The effect of these dopants on the thermal, physical, optical, and laser properties of the host glass compositions are evaluated in detail. Our goal is to understand how the dopant concentrations may be optimized for various laser cavity configurations in order to increase the overall output efficiency in phosphate glasses. Judd–Ofelt analysis [1] was completed on all of the glasses prepared for this study. The intensity parameters are used to determine the radiative decay rates (emission probabilities of transitions) and branching ratios of the Er3+ transitions from the excited-state J manifolds to the lower-lying J? manifolds. The radiative lifetimes of these excited states are determined from the absorption data. Moreover, the Judd-Ofelt results are compared to the McCumber [2] and Reciprocity methods that are also used for calculating laser properties of gain materials. The fluorescence lifetimes of erbium and ytterbium were measured separately and energy transfer efficiencies were calculated.

The main variables that are related in this study are the absorption and emission cross sections at key wavelengths, emission bandwidth and thereby gain coefficient, radiative and excited state lifetimes of the various dopants, and the thermo-mechanical performance of the glass in relation to thermal lensing effects. We show that significant improvement in laser performance can be achieved by utilizing our recent findings.

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8959-80, Session PTue

Multi-annular channel liquid cooled Nd:YAG thin disk laser medium

Jian Mu, Guoying Feng, Huomu Yang, Hong Zhang, Sichuan Univ. (China); Shouhuan Zhou, Sichuan Univ. (China) and North China Research Institute of Electro-Optics (China)

A novel cooling method of multi-annular channel liquid cooling for thin disk laser is proposed. Many other cooling methods proposed by many researchers have a common defect, which is the gain medium within a non-uniform absorbed pump distribution and with a uniform cooling or overall cooling at the same time, naturally caused a result that is the temperature distribution in the gain medium would not be uniform. And the non-uniform distribution of temperature may cause a serious distortion in the gain medium. However, the temperature distribution in the gain medium is getting into uniform utilizing the method of multi-annular channel liquid cooling, which is proved by a numerical model (see in fig 1) using Ansys software.

In the modeling, the distribution of temperature in the medium varies with the changes of the flow rate and temperature of the coolant in each annular channel. A wonderful uniform temperature distribution could be obtained in the gain medium with arbitrary power and profile of pump light by setting a tailored parameter of the coolant in each annular channel. The highest temperature difference in the gain medium with multi-annular channel liquid cooling is much less than that with a uniform cooling (see in fig 2). And the thermal effect has been well suppressed, this method could be a new idea for designing the thin disk laser's cooling system. The experimental test is being carried out.

Conference 8960: Laser Resonators, Microresonators, and Beam Control XVI

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8960-1, Session 1

Nonlinear dynamics of comb generation in optical microresonators *(Invited Paper)*

Tobias Hansson, Daniele Modotto, Stefano Wabnitz, Univ. degli Studi di Brescia (Italy)

The generation of optical Kerr frequency combs using microresonators has attracted much interest, because of their numerous potential applications such as optical clocks, sensing and spectroscopy. Microresonator frequency combs can be theoretically described using two equivalent formalisms. The optical field can either be modeled using coupled mode equations for the slow temporal evolution of each frequency component, or it can be modeled in the time-domain using a two time-scale approach described by a driven and damped nonlinear Schrödinger equation. In this presentation, we consider the nonlinear dynamics of frequency comb generation in microresonators, which in its initial stage can be given a simple interpretation in terms of modulational instability (MI) of the CW pump field. MI in microresonators may also occur in the normal dispersion regime, although only a limited region there exhibits stable soft-excitation comb states. We predict that stable frequency combs and trains of soliton pulses may alternatively be generated in both the normal and anomalous cavity dispersion regimes using a dual-frequency input pump. We also consider the bistable behavior of microresonators in the presence of multiple sidebands. Important qualitative insights into this dynamics of the comb generation, including low-dimensional chaotic regimes, can be obtained by using truncated three or four wave models. The results of the finite mode truncations are compared and found generally to be in good agreement with full numerical simulations. This work was supported by the Cariplo Foundation

8960-2, Session 1

Chip-scale ultrafast solitons and frequency comb mode-locking *(Invited Paper)*

Chee Wei Wong, Shu-Wei Huang, Columbia Univ. (United States); Sylvain Combrié, Thales Research & Technology (France); Pierre Colman, DTU Fotonik (Denmark); Alfredo De Rossi, Technical Univ. of Denmark (France); Chad A. Husko, The Univ. of Sydney (Australia); Lute Maleki, Andrey B. Matsko, OEwaves, Inc. (United States); James F. McMillan, Jinghui Yang, Heng Zhou, Columbia Univ. (United States)

Recent advances in sub-wavelength nanoscale platforms have afforded the control of light from first principles, with impact to ultrafast sciences, optoelectronics and precision measurements. In this talk we will highlight two coherent examples where emerging mesoscopic systems can make a difference. First, we will report our studies of ultrafast solitons on-chip, where we observed the phase-resolved dynamics of Kerr slow-light solitons and Drude carrier dynamics at picojoule levels [Scientific Reports 3, 1100 (2013); Nature Photonics 4, 862 (2010)]. The self-frequency chirp, along with the highly dispersive slow-light band edge in photonic crystals, gives rise to soliton acceleration, suppression of soliton recurrence, as well as Cerenkov radiation dynamics.

Secondly, we will describe recent advances in chip-scale Kerr frequency comb oscillators, where we have recently observed sub-100-fs pulse mode-locking till date. Specifically, coherent mode-locking was observed on-chip in the normal dispersion regime, verified by phase-resolved spectroscopy at sub-100-attojoule sensitivities. The normal dispersion architecture broadens the application space of chip-scale mode-locking and is supported by first-principles coupled mode theory, in remarkable agreement with direct time-domain measurements.

8960-3, Session 1

Two-cycle pulse generation from mode-locked Kerr frequency combs based on an integrated dispersion-flattened micro-resonator *(Invited Paper)*

Lin Zhang, Anuradha M. Agarwal, Lionel C. Kimerling, Jurgen Michel, Massachusetts Institute of Technology (United States)

Microresonator-based frequency combs attract a great deal of research interest in recent years and are promising for achieving on-chip multi-wavelength sources, functional signal processing units, and chip-scale frequency metrology subsystems. In this paper, we show that octave-spanning frequency combs can be generated in dispersion-flattened microring resonators. The resonator is formed by a strip/slot hybrid waveguide, which makes it possible to produce a flat and low dispersion over an octave-wide bandwidth. In our case, anomalous dispersion within 0~20 ps/nm/km is obtained between two zero-dispersion wavelengths at 1150 and 2350 nm, respectively. Such flattened dispersion profiles allow for the generation of mode-locked frequency combs with improved spectral flatness of comb lines, using relatively low pump power (~500 mW). Numerical simulations using the Lugiato-Lefever model show that the generated Kerr combs have a power drop of comb lines as low as 10 dB over an octave-spanning wavelength range. Two-cycle cavity solitons with a pulse width of ~10 fs can be generated on a chip, associated with these octave-spanning spectrally coherent frequency combs, with self-steepening and stimulated Raman scattering taken into account in our simulations. It is shown in this work that the far apart zero-dispersion wavelengths great facilitate the reduction of the comb-line power drop, while maintaining small anomalous dispersion over such a wide bandwidth allows for using a low pump power to generate octave-spanning combs.

8960-4, Session 1

Kerr comb generation from the perspective of spatial dissipative structures *(Invited Paper)*

Aurélien Coillet, Irina V. Balakireva, Khaldoun Saleh, Rémi Henriet, Laurent Larger, Yanne K. Chembo, FEMTO-ST (France)

The theoretical understanding of Kerr combs has been the object of extensive efforts worldwide in the last ten years. Several insights have been provided since then into this problem and have enabled significant progress for the optimization and tailoring of these combs. Here, we investigate the formation of dissipative structures in crystalline whispering-gallery mode disk resonators that are pumped in different dispersion regimes. In the Fourier domain, these dissipative structures correspond to specific types of mode-locked Kerr optical frequency combs. Depending on the sign of the second-order chromatic dispersion and on the pumping conditions, we show that either bright or dark cavity solitons can emerge, and we show these two regimes are associated with characteristic spectral signatures that can be discriminated experimentally. We use the Lugiato-Lefever spatiotemporal formalism to investigate the temporal dynamics leading to the formation of these azimuthal solitons, as well as the emergence of Turing patterns. The theoretical results are in excellent agreement with experimental measurements that are obtained using calcium and magnesium fluoride disk resonators pumped near 1550 nm.

8960-5, Session 1

Microresonator Kerr frequency combs: mean-field model and temporal cavity solitons *(Invited Paper)*

Stephane Coen, The Univ. of Auckland (New Zealand)

Kerr microresonators excited with continuous-wave light to generate broadband frequency combs are the microscopic analogues of passive optical fibre resonators which have been studied for decades with a mean-field Lugiato-Lefever equation. Such a mean-field model is well known to support temporal cavity solitons, i.e. localized dissipative structures that can persist indefinitely in the resonator. As the spectral signature of temporal cavity solitons periodically leaving the cavity is - by virtue of the Fourier theorem - a periodic frequency comb, it is natural to seek a description of Kerr combs in terms of cavity solitons. We will show how the mean-field model provides a very efficient way to compute even octave-spanning Kerr combs. These simulations reveal the role of temporal cavity solitons in the Kerr comb dynamics. In particular, dispersive waves emitted by cavity solitons account for well recognisable spectral features of experimental Kerr combs and the well-known dynamical instabilities of cavity solitons lead to powerful insights into the unstable regimes of Kerr combs, oscillatory and chaotic, which have been reported in the literature. The bifurcation diagram of cavity solitons also reveal that Kerr comb formation will always go first through unstable and turbulent regimes associated with modulational instability. It is the eventual condensation of this turbulent field into cavity solitons and their subsequent interactions which lead to a stable frequency comb. A semi-analytical description of temporal cavity solitons also allows to derive a simple expression for the bandwidth of Kerr combs, which reveals what are the most interesting parameters to optimize.

8960-6, Session 2

Non-Lorentzian pump resonances in whispering gallery optical parametric oscillators

Ingo Breunig, Anni Bückle, Christoph S. Werner, Albert-Ludwigs-Univ. Freiburg (Germany); Karsten Buse, Albert-Ludwigs-Univ. Freiburg (Germany) and Fraunhofer-Institut für Physikalische Messtechnik (Germany)

Whispering gallery resonators (WGRs) combine ultra-high quality factors with small mode volumes and flexible in- and out-coupling of light. They can be fabricated from non-centrosymmetric crystalline materials. Thus, efficient frequency converters based on second-order nonlinear-optical effects such as optical parametric oscillation can be realized using WGRs, providing monolithic sources for tunable coherent light. The most convenient way to characterize these devices is to scan the pump frequency across a cavity resonance and to measure simultaneously the power of the transmitted pump light as well as those of the generated light fields. Several experiments have revealed that during optical parametric oscillation the pump resonance strongly differs from a Lorentzian shape.

Here, we theoretically and experimentally analyze these line-shape distortions. We extend previously published analytical descriptions in order to account for non-resonant pump light. The predictions made by our model are verified experimentally: It turns out that the line-shape of the pump resonance strongly depends on the coupling strength of the pump light and on the loss ratio between generated light and pump light. The line-widths, i.e. the losses, for the light generated by the parametric process, can be gained without measuring them directly. Our model is not only useful for understanding and characterizing whispering gallery optical parametric oscillators, but also for the active stabilization of these devices.

8960-7, Session 2

Multicolour emission in silica whispering gallery mode microspherical resonators *(Invited Paper)*

Gualtiero Nunzi Conti, Istituto di Fisica Applicata Nello Carrara (Italy); Daniele Farnesi, Museo Storica della Fisica e Ctr Studi e Ricerche Enrico Fermi (Italy); Andrea Barucci, Simone Berneschi, Istituto di Fisica Applicata Nello Carrara (Italy); Giancarlo C. Righini, Museo Storica della Fisica e Ctr Studi e Ricerche Enrico Fermi (Italy); Silvia Soria, Istituto di Fisica Applicata Nello Carrara (Italy)

High quality factor whispering gallery mode microresonators are ideally suited for nonlinear optical interactions. We demonstrate a variety of nonlinear interactions in silica microspheres, consisting in third harmonic generation and Raman assisted TSFG in the visible. A tunable, CW multicolour emission in silica microspheres has been quantitatively measured controlling the cavity mode dispersion by choosing suitable sized microspheres and exciting the proper modes for efficient frequency conversion.

8960-8, Session 2

Quantum correlations in silicon nitride cavities *(Invited Paper)*

Michal F. Lipson, Cornell Univ. (United States)

We demonstrate quantum correlations between signal and idler modes of an on-chip silicon nitride OPO with ultra high quality factor

8960-9, Session 2

Phase-matching and polarization in on- and off-axial uniaxial whispering gallery mode resonators *(Invited Paper)*

Harald G. L. Schwefel, Max-Planck-Institut für die Physik des Lichts (Germany)

Phase-matching is a natural requirement for efficient non-linear conversion in all optical chi(2) processes. Whispering gallery mode (WGM) resonators made of such materials, for example lithium niobate, have been demonstrated to exhibit extremely high conversion efficiencies given that phase matching conditions are fulfilled.

Mostly, such resonators are z-cut, where the optic axis coincides with the symmetry axis of the resonator. Although exploiting birefringence can compensate dispersion, nonlinear gain can only be achieved in a small wavelength regime, which can be slightly tuned via the crystals temperature. However, by carefully taking into account the geometrical dispersion of the modes, it can be shown that the process tolerates stronger deviation in terms of wavelength than one might expect for collinear phase matching in bulk crystals. This is especially true for SFG/DFG between frequencies far apart from each other like optical and microwave domain. A rather new approach for ultra-broadband nonlinear conversion in WGM resonators uses the so called x-cut or, more general, angle-cut configuration. Here, the optic axis is tilted by up to 90° against the optic axis, giving rise to novel modal structures in terms of their polarization. In these systems one of the modes (the extraordinary one) experiences a varying index of refraction while the light is travelling along the equator of the resonator. Such index modulation allows for partial phase matching between differently polarized modes over an extremely broad wavelength interval, while keeping the conversion efficiency at a reasonable level due to the high Q factors of the WGM resonator. We show recent results for the latter two schemes.

8960-10, Session 3

Brillouin cavity optomechanics with microfluidic devices *(Invited Paper)*

Gaurav Bahl, Univ. of Illinois at Urbana-Champaign (United States); Kyu H. Kim, Univ. of Michigan (United States); Kewen Han, Univ. of Illinois at Urbana-Champaign (United States); Wonsuk Lee, Jing Liu, Xudong Fan, Tal E. Carmon, Univ. of Michigan (United States)

Cavity optomechanical devices (resonant in both optical and mechanical domains) have been demonstrated to allow the parametric excitation and cooling of mechanical vibration, by exploiting radiation pressure, gradient force, and electrostrictive Brillouin scattering. Optomechanical systems have till date only operated in dry environments. Here we describe a new class of optomechanical devices that enable the coupling of light with mechanical and microfluidic systems. We confine test liquids inside hollow microfluidic optomechanical resonators and show that ultra-high optical quality factors are preserved, and that we can optically actuate high-Q mechanical modes of the liquid-filled resonator.

Mechanical whispering-gallery modes (WGMs), composed of surface acoustic waves traveling at the speed of sound, can be generated by means of electrostrictive stimulated Brillouin scattering. Briefly, light from a (pump) optical WGM directly actuates an acoustic WGM via optical electrostriction. At the same time photoelastic scattering generates a second optical signal (Stokes). The beat note of the pump and Stokes optical signals obtained on a high-speed photodetector is a direct measure of the mechanical vibration. We infuse the devices with distilled water and sucrose solutions and observe that mechanical vibrations are sustained even with high-viscosity analytes. These capillary optomechanical resonators can operate on sub-picoliter analytes and may be useful for biological sensing applications, by providing a new acoustic-sensing `degree of freedom' for optical sensing experiments.

Citation: G. Bahl, K. H. Kim, W. Lee, J. Liu, X. Fan, T. Carmon, “Brillouin cavity optomechanics with microfluidic devices,” Nature Communications, 4:1994, doi:10.1038/ncomms2994, 2013.

8960-11, Session 3

Direct spectral and temporal control of the resonant optical propulsion of dielectric microspheres in evanescent fiber couplers

Yangcheng Li, The Univ. of North Carolina at Charlotte (United States); Alexey V. Maslov, Univ. of Nizhni Novgorod (Russian Federation); Ana M. Jofre, Vasily N. Astratov, The Univ. of North Carolina at Charlotte (United States)

The giant resonant optical forces on microspheres have been observed recently [1], however these forces have been difficult to control because whispering gallery modes (WGMs) have random spectral position in size-disordered microspheres. In this work, we realized a direct control of the spectral detuning between WGMs in microspheres and laser emission line. This was achieved based on a combination of ultrahigh resolution spectroscopy and optical tweezers manipulation of microspheres in fiber-taper integrated microfluidic platforms. Our results confirm the existence of extraordinary high force peaks with the magnitude determined by the total momentum flux of the fiber mode. We proved that the spectral shape of the force peak correlates with the corresponding dip in the transmission spectrum. These observations are found to be in a very good agreement with our resonant propulsion theory [2]. By studying temporal dependence of the fiber transmission power for resonant propulsion events we demonstrated the existence of a stable radial trap in the course of propelling microspheres over millimeter-scale distance. We also established a correlation between the instantaneous velocity of microsphere and the fiber transmission power which was attributed to variations of the microsphere-to-fiber distance. Our results form the basis for sorting resonant microspheres on a massive scale which can lead to development of new technology in microspherical photonics.

[1] Y. Li, et al., “Giant resonant light forces in microsphericalphotonics,” Light: Science & Applications 2, e64 (2013)

[2] A. V. Maslov, et al., “Resonant propulsion of a microparticle by a surface wave,” Phys. Rev. A 87, 053848 (2013)

8960-12, Session 3

Resonant enhancement of optical forces associated with the excitation of whispering gallery modes in microparticles *(Invited Paper)*

Alexey V. Maslov, Michael I. Bakunov, Univ. of Nizhni Novgorod (Russian Federation); Yangcheng Li, Vasily N. Astratov, The Univ. of North Carolina at Charlotte (United States)

We developed a theory of resonant trapping and propulsion effects in microspherical photonics based on rigorous treatment of Maxwell’s equations [1]. The theory establishes the balance of the electromagnetic momentum flow in the system. The extraordinary high values of the resonant forces observed in recent experiments [2] are explained as a result of the efficient momentum transfer from the initial surface wave to the force on the microparticle. Near the resonance the transverse optical force can be attractive or repulsive depending on the particle-to-surface distance, particle size, and operating frequencies. The transverse force can significantly exceed the value of the propelling force. We show that the nature of optical trapping near the metallic surfaces is connected with a spectral shift of the resonant force peak with the particle-to-surface distance. Our results are found to be in a qualitative agreement with optical trapping and propulsion experiments performed with polystyrene microspheres in the vicinity of tapered water-immersed tapered microfibers [2]. Similar to the excitation of WGMs by surface waves, strong propulsion effects are also predicted to arise from the excitation of WGMs by optical beams in free-space. We obtain a significant enhancement of forces depending on the focusing of the beam as compared to that from plane waves. This work lays out the foundations for resonant microspherical photonics, a new technology which allows sorting of resonant microspherical building blocks on a massive scale.

[1] A. V. Maslov, V. N. Astratov, and M. I. Bakunov, “Resonant propulsion of a microparticle by a surface wave,” Phys. Rev. A 87, 053848 (2013)

[2] Y. Li, O. V. Svitelskiy, A. V Maslov, D. Carnegie, E. Rafailov and V. N. Astratov, “Giant resonant light forces in microspherical photonics,” Light: Science & Applications 2, e64 (2013)

8960-13, Session 3

Flexible microresonators: lasing and sensing

Van Duong Ta, Rui Chen, Handong Sun, Nanyang Technological Univ. (Singapore)

Microresonators have drawn a great deal of interest for their importance in both practical applications and fundamental physics in light-matter interaction. The optical confinement provided by a microresonator greatly enhances the interaction between optical spatial mode and the light emitting materials. Conventional fabrication of microresonators adopting semiconductor processing technology (no matter top-down or bottom-up approach) still faces some challenges. Here we report the feasibility of constructing solid state microresonators with various configurations including spheres, hemispheres and fibres from organic polymer in a flexible way. We realize optically pumped lasing from these structures after incorporating organic dye materials and/or colloidal quantum dots into the resonators. The lasing characteristics have been systematically examined in terms of size dependence, temperature dependence and polarization. The longitudinal optical modes are well defined by WGM lasing. We are also able to tune the resonance modes by deforming the shape of micro-spheres, representing the facile manipulation of light-

matter interaction. Finally refractive index sensing with high sensitivity can be readily realized from these structures enabled by the existence of evanescent waves and improved by Vernier effect in coupled resonators.

8960-14, Session 4

Challenges in resonant cavity biosensor design: collection efficiency and specificity *(Invited Paper)*

Andrea M. Armani, Simin Mehrabani, Victoria Sun, Samantha McBirney, Rasheeda M. Hawk, Eda Gungor, Michele Lee, The Univ. of Southern California (United States)

Resonators are an ideal platform for high sensitivity detectors. In past work, by monitoring a resonant frequency or photon lifetime change, they have been used to detect the presence of analytes and binding kinetics. More recently, they have been used to create a cavity-based laser, and lasing wavelength is monitored. However, in all experiments, while significant effort is placed on optimizing the device sensitivity, the specificity and the collection efficiency were somewhat overlooked. These parameters are equally important. A high collection efficiency can balance a poor sensitivity in many applications. Additionally, a very accurate specificity is critical to ensure a low number of false positive and false negative readings.

To improve the collection efficiency, it is necessary to transition from relying on diffusion to leveraging directed fluid flow. Additionally, the devices should be placed in the region of highest fluid flow. To optimize specificity, appropriate targeting analytes should be covalently attached to the surface of the device. While there are a range of biological moieties to choose from, such a biotin and antibodies, there is also a wide range of synthetic options, such as reactive polymers.

In the present work, we will discuss techniques to improve collection efficiency and methods to attach biological and polymeric targeting elements. We will discuss several of the COMSOL 3D Multiphysics simulations which incorporate fluid flow, mass transfer and binding kinetics. We will also discuss several of the recently developed biological and chemical targeting strategies and representative detection experiments.

8960-15, Session 4

Detection of single nanoparticles and lentiviruses using microcavity mode broadening *(Invited Paper)*

Yun-Feng Xiao, Linbo Shao, Xue-Feng Jiang, Qihuang Gong, Peking Univ. (China); Frank Vollmer, Max-Planck-Institut für die Physik des Lichts (Germany)

Long intracavity photon lifetimes and strong light confinement of the whispering gallery mode (WGM), described by high quality factors (Q) and small mode volumes (V) respectively, enhance light-matter interactions in optical microcavities, and show therefore a promise for ultrasensitive biosensing applications. Binding of polystyrene (PS) nanoparticles, viruses, DNA oligonucleotides and proteins on microcavities has been successfully detected by essentially monitoring either the resonance wavelength shift or the nanoparticle scattering-induced mode splitting. However, environmental thermal noise and unintended frequency drift of the probe laser hinder detection limit by monitoring the resonance wavelength shift, while the hardness in fabrication of ultra-high-Q modes supported microcavities, typically approaching or even exceeding 10^8, not only restricts the material of microcavities to silica, but also hinders the real sensor application.

Here, we report a new detection, that is monitoring nanoparticle-scattering-induced mode broadening in a free-space-coupled deformed microcavity, which would remove the strict requirement concerning ultra-high-Q mode cavities, while still remaining reliable and sensitive. With this advantage, large quantity production of microcavities in practical applications is therefore promised, and biocompatible materials, such as polymers, can be used in fabrication.

8960-16, Session 4

Spherical optical microresonator array as a multi-purpose measuring device

Thomas Weigel, Henrik Dobbelstein, Cemal Esen, Gustav Schweiger, Andreas Ostendorf, Ruhr-Univ. Bochum (Germany)

Optical resonances of spherical microresonators, also known as whispering gallery modes, are of great interest for high sensitivity measurements. Such particles can be used for the determination of concentration, temperature, pressure, force or strain. The quantity to be measured influences the position of the resonances. The standard experimental technique is to place the resonator in close proximity to a single mode light guiding fiber. Light of a tunable narrow band laser is coupled into this fiber and the transmitted light is recorded. Unfortunately, for this purpose, an expensive low-bandwidth tunable laser system with high accuracy is needed. The resonance position depends also on the size of the particles. When applying laser light with a distinct wavelength on an array of microresonators with slightly different sizes, only a part of the particles are in resonance. A change of the quantity to be measured by the resonator array changes the resonance properties of each particle and so the intensity distribution over the whole array. Therefore, using a microresonator array it is sufficient to measure the intensity distribution over all particles at a fixed wavelength. The change of this distribution as function of the change of the quantity to be measured is evaluated. No expensive tunable laser is necessary. Here, we demonstrate that pressure and temperature can be measured successfully using a microresonator array.

8960-17, Session 4

Optimization of whispering gallery modes in microbubble resonators for sensing applications

Jonathan M. Ward, Yong Yang, Síle G. Nic Chormaic, Okinawa Institute of Science and Technology (Japan)

Recently developed Liquid Core Optical Ring Resonator (LCORR) sensors are a kind of hybrid micro resonators, i.e. they are multi layered. In this paper we discuss a relatively new type of LCORR, namely the microbubble resonator. The micorbubble is a thin spherical shell made from a fused silica micro capillary by locally heating with a CO2 laser while at the same time pressurizing internally. By controlling the CO2 laser heating zone, a spherical exterior shape can be achieved with a controllable wall thickness. LCORR have proven to be good candidates for sensing liquid properties, since evanescent light can penetrate into the liquid in the interior core area. However most of the WGM energy is still propagating in the shell structure thus high Q is maintained. Sensitivity can be increased by making the shell thinner thereby increasing the intensity of the WGM in the liquid core. However when the shell thickness is around one wavelength or less, light can easily tunnel out, causing the resonant line width to broaden, which limits the total resolution. Therefor a trade off should be achieved by certain shell thickness in a fixed size microbubble. So far this optimization of microbubble resonators has not been reported. In this paper, the dependence of Q on diameter and shell thickness is obtained from numerical simulations and the geometrical parameters for high resolution sensing are optimized. Three types of sensing applications are discussed (pressure, refractive index and particle sensing) and it is shown that ultrahigh sensitive can be achieved.

8960-18, Session 4

Multi-layered resonators for improved electric field detection

Tindaro Ioppolo, M. Volkan Ötügen, Southern Methodist Univ. (United States)

In this study, we carry out an analytical investigation to determine the efficacy of multi-layer dielectric micro-sphere resonators as high-resolution electric field sensors. The use of a large number of layers with different electrical and mechanical properties allows for optimum dielectric constant and elastic modulus gradients within the sphere to maximize sphere resonator's sensitivity to external electric field. The external electric field applied to a dielectric sphere induces an elastic deformation of the resonator (electrostriction effect), leading to shifts in its whispering gallery optical modes (WGM). The non-uniform distribution of the dielectric constant leads to a gradient in the electric field within the sphere. This in turn induces non-uniform body force on the sphere when subjected to an external electric field. By also appropriately varying the elastic modulus of the layers, the electrostictive deformation of the sphere can be maximized. In the full paper we will present the results of a mathematical model describing the effect of the electric field on the WGM shift of layered micro-spherical resonators.

8960-19, Session 5

Simplified hollow-core microstructural optical fiber laser with intense output and polarized radial emission

Zhi-Li Li, Wen-Yuan Zhou, Yan-Ge Liu, Min Yan, Jian-Guo Tian, Nankai Univ. (China)

Optofluidic based microcavity lasers are of particular interest for integration devices?with their characteristic of tunable emission spectrum, ultrahigh-Q, ultralow-threshold and a small footprint. We introduce a novel simplified hollow-core microstructural optical fiber (SHMOF) laser with intense output and purely polarized radial emission. The SHMOF comprises a large hexagonal core with six surrounding crown-like air holes. The microfluidic channel is composed of a nearly cylindrical center hole of the SHMOF, which is made by selectively blocking off other holes of the SHMOF. The fiber core formed cavity which filled with a microfluidic gain medium (Rhodamine 6G) plug was lateral pumped by a 532nm nanosecond pulse laser. Compared with axially pumping way, the side-pumping scheme has more flexible means and more loose condition without precision free space to fiber coupling. For pump energy at threshold as low as 80 nJ/pulse, single mode laser oscillation was observed at about 570 nm. And when pump energy was added to a higher value above the threshold, an intense output of a unique radiating field pattern characterized by cylindrical symmetry emerged in the azimuthal direction of the fiber. The explanation of this result lies in the particularity structure of the SHMOF in our experiment. Fiber's silica nanowire ring surrounding the hollow core plays the role of an antiresonant reflecting optical wave-guide. That allows most pump light conducted in the structure transmitting in the form of evanescent wave, which is coupled into the gain medium in the center hole. Based on evanescent-wave-coupled gain, the stimulated and amplified fluorescences express a strong resonance in the hole, which lead to the generation of single mode laser emission. This attractive capability of realizing the microfluidic gain medium laser within a single SHMOF, presents opportunities in fiber laser array composed microsystems and fluorescence signal amplification for chemical and biological analysis.

8960-20, Session 5

Multiphoton excitation of organic chromophores in microbubble capillary resonators

Gregory A. Cohoon, Khanh Q. Kieu, Robert A. Norwood, College of Optical Sciences, The Univ. of Arizona (United States)

We report the observation of multiphoton excitation of organic chromophores in microbubble whispering gallery mode resonators. The high-Q microbubble resonators are fabricated from 80?m outer diameter and 50?m inner diameter fused silica capillaries. The capillaries are slightly pressurized and heated using the arc from a fusion splicer. This forms the hollow bubble shape which can then be filled with liquid or gas for interrogation. Microbubbles fabricated in this manner and used in this paper have diameters ranging from 200 to 300?m and a wall thickness of 2 to 6?m .The whispering gallery modes of the microbubble resonators are excited in the conventional method using tapered optical fiber (made from Corning HI1060) and show an average Q-factor of 10^6. A 5x10^-3M solution of Rhodamine 6G dye is prepared in ethanol and injected into the microbubble. Throughout the experiment dye is flowed through the system. The resonator-dye system is excited by coupling light from a 980nm laser diode into the resonator. The light in the resonator interacts with the dye and produces a bright two-photon fluorescence signal centered at 530nm which is detected using a spectrum analyzer. The two photon fluorescence signal is present and visible by the naked eye at CW pump powers as low as 5mW.

8960-21, Session 5

High-Q plasmonic bottle microresonators

Mohd Narizee Bin Mohd Nasir, Ming Ding, Ganapathy Senthil Murugan, Michalis N. Zervas, Univ. of Southampton (United Kingdom)

Surface Plasmon Waves (SPWs) supported by thin metal films have been used to implement high performance surface sensitive devices, such as refractometric and biochemical sensors. Recently all-glass bottle microresonators (BMRs), supporting whispering-gallery modes (WGM), have been studied in-depth with the intention to be used in advanced photonic applications, such as CQED, nonlinear devices and miniaturized sensors. In this work, we combine the two structures and demonstrate the first hybrid plasmonic BMR (PBMR). A gold layer has been deposited on the top surface of a glass BMR, fabricated by the "soften-and-compress" technique. We developed a polarization-resolving measurement set-up to fully characterize fabricated PBMRs. The uncoated BMR had 181?m waist diameter, 125?m stem diameter and 400?m length. Due to the surface curvature the gold film covered only the top BMR half with a characteristic meniscus shape with maximum thickness of 30nm. The meniscus provides appropriately tapered edges, which facilitate the adiabatic transformation of BMR WGMs into SPW and vice-versa. This results in low transition losses, which combined with partially-metal-coated resonator, can result in high hybrid-PBMR Q's.

The transmission spectra of the hybrid PBMR are dramatically different to the original uncoated BMR. Under TE(TM) excitation, the PBMR showed composite resonances with Q of ~2100(850) and almost identical ~3nm FSR. We have accurately fitted the observed transmission resonances with Lorentzian-shape curves and showed that the TE/TM composite resonances comprise two/three partially overlapping resonances with Q's in excess of 2900 and 2500, respectively. These are the highest Qs observed in plasmonic microcavities.

8960-22, Session 5

Level-repulsion in hybrid photonic plasmonic resonators: enhancing WGM biosensing *(Invited Paper)*

Frank Vollmer, Matthew R. Foreman, Martin Baaske, Max-Planck-Institut für die Physik des Lichts (Germany)

Combination of optical microresonators with metallic nanoparticles (NPs), supporting localized surface plasmons, has recently attracted much attention, due to the opportunities it affords in e fficient light routing, field confinement and enhanced whispering-gallery mode (WGM) biosensing. We study theoretically as well as experimentally the hitherto overlooked phenomenon of level repulsion when coupling high Q optical microcavities and plasmonic NPs. The results are important for WGM biosensing where large reactive coupling to plasmonic NPs results in detectable WGM frequency shifts, and maximizing near field enhancements of the resultant mode are necessary to achieve single molecule detection. We will also illustrate how DNA nanotechnology can be utilized to improve specificity in plasmon enhanced WGM biosensing.

8960-23, Session 5

Interfacing whispering gallery mode microresonators for environmental biosensing *(Invited Paper)*

Heather K. Hunt, Jeremy L. Dahmen, Univ. of Missouri-Columbia (United States); Carol E. Soteropulos, Univ. of Missouri (United States)

Label-free biosensors that combine high sensitivity and high specificity characteristics have shown tremendous potential for applications in medical diagnostics, and have more recently been extended to the food safety and environmental monitoring arenas. A unique type of label-free, optical biosensor, based on Whispering Gallery Mode microresonators, has tremendous potential to revolutionize biodetection due to its extreme sensitivity. The primary limitation of these biosensors, however, is that they require the addition of biorecognition elements to specifically target a biological species of interest. Therefore, the ability to selectively functionalize the microresonator for a specific target molecule, without degrading device performance, is extremely important, and represents the next step in translating these devices from laboratory to field environments. Here, we demonstrate a variety of straightforward bioconjugation strategies that not only impart specificity to optical microresonators, but also allow for the creation of multi-use platforms for complex environments. Of particular interest is the ability to detect harmful bacteria, insects, and fungi in crop and water systems. The resulting surface chemistries are illustrated with XPS, SEM, and fluorescence and optical microscopy, and the device sensitivity is determined via quantitative microcavity analysis. The ability to minimize non-specific adsorption and target unique molecules in complex environments is demonstrated via ellipsometry and in situ device testing. The resulting devices can be recycled several times without loss of sensitivity. By combining these high sensitivity biosensors with appropriate biochemistries, the resulting platforms can be extended to address broader issues in environmental biosensing that directly impact agriculture.

8960-24, Session 5

Microcavity optics with high Q micro-bottle resonators *(Invited Paper)*

Lei Xu, Fudan Univ. (China)

High Q whispering gallery mode resonators have shown significant potential as micro-optical devices for optical nonlinearity, ultralow threshold lasers and optical nonlinearity generation, optical buffers and modulators for optical communications, extremely low detection limit for bio and nanoparticle sensing and new research era such as optomechanics. Many types of high Q resonators have been explored, such as spheres, toroids, capillary tubes, as well as many on-chip devices.

Micro-bottle resonator is a special type resonator. It is formed from capillary tube but has better optical field confinement, on the other hand, it still keeps its ability to allow optofluidics experiments to be carried out. In addition to its radius, the wall-thickness, the bottle shape are other dimensions that can be engineered for special purposes. We fabricated thin-wall micro-bottles by blowing bobble from capillary tubes. The micro-bottle resonator formed has very high Q value around 5?107.

Our first experiment is optical comb generation from micro-bottle resonators. Optical comb generation requires both energy and momentum conservations. Since whispering gallery mode resonant frequency is not equally spaced, energy conservation requires special dispersion engineering. We found that in micro-bottles, the thickness of the bottle can be used to tune the resonator dispersion, as a result, optical comb is successfully generated in micro-bottles, meanwhile, comb is not allowed in the same size sphere resonators.

Next, we realized an ultralow detection limit sensor in micro-bottle resonator by using differential mode sensing scheme. By using two resonators in the same resonator, one as the sensing mode and the other as the reference mode, we successfully suppress both low frequency noises (coming from laser frequency drift and thermo drift) and high frequency noises (coming from vibrational noises) and reach an ultralow detection limit of 8.3 fg/ml (~0.13 fM) for BSA molecules.

Finally we carried out optomechanics experiment by using micro-bottle resonators. various mechanical modes can be selected by exciting different families of optical modes. With different liquids contained inside the device, these mechanical modes can be tuned and have different sensitivities. At last, with the benefit of thin wall, the optical and mechanical modes of the MBR are monitored at the same time, and a 2-D sensor for microfluidics is obtained.

8960-25, Session 6

Recent explorations in whispering gallery microcavities for functional devices

Sahin Kaya Ozdemir, Bo Peng, Jiangang Zhu, Faraz Monifi, Huzeyfe Yilmaz, Obi Kenechukwu, Steven H. Huang, Xu Yang, Lan Yang, Washington Univ. in St. Louis (United States)

Whispering-Gallery-Mode (WGM) optical microcavities have attracted lots of attentions for their superior capabilities to significantly enhance light-matter interactions, which are attributed to their microscale mode volumes and ultra-high-quality factors. They have shown great promise for a variety of fields of science, spanning from atom-cavity coupling and optomechanics to on-chip microcavity lasers and ultra-sensitive label-free bio-chemical sensing. In this talk, after briefly introducing the physical concepts and milestone works using WGM microcavities, I will report recent progress in our group towards developing functional platforms using single and coupled high-Q WGM microcavities (photonic molecules) and microlasers for detecting and measuring nanoscale structures and biomolecules with detection limits lower than many other existing optical techniques. I will present a process to encapsulate a fiber taper coupled chip-scale high-Q WGM resonator in a low refractive-index polymer. I will also discuss exploring fundamental physics, such as parity-time symmetry and light-matter interactions in high-quality WGM resonators, which can be used to achieve a new generation of optical systems enabling on-chip manipulation and control of light propagation.

8960-26, Session 6

Real-time measurement of the dynamic response of a microresonator *(Invited Paper)*

Jong H. Chow, The Australian National Univ. (Australia); Malcolm B. Gray, National Measurement Institute of Australia (Australia)

We demonstrate real-time and simultaneous measurement of dispersion and dissipation dynamics of a whispering gallery mode (WGM) microresonator for detecting nanoparticles. Microresonators are increasingly being used for cavity-enhanced optical sensing. Typically this is enabled by the interaction between the evanescent field and a particle at or near the microresonator surface. Due to the small modal volume of these resonators, a single molecule or nanoparticle can cause significant changes in a) intra-cavity loss due to dissipation, and b) optical path length due to dispersion.

We use two highly sensitive and complementary radio-frequency laser modulation methods to obtain this complete real-time response of the microresonator. For detecting optical path length changes, we use the well-established Pound-Drever-Hall (PDH) frequency locking technique. For the measurement of cavity losses, we use the recently developed cavity-enhanced amplitude modulation laser absorption spectroscopy (CEAMLAS) technique. The PDH technique is used for detecting minute resonance frequency detuning, while CEAMLAS measures changes in resonator coupling. The simultaneous use of these two techniques enables the measurement of complementary nanoparticle features: PDH determines the volume-refractive index product of the particle while CEAMLAS measures the particle scattering cross section. We show that dissipative sensing allows up to 16.8 dB improvement in resolution over dispersive measurements alone. This promises enhanced sensitivity in future applications such as biomolecule detection.

8960-27, Session 6

Optically pumped gold nanorod plasmonic microlaser

Ce Shi, Soheil Soltani, Andrea M. Armani, The Univ. of Southern California (United States)

Whispering gallery mode optical resonators are able to store light inside the device in circulating orbits for long periods of time. As a result, high optical field intensities build-up inside the cavity, making them an ideal platform for the development of nanolasers. This system has been used to create laser devices based on rare earth and quantum dot gain medium; however, the combination of metal nanoparticles with microcavities to create a laser has yet to be studied. Previous research using nanorods deposited on a coverslip has demonstrated that gold nanorods exhibit two-photon emission when illuminated with a high power laser. However the emission is very broad, covering hundreds of nanometers, and this platform is not feasible for a true on-chip microlaser design. In the present work, a microlaser based on hybrid silica microtoroid resonant cavity coated with gold nanorods are theoretically modeled and experimentally demonstrated. Through 3-D COMSOL Multiphysics finite element method simulation, the interaction between the optical mode of the resonator and the surface plasmon resonance of the gold nanorod is modeled both on and off resonance. We also experimentally demonstrate a nanorod microlaser fabricated by conformally coating a microtoroid device with a polymer-nanorod film. The nanorod geometry is optimized such that the longitudinal mode overlaps with the resonance wavelength of the microtoroid. We successfully demonstrated a visible laser at 581nm with 20?W-threshold and an approximately 1nm linewidth.

8960-28, Session 6

Heterodyning cavity-based microlasers to improve sensing performance

Ashley J. Maker, Andrea M. Armani, The Univ. of Southern California (United States)

Due to their narrow linewidth lasing peaks, microlasers based on whispering gallery mode optical resonators are becoming increasingly useful in sensing applications. Changes in the microlaser's environment cause the lasing wavelength to shift, enabling detection with high resolution. However, the performance of these devices is often limited by the optical spectrum analyzers used in detection experiments, which lack the speed and sub-picometer resolution needed to measure small changes in the microlaser's output.

One promising approach to overcome this limitation is heterodyning the microlaser's output. In the present work, we successfully heterodyne a microlaser sensor based on a neodymium-doped silica toroid platform pumped at 765nm. Combining the microlaser's 1064nm emission with a 1064nm reference laser produces an easily detectable low frequency beat signal. Monitoring the beat frequency on an electrical spectrum analyzer (ESA) enables wavelength shifts to be detected with high speed and sub-picometer resolution.

As a proof of concept, temperature sensing experiments are performed by tracking the beat frequency as the microlaser is heated. To directly determine the improvement in sensitivity and signal to noise, comparison experiments are also performed by tracking the resonant wavelength and lasing wavelength. We experimentally show that heterodyning improves the microlaser's detection limit, signal to noise, and time resolution by as much as 50-fold compared to the non-heterodyned laser approaches. Narrowing the microlaser's linewidth and reducing noise could increase this enhancement even further. Therefore, heterodyning will significantly benefit both the performance of microlaser sensors and their many applications.

8960-29, Session 7

UV laser line for semiconductor surface processing

Lisa Kleinschmidt, Vyacheslav Grimm, Mikhail M. Ivanenko, Alexei Krasnaberski, Vitalij N. Lissotschenko, LIMO Lissotschenko Mikrooptik GmbH (Germany)

In the last years we have developed a family of ultra-narrow laser lines with green DPSS lasers as sources. These lines are very useful tools for the crystallisation of thin Si layers for AMOLED displays and other applications in microelectronics. However, novel lift-off technologies for flexible displays and high brightness LEDs require a stronger light absorption, which is attainable at shorter wavelengths. Thus the laser lines in the UV-range with lengths from a few up to a several hundred mm, line widths from 10 to 30 µm and long depth of focus are well suited for these applications. A low cost of ownership is important; it can be provided with further development of UV DPSS lasers with an extended lifetime.

We consider general optical concepts for shaping ultra-narrow lines with multi-mode UV lasers. Especially two different optical designs are presented; each provides a line length of 100 mm with an inhomogeneity below 2.5 %, but different line widths of 10 µm and 32 µm. Both designs are based on a micro-optical anisotropic beam transformation technique, which affords strong focusing with a large depth of focus (DOF). At the 3% intensity variation level the DOF is 100 µm for the 10-µm line and 1000 µm for the 32-µm line. The large working distance of 100 mm is a further system advantage. In addition concepts for up to 750 mm long lines are reviewed, whereas several lasers are coupled.

8960-30, Session 8

Efficient optical design and measurement technique to realize six sigma laser processing

Michael J. Scaggs, Gilbert J. Haas, Haas Laser Technologies, Inc. (United States)

A six sigma laser processing system is proposed that utilizes real time measurement of ISO 11146 and ISO 13694 laser beam parameters without disrupting the process beam and with minimal loss. If key laser beam parameters can be measured during a laser process, without a disruption to the process, then a higher level of process control can be realized. The difficulty in achieving this concept to date is that most accepted beam measurement techniques are time averaged and require interruption of the laser beam and therefore have made it impractical for real time measurement which is necessary to consider six sigma process control.

Utilizing an all passive optical technique to measure a laser's beam waist and other parameters for both focused and unfocused beams, the direct measurement of the ISO laser beam parameters are realized without disruption to the process and with minimal loss. The technique is simple enough to be applied to low and high power systems well into the multi-kilowatt range. Through careful monitoring of all laser beam parameters via software control of upper and lower limits for these parameters, tighter quality control is possible for achieving a six sigma process. In this paper we describe the optical design for both low and high power laser systems and how six sigma laser processing may be realized.

8960-31, Session 8

Active wavefront control in Hilase multislab high-average-power laser system

Jan Pilar, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Stefano Bonora, Univ. degli Studi di Padova (Italy) and Institute of Physics of the ASCR, v.v.i. (Czech Republic); Ondrej Slezák, Antonio Lucianetti, Tomás Mocek, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

The next generation of high-average-power laser systems is counting on new active materials capable of sustainable amplification and new geometries offering higher surface to volume ratio, allowing efficient cooling during the operation. One of the main challenges in such laser systems is the suppression of the thermal effects induced by the high-average-power nature of the amplified laser beam.

Hilase project is developing a cryogenically cooled Yb:YAG laser system based on multi-slab geometry. The laser system will deliver pulses providing 100 J at 10 Hz repetition rate. We present an adaptive optics system for active wavefront correction of the first stage amplifier capable of generating 100 W of average output power with transverse dimensions of 20 mm x 20 mm. This first stage amplifier operation was simulated numerically emphasizing wavefront distortions. Based on these simulations, wavefront aberration demonstrator was assembled in the laboratory. The adaptive mirror was subsequently used for the wavefront correction. The results of this experiment will be compared with numerical simulations.

8960-65, Session PTue

Analysis of a right angle conical reflector resonator by the transfer matrix method

Dongxiong Ling, Hongcheng Wang, Dongguan Univ. of Technology (China)

A resonator with a right angle conical reflector has been proposed to produce high power CO_2 laser beams. To analyze eigenfields of the right angle conical reflector resonator, this paper adopts and demonstrates the transfer matrix method. In this paper the mode-fields and corresponding losses are described as eigenvectors and eigenvalues of a transfer matrix according to the self-reproducing principle of laser field. By solving the transfer matrix for eigenvectors and eigenvalues, we obtain field distributions and losses of the dominant eigenmodes. The calculation results reveal that the right angle conical reflector resonator could be used for a high power CO_2 laser to achieve low-order modes. However, the beam quality is reduced due to the residual blind-hole, which is in accord with the experimental result.

8960-66, Session PTue

Investigation of the low power stage of a 1178nm Raman system

Leanne J. Henry, Air Force Research Lab. (United States); Michael Klopfer, The Univ. of New Mexico (United States); Cody Mart, University of Arizona (United States); Jacob Grosek, Air Force Research Lab. (United States); Ravinder K. Jain, The Univ. of New Mexico (United States)

There is interest in frequency doubling a 1178 nm narrow linewidth fiber laser source for sodium guidestar laser applications. Briefly, a 1178 nm seeded and 1069 nm pumped Raman laser system where the second Stokes is amplified in a PM 10/125 1121 nm resonator cavity defined by high reflector fiber Bragg gratings has the potential of producing high output powers of narrow linewidth 1178 nm. Experiments were performed for resonator cavities of lengths 11 to 111 m. The cavities were seeded with approximately .023 W of 1178 nm with pump levels of 1069 nm up to 12.5 W. As currently configured, a maximum of 450 mW of 1178 nm was obtained from a cavity 111 m in length before the experiment was stopped out of concern for the 1178 nm back reflection. The system is being reconfigured to enable insertion of additional isolation in the 1178 nm leg to enable realization of the full system potential. Also, four wave mixing resulted in significant 1121 nm power leakage from the cavity. Usage of a non-linear model containing only Raman and SBS along with absorption is insufficient to describe the system since four wave mixing has a major impact on performance. A non-linear model containing four wave mixing in frequency space was written and is able to predict trends associated with short cavities. A goal of this work is to model the system in the time domain to enable investigation of longer cavities. The latest experimental and modeling results will be presented.

8960-67, Session PTue

Liquid core microbubble resonators for highly sensitive temperature sensing

Jonathan M. Ward, Yong Yang, Síle G. Nic Chormaic, Okinawa Institute of Science and Technology (Japan)

In this paper, we present results from a relatively new type of optical microcavity, namely the microbubble whispering gallery resonator. The thermal shifting of whispering gallery modes (WGMs) in a liquid core microbubble resonator is investigated. It is shown that not only can a negative refractive index core liquid work against thermal shifting of the WGMs, but it can also be used to increase the sensitivity of the WGMs to temperature changes. A microbubble with a diameter of 62 μm and a wall thickness of ~ 1 μm is fabricated and connected to a syringe pump via a glass capillary which allows different fluids to be passed through the microbubble. The thermal shift rate is determined for different WGMs when the core of the microbubble is filled with air, water and ethanol. Sensitivities as high as 100 GHz/K (0.2 nm/K at wavelength of 775 nm) are observed when the microbubble core is filled with ethanol. This is the largest thermal shift rate reported for a WGM resonator. The

Q-factors for the most sensitive WGMs are typically 10^5, equivalent to a measurement resolution of 8.5 mK. The measured shifts are compared against Finite Element Model (FEM) simulations. It is determined that the shift rate is highly dependent on the order of the WGM. We also show that thermal behaviour of the WGMs in thin-shelled air-filled microbubble is different to a solid microsphere.

8960-68, Session PTue

Digital control of laser modes with an intra-cavity spatial light modulator

Sandile S. Ngcobo, Igor A. Litvin, Liesl Burger, Council for Scientific and Industrial Research (South Africa); Andrew Forbes, CSIR National Laser Ctr. (South Africa) and Univ. of KwaZulu-Natal (South Africa)

The control of the spatial intensity output from a laser has been demonstrated for over many decades now and it has been performed using customized intra-cavity elements such as apertures and diffractive optics. The main disadvantage has been the intra-cavity optical elements which can only be used to shape a single particular beam profile at a time. We have overcome this limitation with the first digital laser comprising an electrically addressed reflective phase-only spatial light modulator (SLM) as an intra-cavity holographic mirror where the amplitude and phase of the mirror are controlled by writing a new computer generated gray scale image on the SLM. We demonstrate that a digitally controlled digital laser for on-demand laser mode is possible by switching between several spatial modes on a standard solid state laser resonator.

8960-69, Session PTue

Optimized Findlay Clay analysis for diode side-pumped Nd:YAG lasers

Avid Farhoodfar, San Jose City College (United States) and International Technological Univ. (United States); Sydney Sukuta, San Jose City College (United States)

The standard Findlay Clay Analysis cannot be applied to diode side-pumped Nd:YAG lasers because both the pump wavelength as well as the gain change with the diode current and the cooling water temperature.

We have developed modified method which is based on the variation of the cooling water temperature to determine the lowest threshold for each output coupler.

We have applied this technique to a 300 Watt class side Nd:YAG rod laser. The resulting Findlay Clay plot exhibits very good linearity and the measured gain and loss were confirmed by comparing measured output power at different cooling water temperatures with theoretical values provided by a Rigrod power model.

8960-70, Session PTue

Investigation of ring resonators with bidirectional regions

Alan H. Paxton, Harold C. Miller, Air Force Research Lab. (United States)

No Abstract Available

8960-32, Session 9

On phase noise of self-injection locked semiconductor lasers

Danny Eliyahu, Elijah B. Dale, Wei Liang, Vladimir S. Ilchenko, Andrey B. Matsko, David J. Seidel, Lute Maleki, OEwaves, Inc. (United States)

We study spectral purity and long-term stability of microresonator-based self-injection locked semiconductor lasers operating at 1,550 nm and 780/795 nm. The locking is realized using resonant optical feedback originating from stimulated Rayleigh scattering in the resonator host material. We studied phase noise of the lasers using both homodyme and heterodine techniques. Instantaneous laser linewidth smaller than 100 Hz is demonstrated. Long term frequency drift of the lasers does not exceed 10 MHz.

8960-33, Session 9

Progress towards Whispering Gallery Mode Resonator based Spectroscopy in Mid-Infrared *(Invited Paper)*

Nan Yu, Kamjou Mansour, Aaron Rury, Jet Propulsion Lab. (United States); Ivan S Grudinin, Jet Propulsion Lab (United States)

High-Q whispering gallery mode (WGM) resonators have been largely explored in the visible and Near-IR wavelength regions. With some of crystalline materials, their use can be extended to the Mid-IR where molecular gases not only have very rich characteristic spectral lines but also very large absorption cross sections. Here we report measurements of WGM resonator characteristics and applications in the Mid-IR as progress towards use in spectroscopy. Using cavity ringdown techniques, we have measured ringdown times for several high-Q WGM resonators in excess of several hundred ns, corresponding to effective Q values greater than 1x10^8 in the wavelength region beyond 3 um. Much higher Q values are expected. High-Q WGM resonators also serve as excellent frequency discriminators for measurement and reduction of laser frequency noises. We use WGM lasers for characterizing and narrowing linewidth of semiconductor lasers including quantum cascade lasers. Both passive injection locking and active frequency locking are being explored. Linewidth reduction from MHz to kHz in distributed-feedback semiconductor lasers has been achieved. Based on these results, we discuss the application of high-Q resonators with low phase noise Mid-IR lasers for the generation of optical frequency combs and their application to molecular spectroscopy.

8960-34, Session 9

Investigation on high speed directly modulated microcircular lasers *(Invited Paper)*

Yong-Zhen Huang, Xiao-Meng Lv, Ling-Xiu Zou, Heng Long, Jin-Long Xiao, Yue-De Yang, Yun Du, Institute of Semiconductors (China)

igh-speed directly modulated microlasers are potential light sources for applications in photonic integrated circuits and optical interconnection with the merits of smaller footprint and lower power consumption. In this talk, we will investigate high speed modulation characteristics for microcircular lasers theoretically and experimentally. Firstly, circular microlasers connecting with a 2-?m-width output waveguide laterally confined by a BCB cladding layer were investigated based on small signal modulation and large signal eye-diagram measurements. Furthermore, the small signal responses were fitted using equivalent

electric circuit model. Fitting the small signal frequency response of the microlaser by transfer function, we obtain the resonance frequency fR, the damping factor ?, and pole frequency fp of the electric circuit. The highest resonance frequencies of 12.5 and 6.9 GHz are obtained at a heat sink temperature of 290 K for the microcircular lasers with radii of 10 and 15 ?m, respectively. The obtained damping factor versus squared resonant frequency fR2 is fitted by the linear relation .The maximum possible 3dB bandwidth of 44 GHz is estimated from the measured K factor of 0.20 GHz-1 for the 10-?m-radius microlaser. Clear eye diagrams at 12.5Gbit/s were observed for the microlaser with the radius of 15 ?m.

Then, InAlGaAs/InP microring lasers with ring width of 5 μm and external radius of 10 μm were fabricated by connecting with a 2-μm-wide output waveguide. Continuous wave lasing operation is realized with a threshold current of 3 mA at 298 K, and 3 dB bandwidths of 10.8 and 8.7 GHz are obtained at the injection currents of 12 mA at 291 and 298 K, respectively. Finally, the high speed modulation characteristics are investigated for the microlasers under optical injection to enhance the modulation efficiency at the frequency higher than the resonance frequency.

8960-35, Session 9

Spectrally pure RF photonic source based on a resonant optical hyper-parametric oscillator

Wei Liang, Danny Eliyahu, Andrey B. Matsko, Vladimir S. Ilchenko, David J. Seidel, Lute Maleki, OEwaves, Inc. (United States)

We demonstrate a free running 10 GHz microresonator-based RF photonic hyper-parametric generator characterized with phase noise better than -60 dBc/Hz at 10 Hz, -90 dBc/Hz at 100 Hz, and -160 dBc/Hz at 10 MHz. The generator consumes less than 30 mW of optical power. A correlation between the frequency of the continuous wave laser pumping the nonlinear resonator and the generated RF frequency is confirmed. The experimental data are compared with results of numerical simulations of the system.

8960-36, Session 9

Phase-matched coupling to whispering gallery mode resonator of large refractive index using metallic diffraction grating

Yanyan Zhou, Nanyang Technological Univ. (Singapore) and A*STAR Singapore Institute of Manufacturing Technology (Singapore); Xia Yu, A*STAR Singapore Institute of Manufacturing Technology (Singapore); Feng Luan, Nanyang Technological Univ. (Singapore)

A metallic diffraction coupling to a whispering gallery mode (WGM) resonator of large refractive index is demonstrated. Conventionally, coupling to resonators of large refractive indices can only be achieved efficiently with silicon waveguides, for which high-Q resonators are difficult to fabricate. Tapered silica fibers, which are commonly recognized as the most efficient coupler, cannot provide the phase match conditions to resonators of larger indices. The metallic grating coupler solves this problem by offering custom phase-match conditions corresponding to different pitch sizes. A 1-D sub-wavelength gold grating with rectangular grooves is designed to couple to a chalcogenide microsphere that has a refractive index of around 2.4. The sub-wavelength grating is able to couple evanescently to the resonator even in a vertical configuration, which has not been possible in any other WGM coupling methods. The coupling is studied using both FDTD simulation and experimental demonstration. Such coupling scheme provides a practical solution to myriad WGM-related applications including sensing, switching, and optical nonlinear effects.

8960-37, Session 10

New directions for high-Q micro cavities *(Invited Paper)*

Kerry J. Vahala, California Institute of Technology (United States)

No Abstract Available

8960-38, Session 10

Crystalline whispering gallery mode resonators: in search of the optimal material

Vladimir S. Ilchenko, Anatoliy A. Savchenkov, Andrey B. Matsko, Lute Maleki, OEwaves, Inc. (United States)

Different applications of crystalline whispering gallery mode resonators call for different properties of the resonator host material. We report on our recent study of the resonators made out of quartz, sapphire, as well as diamond crystals and discuss possible applications of the resonators.

A quality factor exceeding five billion is demonstrated in quartz resonators at telecom wavelength. We observed electrical tunability of WGMs in x-cut resonators and demonstrated an electro-optic modulator with a submegahertz passband at 12 GHz. The resonators are also useful in narrowband agile tunable filters, compact narrow linewidth lasers, and microwave and millimeter wave oscillators.

We demonstrate a nearly spherical diamond whispering gallery mode resonator with quality factor exceeding twenty million at 1,319 nm and 1,550 nm. The resonators with current bandwidth (< 10 MHz at 1,550 nm wavelength) are attractive for laser locking and stabilization. Applications like stable compact optical comb generators as well as Raman optical frequency shifters will be feasible with further improvement of the material.

8960-39, Session 10

Micro-ring resonators for vertical optical emission *(Invited Paper)*

Marc Sorel, Univ. of Glasgow (United Kingdom); Michael J. Strain, Univ. of Glasgow (United Kingdom) and Univ. of Strathclyde (United Kingdom); Vincenzo Pusino, Univ. of Glasgow (United Kingdom); Siyuan Yu, Huanlu Li, Xinlun Cai, Univ. of Bristol (United Kingdom)

Microring and microdisk resonators have become key components in the development of photonic integrated circuits. Their unique potential for dense integration combined with their design flexibility makes them key components in a wide and diverse range of applications such as optical signal processing, metrology, optical telecommunications, non-linear interactions, sensing. Moreover, their integration with other optical components such as Bragg gratings, Mach-Zehnder interferometers or other resonators offers vast opportunities for the design of novel classes of devices with enhanced performance.

The talk will discuss a number of novel photonic integrated geometries built on silicon micro-ring resonators for signal processing and non-linear applications. Particular emphasis will be given to recent developments in microring resonators with sidewall Bragg grating for the vertical emission of optical beams with orbital angular momentum (OAM). Results on devices with on-chip tunability of the OAM state on array and matrix geometries for free-space communications will be presented. The talk will also discuss novel geometries for OAM beam emission based on electrically pumped semiconductor ring and disc lasers.

8960-40, Session 10

Droplet resonator based optofluidic microlasers *(Invited Paper)*

Alper Kiraz, Koç Univ. (Turkey); Alexandr Jonas, Istanbul Technical University (Turkey); Mehdi Aas, Yasin Karadag, Koç Univ. (Turkey); Oto Brzobohat?, Jan Je?ek, Zdenek Pilát, Pavel Zemánek, Institute of Scientific Instruments of the ASCR (Czech Republic); Suman Anand, David McGloin, University of Dundee (United Kingdom)

The tendency of liquid droplets to minimize interfacial energy by minimizing the interfacial area results in nearly spherical shapes in air or other immiscible liquids. Due to their perfect spherical geometry and smooth surface, liquid droplets host high quality whispering gallery modes (WGMs). Their easily deformable nature makes droplet resonators attractive for developing tunable optical components, e.g. tunable light sources. Their high quality WGMs also make them good candidates for refractive index or fluorescence-based sensing. In this presentation I will discuss the recent results we have obtained in the development of optofluidic lasers based on droplet resonators.

We used optical tweezers to demonstrate dye lasing in optically manipulated emulsion droplets surrounded by another liquid or liquid aerosol droplets surrounded by air. We were also able to tune the lasing WGMs of emulsion droplets by optical stretching in a dual beam optical trap. Recently, we have achieved lasing in droplet resonators containing biological gain media such as fluorescent proteins or fluorescent protein expressing bacterial cells. These results can pave the way for new paradigms in biological sensing with droplet resonator lasers.

I will also mention the results we have obtained in ultrahigh resolution spectroscopy of WGMs of surface-supported microdroplets using tapered optical fiber waveguides. (a) We measured ultrahigh quality factors up to 2.3?10^6 of the WGMs of glycerol-water microdroplets standing on a superhydrophobic surface. Using an additional heating laser we were also able to lock the size of salt-water microdroplets benefiting from the competition between resonant absorption of the infrared heating laser by a WGM and condensation in the sample chamber. Finally, by employing a tunable heating laser we were able to precisely tune the locked-size of salt-water microdroplets.

8960-41, Session 11

Self-assembled liquid-crystal microlasers, microresonators, and microfibres *(Invited Paper)*

Igor Musevic, Jo?ef Stefan Institute (Slovenia); Huang Peng, Faculty of Mathematics and Physics, University of Ljubljana (Slovenia); Matjaz Humar, Maryam Nikkhou, Jo?ef Stefan Institute (Slovenia)

When liquid crystals are dispersed in an immiscible fluid, microdroplets of liquid crystal are spontaneously formed in a fraction of a second. They have optically anisotropic internal structure, which is determined by the ordering of liquid crystal molecules at the interface. Spherical droplets of a nematic liquid crystal can function as whispering-gallery-mode microresonators with an unprecedented width of wavelength tunability by an electric field. WGM pulsed lasing in dye-doped nematic microdroplets is sensitive to strain, temperature and presence of molecules that change molecular orientation at the interface. Omnidirectional 3D lasing was demonstrated in droplets of chiral liquid crystals that form 3D Bragg-onion resonators. We present recent progress in this field, including electric tuning of 3D lasing, resonant transport of light between waveguides and liquid crystal resonators. We show that anisotropic fibres could be self-assembled from smectic liquid crystals and we discuss the topology of these fibres, which support Laguerre-Gaussian modes.

8960-42, Session 11

Whispering-gallery modes excitation in microspheres integrated inside microstructured optical fibers *(Invited Paper)*

Kyriaki Kosma, Gianluigi Zito, Foundation for Research and Technology-Hellas (Greece); Kay Schuster, Institut für Photonische Technologien e.V. (Germany); Stavros Pissadakis, Foundation for Research and Technology-Hellas (Greece)

Excitation of circular optical microcavities and observation of light trapping by means of Whispering-Gallery Modes (WGMs) has been a hot topic in the field of Photonics for more than a decade, leading to the realization of several sensing and switching devices. Evanescent field coupling is the most efficient way for exciting such symmetrical light localization structures, while employing, waveguide channels in close proximity, microprisms and tapered optical fibres. Herein we review results referring to a new excitation scheme tailored for the case of microspherical resonators, where the microsphere is integrated inside the empty capillaries of a microstructured optical fiber (MOF). Such an excitation scheme, fuses the advantages arising from the technologies of the spherical micro-resonators and the MOFs, into a single photonic platform that offers new operational, sensing and switching functionalities. Results will be presented with respect to the combination of MOF fibres and microsphere materials used, the light coupling and interrogation methods followed and their yield, while depicting the effect of those parameters into the Q-factor of light localisation and the spectral characteristics of the WGM optical resonation. Further results will refer to the optical excitation of concatenated microspheres stratified inside a single MOF channel, and the use of the microsphere-MOF system as a refractive index sensor. Current work includes optical switching and biosensing experiments; emerging results will be presented on-site.

8960-43, Session 11

Optical microstub resonator lasers

Ganapathy Senthil Murugan, Christophe A. Codemard, Mohd Narizee Bin Mohd Nasir, George Y. Chen, Univ. of Southampton (United Kingdom); Andreas Langner, Heraeus Quarzglas GmbH & Co. KG (Germany); Michalis N. Zervas, Univ. of Southampton (United Kingdom)

We describe the fabrication and optical performance of a new passive and active optical microstub resonator (MSR). The technique is extremely simple and enables the fabrication of high quality resonators. They are primarily cylindrical cavities (“stubs”) 10’s of microns long spliced to two fiber stems of smaller diameter on either side. The splicing makes the edges of the “stub” rounded and smooth, improving the optical performance. The fabricated MSRs had typical stem/cavity diameters of 125µm/200µm, respectively, and 50-200µm lengths. Strong resonances with coupling efficiencies and Q factors > 15dB and 10^6, respectively, were demonstrated.

Using a special Ytterbium doped fiber with doped core diameter of 220µm and cladding diameter of 240µm, we formed active MSRs with 50-500µm lengths and 125µm stem diameters. The active MSRs were side pumped by 980nm single-mode diodes through their stems. Residual pump and generated signal were monitored at the opposite fiber stem end. Strong lasing peaks in the 1060nm wavelength range were observed. No transversely scattered signal/pump light was detected. This indicates that the whispering-gallery modes were formed at the inner doped core/cladding interface. In stark contrast with previous microlaser demonstrations, this laser does not need additional microtapers/waveguides for launching or collecting light. This is the first demonstration of a robust, fully integrated, stand-alone microresonator laser where pump launching and signal collection is achieved by the fiber stems, used to form the microcavity. This is a major advancement and will impact significantly the development of future advanced sensor applications.

8960-44, Session 11

Optical bottle resonator slow light delay line

Misha Sumetsky, Aston Institute for Photonics Technologies (United Kingdom)

In this report, a solution to the central problem of the slow light research – creation of a miniature delay line with a breakthrough performance – is proposed and demonstrated. It is shown theoretically that an optical bottle resonator with a nanoscale radius variation can perform a multi-nanosecond long dispersionless delay of light in a nanometer-order bandwidth with minimal losses. Experimentally, a 3 mm long resonator with a 2.8 nm deep semi-parabolic radius variation is fabricated from a 19 micron radius silica fiber with a sub-angstrom precision. In excellent agreement with theory, the resonator exhibits the impedance-matched 2.58 ns (3 bytes) delay of 100 ps pulses with 0.44 dB/ns intrinsic loss. This is a miniature slow light delay line with the record large delay time, record small transmission loss, dispersion, and effective speed of light.

8960-45, Session 11

Fabrication of microoptical cavities with femtosecond laser pulses

Jintian Lin, Jiangxin Song, Jialei Tang, Shanghai Institute of Optics and Fine Mechanics (China); Wei Fang, Zhejiang Univ. (China); Koji Sugioka, RIKEN (Japan); Ya Cheng, Shanghai Institute of Optics and Fine Mechanics (China)

Whispering gallery mode (WGM) optical microcavities are very attractive for a variety of fields, ranging from fundamental science to engineering applications. Due to the nature of WGM, the light emission from the cavity is mainly in the plane parallel to the substrate, i. e., for the on-chip WGM microcavities such as microdisks, microtoroids, and deformed microcavities fabricated by lithography method. However, this makes an obstacle for many applications that prefer out-of-plane light coupling or extraction. Further integration of WGM microcavities with microfluidic and mirophotonic structures is also not easy with lithography-based approaches. Recently, femtosecond laser micromachining has been proved as a promising solution for high-precision and flexible fabrication of three dimensional (3D) microstructures. Specifically, femtosecond laser micromachining can be used for fabrication of microoptical cavities in different kinds of transparent materials. Here, we show fabrication of microoptical resonators in various types of glasses using a femtosecond laser. The processing mainly consists of formation of freestanding microdisks by femtosecond laser direct writing and subsequent wet chemical etching. CO_2 laser annealing is followed to smooth the microcavity surface. Microcavities with arbitrary 3D configurations can be fabricated with a high quality (Q)-factor above 1 million. We show that the unique 3D fabrication capability provided by femtosecond laser direct writing allows us to create microlasers at low pump threshold and to integrate microresonators with microfluidics for sensing applications.

8960-46, Session 12

Group and phase velocity coupling and decoupling in mode locked lasers *(Invited Paper)*

Ladan Arissian, The Univ. of New Mexico (United States)

Mode-locked lasers can generate near perfect frequency combs, with a constant spacing between teeth. The comb parameters - frequency offset and tooth spacing - are determined by the average phase and group velocities of the pulse circulating in the cavity. It is generally believed that the tooth spacing is simply determined by the cavity length. There are however numerous factors that affect the repetition rate.

For a laser mode-locked by a nanoscale saturable absorber in the middle of the cavity, we show that the repetition rate is not simply proportional to the cavity length. Another observation concerns the changes in group and phase velocities when a glass window is inserted in the cavity, in which 10 GHz pulse trains are generated in a meter long cavity. The third example explains the nonlinear coupling between various colors inside an intracavity pumped optical parametric Oscillator (OPO).

We provide and understanding of the group and phase velocity coupling inside the laser created by intracavity elements such as sub-wavelength elements, thin glasses and OPO crystals. Practical application are the generation of frequency combs of tunable wavelength and repetition rate up to tens of GHz in a meter-long cavity and enhancement of nonlinear frequency conversion.

8960-47, Session 12

A simplified design of resonators for Kerr-lens mode-locked Ti:sapphire lasers exploiting the Z-scan method

Reza Akbari, Arkady Major, Univ. of Manitoba (Canada)

The design of reliable Kerr-lens mode-locked Ti:sapphire lasers has been the subject of a large number of theoretical and experimental studies. One of the most critical design parameters for a reliable KLM initiation and operation, the sensitivity parameter, was introduced by Magni et al. and describes a variation of a laser beam size with intracavity power due to the Kerr lensing effect. Since the sensitivity parameter is associated with the initial conditions, the KLM strength is attributed to the dioptric power of the Kerr medium and its location in the resonator. Unfortunately, calculation of the geometrical cavity parameters for KLM lasers is not a trivial task. In this work we developed an accurate method for the design of KLM cavities which overcomes this limitation and offers practical simplicity. The method is based on a theoretical formalism of the Z-scan method, widely used for the measurements of the nonlinear refractive index. It was found that the Z-scan method offers a simple design procedure of laser cavities with enhanced Kerr lensing effect. Detailed numerical simulations confirmed that the strength of the Kerr lensing effect is generally governed by the separation between the gain medium and the beam waist of a cavity mode, the Rayleigh range of the beam, and the length of the gain medium. The optimization of the model led to the derivation of a simple expression that can be used to calculate the location of the Kerr medium in terms of a stable cavity's parameters. Our results show a good agreement with the well-known Magni plots of KLM sensitivity parameter. A practical "rule of thumb" for straightforward design of KLM cavities was also developed and will be presented.

8960-48, Session 12

26 ps pulses from a passively Q-switched microchip laser

Benjamin Bernard, Georg-Simon-Ohm-Hochschule für angewandte Wissenschaften - Fachhochschule Nürnberg (Germany); Eva Mehner, Georg-Simon-Ohm-Hochschule für angewandte Wissenschaften - Fachhochschule Nürnberg (Germany) and Univ. Stuttgart (Germany); Daniel Kopf, MONTFORT Laser GmbH (Austria); Harald W. Giessen, Univ. Stuttgart (Germany); Bernd Braun, Georg-Simon-Ohm-Hochschule für angewandte Wissenschaften - Fachhochschule Nürnberg (Germany)

Short-pulse laser systems have found entry into industrial micro material fabrication processes on a large scale during the last ten years. Equally the demand of simple, compact and cost-efficient seed sources has grown. The physical parameters needed for short-pulse laser processing range between a few femtoseconds and some ten picoseconds at

repetition rates of up to 1 MHz. Up to now these laser systems are based on high repetition rate oscillators and regenerative amplifiers. These systems are relatively complex and expensive. In contrast a Q-switched microchip laser with a subsequent single pass amplifier permits a much simpler approach. In the following we present a 50 µm $Nd^{3+}:YVO_4$ microchip laser that is passively Q-switched by a semiconductor saturable absorber mirror. The system provides pulse widths around 26 ps at a repetition rate of up to 0.9 MHz. The average output power is 15 mW at a wavelength of 1064 nm. Such a system promises to be a simple and monolithic seed source to be used for micro machining in combination with a single pass amplifier. We will discuss the prospects and limits in terms of pulse width, repetition rate, output power and system stability. We will compare our experimental data to theoretical calculations.

8960-49, Session 13

Nonlinear effects in coherent coupled laser resonators *(Invited Paper)*

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

This invited presentation covers recent experimental demonstrations of nonlinear effects in coupled fiber lasers. The coupled laser system consists of two Yb-doped laser cores in a common cladding, where the cores are coupled together with a Dammann grating. The spacing between the cores is sufficiently large to eliminate evanescent coupling. The optical path length difference between the two lasers is approximately 23 ?m (out of a total fiber length of approx. 3 meters), removing the influence of wavelength shifting on the phase difference between the two lasers. The talk will review the influence of nonlinear effects on the coupled laser output power, phase pulling, operational wavelength, polarization, and hysteresis as a result of modifying the path length between the two laser channels. In our experiment, the physical origin of the nonlinear effect is determined to be the Kramers-Kronig effect. Experiments to measure the magnitude and the characteristics of this effect will be described. Finally, the lasing characteristics will be explained using a simple nonlinear model. We will show that the lasing performance is dramatically improved by the presence of this nonlinearity.

8960-50, Session 13

Simultaneous laser beam combining and mode conversion using multiplexed volume phase elements

Marc SeGall, Clémence Jollivet, Ivan B. Divliansky, Axel Schulzgen, Leonid B. Glebov, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

Compact, high-power lasers delivering good beam quality and narrow line-widths are desired for a large number of applications. Parallel to recent progress of beam combining techniques, a considerable amount of effort has been put into developing large-mode area (LMA) fibers supporting only one or few higher-order modes to increase the damage threshold and reduce nonlinearities. For many high-power applications however a near-diffraction-limited Gaussian spot is desirable.

To combine these efforts, we report on a single volume phase element that can be utilized to efficiently convert higher order modes into the fundamental mode while simultaneously performing beam combining. This is accomplished using a multiplexed hologram recording of several mode converters. As a first step volume phase masks are recorded in plane parallel photo-thermo refractive (PTR) glass samples, converting higher order Hermite-Gaussian modes into a Gaussian profile. One of these mode converters was introduced into one of the arms of a holographic recording setup and a hologram of the phase profile was recorded in another PTR sample. For spectral beam combining in the infrared, the angles and grating tilts during the holographic recording of each phase plate were adjusted, choosing the appropriate grating tilt so that all of the gratings diffracted into a common port. The beam combining efficiency and mode purity of the combined beam are investigated in the far field.

8960-51, Session 13

Wide aperture (mare than 500 mm) deformable mirrors for high power laser beam correction

Alexis V. Kudryashov, Vadim Samarkin, Alexander Alexandrov, Julia Sheldakova, Moscow State Open Univ. (Russian Federation) and Moscow State Technical Univ. (Russian Federation)

No Abstract Available

8960-52, Session 14

Intra-cavity metamorphosis of a Gaussian beam to flat-top distribution

Darryl Naidoo, Igor A. Litvin, Council for Scientific and Industrial Research (South Africa); Alexander V. Laskin, AdlOptica Optical Systems GmbH (Germany); Andrew Forbes, Council for Scientific and Industrial Research (South Africa)

We explore an intra-cavity beam shaping approach to generate a Gaussian distribution by the metamorphosis of a Gaussian beam into a flat-top distribution on opposing mirrors. The concept is tested external to the cavity through the use of two spatial light modulators (SLM), where the first SLM is used to transform a collimated Gaussian into a flat-top distribution and the second SLM is encoded with the conjugate phase of the flat-top for conversion back to a Gaussian. We implement this intra-cavity selection through the use of two optical elements of the refractive variant that are designed from the phase profiles addressed to the SLMs. We consider a solid-state diode side-pumped laser resonator that consists of two planar mirrors where the refractive optics are positioned at the mirrors. We out couple the Gaussian and flat-top beams and we show that we increase the energy extraction while maintaining a beam quality that is comparable to our predictions.

8960-53, Session 14

Improving beam parameters of edge emitting diode laser arrays using optical phase conjugation

Christof Zink, Andreas Jechow, Axel Heuer, Ralf Menzel, Univ. Potsdam (Germany)

Diode laser arrays consisting of narrow-stripe emitters in close proximity often show coupling of the light fields of adjacent emitters. Then these devices operate in a common, so called, supermode. Unfortunately, the coupling is rather weak and at higher output powers spatial multi-mode operation occurs [1]. Using an adapted V-shaped external cavity this coupling can be supported and thus beam quality can be improved generating an out-of-phase locked supermode [2]. However, in such setups even small faults of the optical elements can induce phase distortions of the external feedback field. In practice this limits the phase locking and thus the brightness of the laser. Using optical phase conjugation these distortions can be compensated [3].

Here we present first experimental results of using a passive phase

conjugate mirror in an external cavity setup for phase locking a diode laser array. To characterize the degree of coherence, measurements with and without feedback were obtained. Furthermore, we discuss the possible application of optical phase conjugation to select the in-phase mode, which can be useful for coherent beam combining of larger arrays.

[1] M. Spreemann et al. IEEE J. Quantum Electron., 46, 1619 (2010)

[2] A. Jechow et al. Opt. Commun. 277, 161 (2007)

[3] M. Ostermeyer, R. Menzel: “Laser Resonators with Brillouin Mirrors” Chapter 3 in “Phase Conjugate Laser Optics”, edited by Arnaud Brignon, Jean-Pierre Huignard, (John Wiley & Sons, pages 63-108, 2004)

8960-54, Session 14

Homogenization of the semiconductor laser array by diffractive microlens array

Zhi H. Liu, Huan Yang, Zhen D. Shi, Guo J. Li, Chuan K. Qiu, Chong X. Zhou, Institute of Optics and Electronics (China)

A novel approach is proposed and developed that using diffractive micro-lens array to homogenize the semiconductor laser beam in this paper. Diffractive micro-lens array with phase steps based on the scalar diffraction theory is successfully designed and fabricated, and the structure exhibits high fill factor and excellent accuracy. The paper also simulates and analyses the none-imaging homogenization system by the theory of Fresnel diffraction. Besides, the experiment of beam homogenization has also been carried out, when the diameter of the micro-lens is 0.125mm and the phase steps is 8, at the fast axis, the non-homogeneity is 12.34% and the energy efficiency is 95.74%; at the slow axis, the non-homogeneity and the energy efficiency is 5.42%, 96.6%, respectively. The result shows that the intensity distribution of the focal spot is modulated seriously by multiple-beam interference, which agrees well with the theory and proves that it is reasonable of the system of diffractive micro-lens array for beam homogenization. These insights can helpfully guide the future design and fabrication of diffractive micro-lens array for uniform illumination.

8960-55, Session 15

The digital laser: on-demand laser modes with the click of a button *(Invited Paper)*

Andrew Forbes, CSIR National Laser Ctr. (South Africa) and Stellenbosch Univ. (South Africa) and Univ. of KwaZulu-Natal (South Africa); Sandile S. Ngcobo, Council for Scientific and Industrial Research (South Africa) and Univ. of KwaZulu-Natal (South Africa); Liesl Burger, Council for Scientific and Industrial Research (South Africa) and Stellenbosch Univ. (South Africa); Igor A. Litvin, Council for Scientific and Industrial Research (South Africa)

In this talk I will outline our recent advances in all-digital control of light. Importantly, I will outline how to create a so-called “digital laser”, where a conventional laser mirror is replaced with a phase-only spatial light modulator. This allows the mirror properties to be dynamically changed by altering only the image sent to the device: on-demand laser modes. We demonstrate a myriad of laser beams that can be created from the same device without any realignment or additional custom optics. We “play a movie” inside the laser cavity and show real-time modal changes as the output. We will review the principle, how it works, and outline future application areas.

8960-56, Session 15

Tuneable Gaussian to flat-top resonator by amplitude beam shaping using a digital laser

Sandile S. Ngcobo, Igor A. Litvin, Council for Scientific and Industrial Research (South Africa); Kamel Ait-Ameur, ENSICAEN (France); Andrew Forbes, Council for Scientific and Industrial Research (South Africa) and Univ. of KwaZulu-Natal (South Africa); Abdelkrim A Hasnaoui, Universite des Science et de la Technologie Houari Boumediene (Algeria)

We outline a simple laser cavity comprising an opaque ring and a circular aperture that is capable of producing spatially tuneable laser modes, from a Gaussian beam to a Flat-top beam. The tune-ability is achieved by varying the diameter of the aperture and thus requires no realignment of the cavity. We demonstrate this principle using a digital laser with an intra-cavity spatial light modulator, and confirm the properties of the resonator experimentally

8960-57, Session 15

Application of spatial light modulators for the synthesis of spiral laser beams

Alexander A. Zinchik, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

In the last decade, holographic or diffractive optical tweezers have greatly enhanced the possibilities of manipulating microscopic particles with light. Diffractively created patterns of light can be used to trap and manipulate dielectric particles by intensity gradients. This paper describes the application of liquid-crystal spatial light modulators for the synthesis of spiral laser beams. Spiral beams is a family of laser beams that preserve the structural stability up to scale and rotate with the propagation. Properties of spiral beams are of practical interest for laser technology, medicine and biotechnology. Spiral beams have a complicated phase distribution in cross section because the lines have equal phase form helices.

For the synthesis of spiral beams collimated beam of linearly polarized He-Ne laser passed through two liquid-crystal spatial light modulator. First of them is used in the transmission amplitude-only mode and makes the distribution of the amplitude of the spiral beam. Second modulator operated in reflection phase-only mode and formed the necessary phase shift in the range from 0 to 2π at each point of the cross section of the beam.

As a result of the experiments spiral beams having different angles of rotation during the distribution and having different cross-sectional shape were obtained. The use of liquid-crystal spatial light modulators allows dynamically changed the amplitude and phase distribution, which makes it possible to change the parameters of the laser beam.

8960-58, Session 15

Beam shaping with a laser amplifier

Igor A. Litvin, Oliver J. Collett, Council for Scientific and Industrial Research (South Africa)

In this work we propose and investigate in details a theory of reshaping laser beams into a desirable beam profiles with an end pumped laser amplifier that has a pump beam with a modified intensity profile. We show an essential example of such shaping, the classical illustration of reshaping a Gaussian beam into a Flat –Top beam with this theory. We have obtained the analytical equation which describes the intensity transformation of seed beam in the laser crystal depending on pump intensity distribution. We have developed the analytical formula which

describes the transformation of the seed beam into the desired beam profile in the unsaturated regime of the amplifier. In the case were high pump powers saturated the gain medium we have shown the method of reshaping of the seed beam into the desired beam by a numerically obtained pump intensity profile. Additionally this method can be extended to the cases were the seed beam is shaped to produce the desired output. One the advantages of this method are the ability to reshape multimode beams as the method relies only on the transverse intensity of the beams.

8960-59, Session 15

Engineering of automated assembly of beam-shaping optics

Sebastian Haag, Fraunhofer-Institut für Produktionstechnologie (Germany); Volker R. Sinhoff, INGENERIC GmbH (Germany); Tobias Mueller, Christian Brecher, Fraunhofer-Institut für Produktionstechnologie (Germany)

Beam-shaping is essential for any kind of laser application. Assembly technologies for beam-shaping subassemblies are subject to intense research and development activities and their technical feasibility has been proven in recent years while economic viability requires more efficient engineering tools for process planning and production ramp up of complex assembly tasks for micro-optical systems. The work presented in this paper aims for significant reduction of process development and production ramp up times for the automated assembly of micro-optical subassemblies for beam-collimation and beam-tilting. The approach proposed bridges the gap between the product development phase and the realization of automation control through integration of established software tools such as optics simulation and CAD modeling as well as through introduction of novel software tools and methods to efficiently describe active alignment strategies. The focus of the paper is put on the methodological approach regarding the engineering of assembly processes for beam-shaping micro-optics and the formal representation of assembly objectives similar to representation in mechanical assemblies. Main topic of the paper is the engineering methodology for active alignment processes based on the classification of optical functions for beam-shaping optics and corresponding standardized measurement setups including adaptable alignment algorithms. The concepts are applied to industrial use-cases: (1) integrated collimation module for fast- and slow-axis and (2) beam-tilting subassembly consisting of a fast-axis collimator and micro-lens array. Practical results are discussed. The paper concludes with an overview of current limitations as well as an outlook on the next development steps considering adhesive bonding processes.

8960-60, Session 16

Freeform beam shaping for high-power multimode lasers

Alexander V. Laskin, Vadim V. Laskin, AdlOptica Optical Systems GmbH (Germany)

Widening of using high power multimode lasers in industrial laser material processing is accompanied by special requirements to irradiance profiles in such technologies like metal or plastics welding, cladding, hardening, brazing, annealing, laser pumping and amplification in MOPA lasers. Typical irradiance distribution of high power multimode lasers: free space solid state, fiber-coupled solid state and diodes lasers, fiber lasers, is similar to Gaussian. Laser technologies can be essentially improved when irradiance distribution on a workpiece is uniform (flattop) or inverse-Gauss; when building high-power pulsed lasers it is possible to enhance efficiency of pumping and amplification by applying super-Gauss irradiance distribution with controlled convexity. Therefore, "freeform" beam shaping of multimode laser beams is an important task. A proved solution is refractive field mapping beam shaper like piShaper capable to control resulting irradiance profile – with the same unit it is possible to get various beam profiles and choose optimum one for a particular application. Operational principle of these devices implies transformation of laser irradiance distribution by conserving beam consistency, high transmittance, providing collimated low divergent output beam. Using additional optics makes it possible to create resulting laser spots of necessary size and round, elliptical or linear shape. Operation out of focal plane and, hence, in field of lower wavefront curvature allows to extended depth of field.

The refractive beam shapers are implemented as telescopes and collimating systems, which can be connected directly to fiber-coupled lasers or fiber lasers, thus combining functions of beam collimation and irradiance transformation.

8960-61, Session 16

Laser beams with conical refraction patterns

Yurii V. Loiko, Univ. of Dundee (United Kingdom); Grigorii S. Sokolovskii, Univ. of Dundee (United Kingdom) and Ioffe Physico-Technical Institute (Russian Federation); David J. Carnegie, Univ. of Dundee (United Kingdom); Alex Turpin, Jordi Mompart, Univ. Autònoma de Barcelona (Spain); Edik U. Rafailov, Univ. of Dundee (United Kingdom)

In conical refraction (CR), when an incident light beam passes along an optic axis of a biaxial crystal (BC) it refracts conically giving rise to characteristic CR ring. Every point from the ring has unique linear polarization state and two opposite points are orthogonally polarized. Recently [1], efficient CR lasers, in which optic axis of intracavity BC is aligned along the laser cavity axis, have been reported with optical-to-optical slope efficiency of 74%. Gaussian-like spatial profile of linear polarization from the plane output coupler has been reported in close to hemispherical resonator configuration [1]. CR-like beam of crescent spatial profile has been observed from the curved mirror of such lasers [2]. In this communication we present experimental evidence that crescent-like beams with additional central spot are generated from the plane mirror of the same laser, when its' optical axis is misaligned with respect to the optic axis of biaxial crystal. We show that azimuthal position of zero amplitude point of the crescent ring is controlled by azimuthal orientation of axis misalignment. This observation is demonstrated in CR lasers with Nd-doped KGd(WO4)2 crystals used for intracavity CR. This opens new opportunities for generation of CR-like laser beams.

[1] A. Abdolvand, K. G. Wilcox, T. K. Kalkandjiev, and E. U. Rafailov, ''Conical refraction Nd:KGd(WO4)2 laser," Optics Express 18, 2753-2759 (2010).

[2] K. G. Wilcox, A. Abdolvand, T. K. Kalkandjiev, and E. U. Rafailov, ''Laser with simultaneous Gaussian and conical refraction outputs," Appl. Phys. B 99, 619-622 (2010).

8960-62, Session 16

Diffraction limited focal spot in the interaction chamber using phase retrieval adaptive optics

Nicolas A. Lefaudeux, Emeric Lavergne, Imagine Optic SA (France); Sylvain Monchoce, CEA Saclay, DSM IRAMIS (France); Xavier Levecq, Imagine Optic SA (France)

In order to provide the end user with a diffraction limited collimated beam, adaptive optics phase correction systems are now a standard feature of ultra intense laser facilities.

Generally speaking, these systems are based on a deformable mirror controlled in closed loop configuration in order to correct the aberrations of the beam measured by the wavefront sensor. Such implementation

corrects for most of the aberrations of the laser. However, the aberrations of the optical elements located downstream of the wavefront sensor are not measured and therefore not corrected by the adaptive optics loop while they are degrading the final focal spot.

We present an improved correction strategy and results based on a combination of both usual closed loop and phase retrieval in order to reach diffraction limit at the focal spot inside the interaction chamber. The off axis parabola alignment camera located at the focal spot is used in combination of the deformable mirror and wavefront sensor to get images of the focal spot. The residual aberrations of the focal spot are measured by a Phase Retrieval algorithm using the acquired focal spot images. Then the adaptive optics loop is run in order to precompensate for these aberrations, which leads to diffraction limited focal spot in the interaction chamber.

8960-63, Session 16

Reduction of speckle contrast in multimode fibers using piezoelectric vibrator

Yosuke Fujimaki, Hirokazu Taniguchi, Mitsubishi Cable Industries, Ltd. (Japan)

We experimentally investigate a technique to reduce speckle noise in multimode fibers by using a piezoelectric vibrator. Various types of fibers such as glass fiber, polymer cladding fiber and plastic optical fiber are tested. The speckle pattern in multimode fiber is attributed to the interference between the propagation modes. If the optical fiber is externally vibrated, the propagation mode is coupled to the other modes. Thus speckle pattern is changed by applying vibration to the fiber. If the vibration frequency is sufficiently fast, the speckle patterns are time-averaged and thus output pattern becomes homogeneous. The level of contrast of the speckle pattern is quantified by the speckle contrast which is defined as the ratio of the standard deviation of the intensity to the mean intensity of the speckle pattern. In this experiment, the fiber is fixed on the piezoelectric ceramic plate to apply high frequency oscillations. The output patterns are observed by a CCD camera. It is clearly observed that the speckle contrast is reduced by applying vibration. The reduction of the speckle contrast is less significant in glass fiber than polymer cladding fiber and plastic fiber. The glass fiber comprises glass core, glass cladding and polymer jacket. The applied vibration is damped by the jacket, so the core and cladding is less distorted. The frequency dependences of speckle reduction efficiencies for various fibers are discussed. The comparison between the circular shaped core fiber and non-circular shaped core fiber is also discussed.

8960-64, Session 16

Stability of a laser cavity with non-parabolic phase transformation elements and applications

Igor A. Litvin, Council for Scientific and Industrial Research (South Africa)

In this work we present a general approach to determine the stability of a laser cavity which can include non-conventional phase transformation elements. In the particular case of the intra–cavity elements having parabolic surfaces, the approach comes to the well–known stability condition for conventional laser resonators namely 0≤(1?z/R1)(1?z/R2)≤1. We consider two pertinent examples of the detailed investigation of the stability of a laser cavity firstly with a lens with spherical aberration and thereafter a lens axicon doublet to illustrate the implementation of the given approach. To show the advantages of the method we apply it in the area of the interactivity beam shaping, the mode discrimination and thermal lensing compensation.

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8961-1, Session 1

Using a linearly chirped seed suppresses SBS in high-power fiber amplifiers, allows for coherent combination, and enables long delivery fibers *(Invited Paper)*

Jeffrey O. White, Eliot B. Petersen, Zhi Y. Yang, U.S. Army Research Lab. (United States); Carl E. Mungan, U.S. Naval Academy (United States); George A. Rakuljic, Telaris, Inc. (United States); Arseny Vasilyev, Naresh Satyan, Amnon Yariv, California Institute of Technology (United States)

By operating a diode laser in an optoelectronic feedback loop, a linear chirp of 10^16 Hz/s can be obtained at constant output power. When seeding a high power fiber amplifier with such a source, the backward Brillouin scattering is prevented from reaching the stimulated level because the coherent laser/Stokes interaction is interrrupted. The seed bandwidth as seen by the SBS also increases linearly with fiber length, resulting in a “nearly-length-independent SBS threshold.” In spite of the chirp, the simple and deterministic variation of phase with time preserves temporal coherence in the forward direction. This allows a large tolerance for length mismatch, i.e. a large effective coherence length, which enables coherent combination of multiple amplifiers. Theoretical and experimental results will be presented on SBS suppression and coherent combining in Er fiber amplifiers at the 10W level and in Yb fiber amplifiers at the 300W level. Chirped seed amplification will be compared to other techniques for suppressing SBS and coherent combination.

8961-2, Session 1

Single-frequency Yb-doped photonic crystal fiber amplifier with 800 W output power

Craig A. Robin, Iyad Dajani, Air Force Research Lab. (United States)

A novel acoustic and gain tailored Yb-doped photonic crystal fiber is used to demonstrate over 800 W single-frequency output power with near diffraction limited beam quality at 1064 nm. The large mode area fiber core is composed of 7 individually doped segments arranged to create three distinct acoustic regions and preferential gain overlap with the fundamental optical mode.

8961-3, Session 1

Characterization of photonic bandgap fiber for high-power, narrow-linewidth optical transport

Charlotte R. Bennett, David C. Jones, Mark A. Smith, Andrew M. Scott, QinetiQ Ltd. (United Kingdom); Jens K. Lyngsø, Christian Jakobsen, NKT Photonics A/S (Denmark)

There are many applications that require high-power, narrow-linewidth light with good beam quality and a transport fiber for these applications would allow separation of the laser from the delivery point. Current conventional fibers suffer from non-linearities, in particular Stimulated Brillouin Scattering (SBS), at the tens of Watt level unless longitudinal differences or acoustic phonon confinement are used in the design. Even with these additional features, kilowatt operation is not obtainable for very narrow linewidth. Hollow-core photonic bandgap (PBG) fiber, however, reduces the overlap between the optical intensity and the silica that hosts the acoustic phonons which should increase the SBS threshold. Very little work has been performed to demonstrate whether this is the case. This work presents a full model (including acoustic phonon confinement) and experimental measurement of the SBS spectra and gain, and discusses the issues of coupling such high powers and the limitations due to back-scatter into different optical modes that may be present.

Good agreement of the main features is found between the model and the experimental measurement of the SBS due to acoustics phonons in the silica and it is has been established that non-linear interactions with the air in the core (SBS and Rayleigh scattering) are the power-limiting effects. Even so, small-core COTS PBG fiber designed to work at 1 µm could transport over a kilowatt of power (with linewidths narrower than the SBS bandwidth) over 10 meters in a single mode.

8961-4, Session 1

Single-frequency 1178 nm SDL/Yb-PBGF MOPA with an output power of 31 W

Tomi Leinonen, Tampere Univ. of Technology (Finland); Mingchen Chen, Xinyan Fan, The Univ. of Electro-Communications (Japan); Emmi L. Kantola, Tampere Univ. of Technology (Finland); Akira Shirakawa, The Univ. of Electro-Communications (Japan); Mircea Guina, Tampere Univ. of Technology (Finland)

Fiber amplifiers that exhibit high saturation power require high power seed lasers in master-oscillator power-amplifier (MOPA) configuration. In absence of such, amplifier chains need to be utilized which will add to the cost and complexity of the MOPA. To replace a Raman-amplified diode laser emitting at 1178 nm, we developed a multi-watt Semiconductor Disk Laser (SDL). The SDL was used as a seed laser in an Yb-doped Photonic Bandgap Fiber (Yb-PBGF) amplifier-based MOPA. We believe SDLs offer a promising seed laser platform for high-power fiber amplifiers.

The SDL comprised a GaInAs/GaAs/GaAsP gain chip, a 1-mm-thick etalon for mode selection, and a 3-mm-thick birefringent filter for wavelength tuning. The linearly-polarized output of the SDL was coupled to the Yb-PBGF after a free-space optical isolator. The fiber consisted of an Yb-doped core surrounded by a structure of periodically arranged germanium rods with a pitch of 10.2 µm. To maintain the polarization the fibre comprised two boron rods.

The SDL output power was 3.9 W of which 1.8 W was coupled to the fiber amplifier. The amplifier output was 31 W yielding a gain of 12.4 dB. The linewidth of the amplifier output was measured by a scanning Fabry-Pérot interferometer to be 149±31 kHz, indicating almost no linewidth broadening in the amplification. With further scaling of the output power and frequency doubling, the MOPA system could meet the requirements of future laser-guide-stars.

8961-5, Session 2

Approaching TW-peak powers at >10 kHz repetition rate by multi-dimensional coherent combining of femtosecond fiber lasers

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Classical particle colliders are getting close to the limits given by size and costs of the required accelerator rings. Hence, novel accelerating-concepts are currently under development in projects like ICAN and ICUIL. The most promising approach seems to be laser wakefield acceleration. For this demanding application the required pulse energies are as high as 32 J with pulse peak powers of ~100 TW and a repetition rate of ~15 kHz. This results in average powers of ~480 kW. Available bulk systems can achieve very high pulse peak powers, but cannot handle high average powers. Therefore, the repetition rate at which those pulses are produced is in the low Hz-level. Fiber-based amplifiers are well known for their high average powers even in the fs-pulse regime, but they are typically limited in pulse energy. Nevertheless, there is a way to take advantage of the very high repetition rates of fiber laser systems to achieve the required parameters to effectively accelerate particles. The idea is to use a combination of spatial coherent combining of ultra-short pulses and additional cavity-enhancement to stack the pulses in the temporal domain. The enhanced pulses will be coupled out using an all-reflective switch. Compared to the dimensions of an equally powerful classical particle accelerator, the hence build system would be significantly smaller, cheaper and much more efficient in terms of energy-consumption. Otherwise proposed laser-systems without temporally separated amplification of the pulses have an amplifier-channel count which is several magnitudes higher and hence the system is significantly more expensive.

8961-6, Session 2

Coherent-beam-combining performance in harsh environment

Laurent Lombard, Guillaume Canat, Pierre Bourdon, ONERA (France)

Coherent beam combining (CBC) is a promising solution for high power directed energy weapons. We investigate two particular issues for this application:

First, we study the evolution of phase noise spectrum with power in 100W MOPFA. We study the phase noise power spectrum for increasing pump power. The main variations in the spectrum are located in the low frequency region corresponding to thermal transfer between the fiber core heated by the pump and the fiber environment. The phase noise root mean square evolves linearly with the pump power.

Then, we investigate the performances of CBC in harsh environment. For this purpose, we implement CBC of a watt-level fiber amplifier and a passive fiber using the LOCSET technique and simulate harsh environment by applying strong vibrations created by a hammering drill on the optical table. The applied vibrations spectrum ranges from 1Hz to ~5kHz with a standard deviation of 9m/s2. CBC of the amplifier output and the passive fiber output is performed on a second table, isolated from vibrations. Measurements of the phase difference between both outputs and of the applied vibration are simultaneously performed.

When the phase controller is inactive, the induced phase noise amplitude reaches ~10x2pi at >300Hz and 2pi/15 when only integrating frequencies above 4.1kHz. When the phase controller is active, the amplifier and the passive fiber are successfully combined with a residual phase error below 2pi/15. The -3dB bandwidth of the LOCSET controller has been measured to be ~4.5kHz.

8961-7, Session 2

Spectral beam combination of kilowatt class fiber lasers with reflective volume Bragg gratings

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One of the more promising paths towards achieving~10-100 kW level diffraction limited output powers is through beam combination of lower power fiber amplifiers. Here, we present results on the spectral beam combination of two kilo-Watt class ~1 µm Narrow Linewidth Fiber Amplifiers (manufactured by Nufern) with air cooled reflective Volume Bragg Gratings (VBG), manufactured by OptiGrate. The collimated diffraction limited output of two ~1.1 kW amplifiers centered near ~1062 and ~1064 nm respectively were combined with an uncoated 3-mm-thick VBG recorded in PTR glass. The combined beam with a total output power of ~2 kW was measured to have an M2 ~1.16; the combination efficiency was measured to be 92% with an estimated value of 98% for the case of an anti-reflection coated VBG. Minimal heating, less than 10oC, for the air cooled VBG was observed; the corresponding wavelength change of the VBG was corrected by changing the wavelength of the reflected beam (using a tunable seed source). Parameters of amplifier, volume Bragg grating and beam combiner necessary to achieve power scaling to ~ 10-100 kW's of diffraction limited beam power will be discussed.

8961-8, Session 2

Phase-locked, Q-switched multicore fiber laser by saturable absorber

Akira Shirakawa, Keigo Sato, Hidenori Yamada, The Univ. of Electro-Communications (Japan)

Coherent beam combining of fiber lasers is the important subject for power and energy scaling. Multi-core fiber, in which multiple single-mode gain cores are built in a single fiber format and evanescently coupled with each other, has been extensively investigated. However, since there are as many supermodes as cores, exciting only the in-phase supermode is the key issue for brightness scaling. In this contribution we propose simultaneous phase locking and Q-switching in a multicore fiber laser by a saturable absorber placed in the far field inside a resonator.

We used an Yb-doped multicore photonic crystal fiber (MC-PCF). There are six Yb-doped cores with each mode field diameter of 17.3 um and with the effective mode field area of the in-phase mode of 1245 um2. The cladding pump absorption is ~6 dB/m at 976 nm. The saturable absorber used here was a Cr:YAG crystal, with the initial transmission of 30% and without AR coatings. It was placed in front of the T=30% output coupler, the far-field position in the extended cavity. The in-phase mode forms the highest intensity at the far field and thereby the absorption of the Cr:YAG can be saturated with the lowest power/energy among the six supermodes. The relay lenses in the extended cavity is to control

the saturation in Cr:YAG. In a preliminary experiment, in-phase mode oscillation with 9.6 uJ, 330 ns pulses with a 145 kHz repletion rate was achieved. Further optimization/investigation is now on-going and will be presented at the conference.

8961-9, Session 3

Tunable fiber-based sources and their applications to biomedical imaging *(Invited Paper)*

Chris Xu, Cornell Univ. (United States)

Fiber lasers offer major practical advantages, such as environmental stability, low cost, and good beam quality. Although major progress has been made in the last two decades, short-pulse fiber lasers still have limited impact in biomedical imaging. The reason for the low penetration of fiber femtosecond sources in the biomedical field is due to various performance handicaps, such as pulse energy and wavelength tunability. In this paper, we show soliton self-frequency shift in several fiber types to generate energetic, wavelength tunable femtosecond pulses for multiphoton fluorescence imaging. For example, wavelength tunable, megawatt peak power solitons were generated in a photonic crystal rod at ~ 1700 nm, which enabled direct visualization of sub-cortical neurons for the first time in an intact mouse brain. Fiber-based sources have the potential to provide new performance parameters that are challenging for bulk solid state systems. New fiber-based sources will undoubtedly expand the boundaries of biomedical imaging.

8961-10, Session 3

1.5-um pulsed coherent fiber-optic lidar system for aircraft-based hazard detection

Shantanu Gupta, Wei Lu, Frank Kimpel, Jacob Hwang, Youming Chen, Xung Dang, Horacio Verdun, Fibertek, Inc. (United States)

First generation coherent lidar technology used CO2 lasers and Nd:YAG lasers, leading to room-size systems. With advancing laser technology, 2nd generation systems adopted injection-locked Tm/Ho: YAG (2-um) and Er:YAG (1.6-um) solid state laser technologies, and demonstrated that coherent lidar technology could accurately and reliably measure atmospheric phenomena. The charter for improved aviation safety calls for in-flight optical air-data sensor for detecting a variety of aviation hazards such as turbulence, wind-shear, and wake-vortices. The latter is particularly significant as it affects take-off and landing separation, in increasingly congested airports. This has prompted the development and demonstration of compact, reliable 3rd generation coherent lidar system for use in aircraft instrumentation, using fiber-optic and fiber laser technology.

In this paper, we report on the design and development of a 1.5-um Er-fiber-amplifier based, pulsed coherent fiber-optic lidar system, that is capable of detecting winds in clear air conditions at ranges representative of aircraft landing/take-off conditions. The system uses commercially available components leading to a cost-effective and reliable solution. State-of-the-art high-speed FPGA based programmable operation of the fiber-MOPA transmitter, 2-D scan pattern, and coherent detection via FFT algorithm, leads to real-time operation. The lidar signal processing can be optimized for various conditions, e.g. winds in clear air, in humid/overcast conditions, measuring cloud speed, slam range (i.e. ground hard-target) detection. We have designed, developed and tested a complete prototype lidar system, that produces up to 200?J/pulse at 25kHz repetition rate. Sub meter/sec velocity resolution is demonstrated in lab calibration, as well as a lidar backscatter return SNR sensitivity -140dB. Using this system, at low power of P(avg)~1W, we have also demonstrated line-of-sight (radial) velocity measurement of winds in clear air to ~0.7 km range, and speed of thin clouds at >2.1 km range. In this paper, we further discuss details of the design tradeoffs, test and characterization of the sub-systems and its impact on coherent lidar performance, with ongoing improvements for a multi-functional sensor.

8961-11, Session 3

High-power, narrowline, 1.5-um fiber-amplifier lidar transmitter for atmospheric CO2 detection

Wei Lu, Doruk Engin, Mark E. Storm, Shantanu Gupta, Fibertek, Inc. (United States)

The goal of the Active Sensing of CO2 Emissions over Nights, Days, and Seasons (ASCENDS) mission is to enhance understanding of the role of CO2 in the global carbon cycle. Several LIDAR methods have been proposed and demonstrated for CO2 detection, via airborne campaigns, for eventual transition to a space mission. A traditional choice of the laser is in the strong 2-µm absorption band of CO2, where Tm3+ and Ho3+-doped solid-state lasers are available. An alternate wavelength of interest for CO2 sensing is the weaker overtone absorption bands near 1.572-µm, where the mature, high-reliability 1.5-µm fiber-amplifier technology derived from fiber-optic telecom heritage can be exploited. This necessitates sufficient power scaling in 1.5-µm fiber-amplifiers in the L-band (1572nm), either in the in the CW-mode for modulation spectroscopy based integrated-path differential absorption lidar, or in the pulsed-mode for a direct-detection lidar. For accurate estimate of CO2 mixing ratio, measurement of atmospheric O2 is also needed, that can be accomplished via the frequency doubling of the 1529 nm Er-fiber amplifier output. Pressure broadened atmospheric lines dictate line widths <100 MHz.

We report on the design, development and testing of 1.57-um L-band fiber-laser architecture using Er/Yb-doped fibers and high-reliability 1.5-um fiber-optic components, meeting the desired requirements for lidar transmitter requirements for low earth orbit space mission. This consists of a stable narrow linewidth (<1MHz) seed laser diode, a programmable waveform pulse generator, and multiple stages of polarization-maintaining (PM) Er-doped fiber amplifiers with increasing mode-field area. Using this baseline architecture, we have demonstrated 10W CW output at 1572nm with more than 10% wall-plug efficiency. In pulsed operation, we demonstrated up to 475-?J energy per pulse at 1572.3nm, and up to 250-?J energy per pulse at 1529.1nm wavelength, for 1.5-?sec wide pulse at a 10 kHz repetition rate, at 100MHz line width. The output beam is diffraction limited, and the polarization-extinction-ratio (PER) is ~17dB. The optical to optical conversion efficiency is ~17% with respect to the total pump power.

8961-12, Session 3

High-power fiber lasers in geothermal, oil and gas *(Invited Paper)*

Mark S. Zediker, Foro Energy, Inc. (United States)

The subject of this paper is the requirements, design, fabrication, and testing of a prototype laser rock drilling system capable of penetrating even the hardest rocks found deep in the earth. The Oil and Gas industry still uses many of the technologies that were in use at the turn of the 19th century. The drilling industry started with a great innovation with the introduction of the tri-cone bit by Howard Hughes in 1908. Since then, the industry has modified and optimized drilling systems with incremental advancement in the ability to penetrate hard crystalline rock structures. Most oil producing reservoirs are located in or below relatively soft rock formations, however, with the growing need for energy, oil companies are now attempting to drill through very hard surface rock and deep ocean formations with limited success. This paper will discuss the types of laser suitable for this application, the requirements for putting lasers in the field, the technology needed to support this laser application and the test results of components developed specifically by Foro Energy for the drilling application.

8961-13, Session 4

Advanced hollow-core fibers: overcoming the challenges of polarization and modal control *(Invited Paper)*

John M. Fini, OFS Labs. (United States)

Hollow core fibers offer remarkable performance improvements in many systems, including ultra-low nonlinearity for high capacity transmission, minimum possible delay in a low-latency network, and high damage threshold for power delivery. Challenges intrinsic in hollow-core guidance have precluded many interesting applications: to achieve low-loss, conventional hollow-core fibers must give up single-modedness and polarization control. We report novel low-loss fibers eliminating unwanted modes using Perturbed Resonance for Improved Single-Modedness (PRISM), and simultaneously achieving polarization control. Using improved fabrication and design, these allow use of low-nonlinearity fibers in applications such as precision interferometry, where a well-controlled mode and polarization are required.

8961-14, Session 4

Design of double-cladding large mode area all-solid photonic bandgap fibers

Enrico Coscelli, Univ. degli Studi di Parma (Italy); Thomas T. Alkeskjold, NKT Photonics A/S (Denmark); Annamaria Cucinotta, Stefano Selleri, Univ. degli Studi di Parma (Italy)

Recently, all-solid Photonic Bandgap Fibers (PBGFs) have been appointed as one promising solution for the development of large mode area fibers to be employed in high power lasers and amplifiers. Nevertheless, most of the Large Mode Area (LMA) PBGFs reported so far are passive fibers, and very few designs of active Double Cladding (DC-) PBGFs have been developed, mostly limited to small core diameters. To fully exploit the good properties of all-solid PBGFs in high power amplifier systems, such as the capability to perform distributed filtering of amplified spontaneous emission, a further effort in the design of active LMA DC-PBGFs is required.

In active DC fibers, high differential gain between the Fundamental Mode (FM) and the High-Order Modes (HOMs) should be exploited for effective suppression of the latter ones, which can be achieved by delocalizing their mode field so that overlap with the active region is sufficiently low.

In this paper the single-mode properties of a wide range of active LMA DC-PBGFs have been numerically analyzed by means of a complex full-vector modal solver based on the finite-element method. Simulation results have shown that state-of art single-cladding PBGFs designs that provide high HOM losses in passive fibers are not necessarily able to efficiently delocalize the HOMs if the pump cladding is added. Innovative design approaches, relying on the coupling of the HOMs with cladding defects, have been considered to overcome this issue, providing effective HOM suppression while allowing bending down to coil diameter below 30cm.

8961-15, Session 4

Novel multifocus tomography for measurement of microstructured and multicore optical fibers

Andrew D. Yablon, Interfiber Analysis (United States)

A novel multifocus tomographic algorithm for reconstructing an optical fiber's cross sectional refractive index distribution from transverse projections is described. This new algorithm is validated against measurements of both microstructured and multicore optical fibers, which were not previously measurable. Optical fiber tomographic measurements recently made by several research groups using different technologies have all suffered from the same limitation, namely that typical fiber diameters (several hundred microns) exceed the imaging depth-of-field (approximately one micron) by several orders of magnitude. The new algorithm combines data acquired from a multiplicity of focal planes to overcome this limitation, yielding measurements with extremely fine spatial resolution over large transverse dimensions, thereby providing the first-ever high quality measurements of microstructured and multicore fibers. This new measurement approach is broadly applicable to any tomographic problem in which the depth-of-field is greatly exceeded by the transverse dimension of the specimen. Many types of transverse optical fiber measurement technologies, including interference microscopy, quantitative phase microscopy (QPM), residual stress measurement, differential interference contrast (DIC) microscopy, and spontaneous emission tomography will benefit from this new algorithm, which will greatly facilitate characterization of optical fibers for high-power applications.

8961-16, Session 4

Kagome fiber beam delivery of high-energy ultrafast laser and application to microprocessing

Benoit Debord, Madhoussoudhana Dontabactouny, Meshaal Alharbi, Coralie Fourcade-Dutin, XLIM Institut de Recherche (France); Clemens Hönninger, Eric P. Mottay, Amplitude Systèmes (France); Frederic Gérôme, XLIM Institut de Recherche (France); Fetah A. Benabid, GLOphotonics SAS (France) and XLIM Institut de Recherche (France)

Ultrafast lasers are now used in a growing number of industrial applications, thanks to their increasing average power and ability to precisely process material with virtually no heat dissipation or thermal effects. On the other hand, fiber delivery of high power lasers has changed industrial laser processing by offering higher flexibility in demanding manufacturing environments. Until recently, ultrafast lasers could not benefit from this flexibility, since the high intensity of the beam prevented high energy propagation in optical fibers.

We present a new fiber delivery system of ultrafast lasers, using a Kagome type hypocycloid core Kagome photonics crystal fiber. This fiber exhibits losses as low as 45 dB/km. We report on propagation of 500 fs, 1 mJ pulses over a distance up to 10 m. By gas filling of the fiber hollow core, we were also able to demonstrate compression down to 49 fs, and peak intensity up to 0.3 PW/cm2.

Transmission measurements between 70 and 80% were measured, depending whether the core was filled with air or Helium. No observable damage to the fiber structure was recorded. The fiber guided the beam with near single mode operation (M2 ~1.2, unchanged from laser output), and no significant change in mode area or M2 upon fiber bending.

We finally demonstrate ultrafast laser ablation and micromachining on glass, metal and semiconductor materials and discuss future systems requirements.

8961-17, Session 4

Negative curvature hollow core fibers: design, fabrication, and applications *(Invited Paper)*

Andrey D. Pryamikov, Fiber Optics Research Ctr. (Russian Federation)

The hollow core microstructured fibers (HC MOFs) confine the light inside a hollow core surrounded by a microstructured cladding. Recently, a new type of HC MOFs with a negative curvature of the

core – cladding boundary and a simplified cladding has been proposed. Such construction of HC MOF leads to a complication of the boundary conditions for the core modes and strengthen their localization in the air core. Negative curvature silica HC MOFs guide the light in mid IR spectral range where the material loss of silica glass is very high. Negative curvature HC MOFs have a great potential for different applications.

8961-18, Session 5

Scaling peak power in ultrafast fiber lasers *(Invited Paper)*

Jens Limpert, Friedrich-Schiller-Univ. Jena (Germany)

The recent demonstration of rare-earth-doped fiber lasers with a continuous-wave output power approaching the 10 kW-level with diffraction-limited beam quality has proven that fiber lasers constitute a power-scalable solid-state laser concept. To generate intense ultrashort pulses from a fiber several fundamental limitations have to be overcome. Nevertheless, novel experimental strategies, including coherent combination, and very large mode area fiber designs offer an enormous potential towards ultrafast laser systems with high average powers (>kW) and high peak power (several GW, potentially even TW-class peak power). The challenges, achievements and perspectives of ultrashort pulse generation and amplification in fibers will be reviewed.

8961-19, Session 5

Towards high-power and high-energy femtosecond fiber lasers

Peng Wan, Lih-Mei Yang, Jian Liu, PolarOnyx, Inc. (United States)

This paper presents the newest development of high power and high energy ultrafast fiber lasers in 1 μm and 2 μm regimes at PolarOnyx Inc.

In the kW Yb doped fiber laser experiment, a 1064 nm seed laser (PolarOnyx Laser, Uranus series, stretched to 1 ns) at an average power of 50 W at repetition rate of 80 MHz was injected into a kW power amplifier which is assembled with a double cladding (40/400) LMA fiber to boost the average power to 1050W. The pulse duration of 850 fs is obtained after grating compressor.

In another mJ pulse energy experiment, a Yb doped PCF amplifier is seeded with a 1030 nm fiber laser (PolarOnyx Laser, Uranus series, 50 μJ at 100 kHz). The PCF amplifier boosts pulse energy to 1.1 mJ before compression and 0.82 mJ after compression with pulse duration of 710 fs.

In the Tm-doped fiber laser experiment, an average power of up to 76W is achieved at wavelength of 2012 nm. In the seed oscillator, a chirped fiber Bragg grating is used to compensate the anomalous dispersion from regular fiber. The seed oscillator is designed to generate pulse train at repetition rate of 31 MHz. After multiple-stage fiber amplifier with chirped pulse amplification, an average power of 76 W is achieved. High efficient pulse compression is realized with Chirped Bragg Gratings (OptiGrate), and pulse duration is 870 fs.

8961-20, Session 5

Divided-pulse nonlinear compression

Florent Guichard, Yoann Zaouter, Amplitude Systèmes (France); Marc Hanna, Frédéric Druon, Lab. Charles Fabry (France); Eric P. Mottay, Amplitude Systèmes (France); Patrick Georges, Lab. Charles Fabry (France)

Nonlinear post-compression is a well-established technique to reduce the pulse duration of high power, high energy femtosecond laser systems. In such systems, the incident laser field is strongly confined in a solid-core fiber, Kagome-type hollow-core fiber or a gas-filled capillary that preserve a high intensity over an extended distance, and allow large spectral broadening via self-phase modulation. Suppression of the induced chirp produced by the nonlinear interaction in the medium with appropriate dispersive elements then leads to pulse-shortening. However, these systems are limited in output energy by various effects such as gas-ionization, self-focusing, or optical damage. These phenomena limit the scalability of the above-mentioned approaches to few-mJ for capillary setups and the μJ-level when using fused-silica fibers. In this contribution, we implement a passive spatio-temporal coherent combining scheme in order to scale the energy of such systems. In a proof of principle experiment we demonstrate the generation of 7.5 μJ 71 fs pulses in a solid-core fiber. Multi-μJ output energy beyond the self-focusing critical power of silica is achieved by temporally and spatially dividing the incident pulse in 32 replicas, thereby reducing the peak power by the same factor. Spectral broadening occurs in a 45 μm mode-field diameter rod-type fiber before coherent combination of the replicas to reconstruct a single output pulse. The system efficiency is studied as a function of increasing number of replicas, revealing a weak dependence on the number of temporal division stages. These results represent, to our knowledge, the first use of coherent combining outside the context of optical amplifiers, and show that it can be used in any energy-limited optical setup, including systems that manipulate sub-100 fs pulses.

8961-21, Session 5

Analysis of divided-pulse amplification for high-energy extraction

Marco Kienel, Arno Klenke, Steffen Hädrich, Tino Eidam, 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 performance scaling of femtosecond laser systems to even higher levels while maintaining high beam quality becomes challenging due to the occurrence of nonlinear effects, thermo-optic effects, and optically induced damage. In addition to state-of-the-art techniques to reduce the intensity during amplification further, the coherent beam combination is a promising approach. In principle, it can be divided into spatially and temporally separated amplification, where especially the latter case, referred to as divided-pulse amplification, is a promising technique for optical fibers, which are capable of storing a high amount of energy that typically is not extractable with a single ultrashort pulse. Typically, so-called passive beam combining implementations are employed, which benefit from intrinsic phase adaption of the divided pulses. However, saturation of the amplifier in the high pulse-energy regime causes a drastic degradation of the combining efficiency.

In this contribution the energy-scaling potential of such passive divided-pulse amplification implementations is analyzed by means of a simplified model. It is shown that the symmetry requirements lead to a drop in efficiency resulting from a deformation of the pulse train shape based on saturation and the resulting nonlinear phase differences. As solution an active divided-pulse amplification implementation is presented, which breaks the symmetry requirements allowing for an independent control of the amplified output pulse train from the input pulse train and efficient recombination at high pulse energies. With this 380 fs pulses at 1 mJ has been achieved. Moreover, a 6.5 mJ amplified pulse train has been achieved without damaging the fiber.

8961-22, Session 5

215 µJ, 16 W femtosecond fiber laser for precision industrial micro-machining

Kyungbum Kim, Xiang Peng, Wangkuen Lee, Raydiance, Inc. (United States); Xinhua Gu, JDSU (United States); Michael M. Mielke, Raydiance, Inc. (United States)

Within the last few years, a robust market has developed for femtosecond lasers that enable precision micro-machining with high speed, consistency and reliability in factories around the world—where temperature, humidity, debris and handling conditions rule out the use of conventional femtosecond lasers. In this presentation, we will describe the design of our industrial grade femtosecond fiber lasers and demonstrate unprecedented performance at 215 ?J pulse energy, ~510 fs pulse duration and 16 W average power from a monolithic fiber chirped pulse amplifier chain. The laser system architecture is based on the well-known chirped pulse amplification (CPA) technique to minimize self-phase modulation (SPM) during the amplification of high peak power pulses. The light generation and amplification stages comprise a monolithic fiber chain, where all components and subassemblies are sequentially fusion spliced. A key high-energy enabling feature of the laser system is the core-pumped, large mode area (LMA) erbium fiber amplifier. The fiber gain block has mode field area (MFA) of 1060 ?m2 and sustains single mode propagation owing to the combination of fiber design, optimized input mode launch, core pumping to isolate gain to the fundamental mode, and proper fiber mounting technique. The output spatial beam comprises the fundamental Gaussian mode with diameter of 6 mm, divergence <1 mrad, and M2< 1.3. Further details of these characteristics, along with all other relevant laser system performance, will be illustrated in the presentation.

8961-23, Session 6

Realizing the first low-loss optical fibers *(Invited Paper)*

Donald B. Keck, Corning Incorporated (United States)

Over 40 years ago, a Corning Inc. team invented the first low-loss optical fiber usable for telecommunications. This critical breakthrough started a global effort that resulted in the Information Age in which we live. Some of the stories of this fiber-invention will be shared together with other thoughts concerning this technological revolution.

8961-24, Session 6

Fibre lasers: Past, present, and what next? *(Invited Paper)*

David N. Payne, Univ. of Southampton (United Kingdom)

No Abstract Available

8961-25, Session 6

The first fiber Raman amplifiers and lasers *(Invited Paper)*

Rogers H. Stolen, Clemson Univ. Research Foundation (United States)

Fiber nonlinear optics has become a huge field since its inception over 40 years ago. Fiber Raman lasers and amplifiers find application in optical communications and the simple fiber geometry has contributed to understanding of optical nonlinearities and solitons. Nonlinearities can also limit optical power in fiber lasers and distort signals in optical communications. Fear of these negative limitations stimulated the first investigations of Raman amplification in optical fibers. Here we review some of those first efforts to observe and study Raman amplification and Raman lasers in fibers and give credit to some of the researchers involved in that work.

8961-26, Session 7

Nanowires in photonic crystal fibers: from plasmonics towards nonlinear optics *(Invited Paper)*

Markus A. Schmidt, Institut für Photonische Technologien e.V. (Germany); Patrick Uebel, Nicolai Granzow, Philip St. John Russell, Max-Planck-Institut für die Physik des Lichts (Germany)

Placing large aspect?ratio nanowires made from metals or soft glasses into fibers leads to new application areas of optical fibers. Using our pressure?assisted melt?filling approach various hybrid fibers have been fabricated by filling the air holes of photonic crystal fibers with materials such as noble metals, semiconductors, fluids or low?melting compound glasses. In this talk I will review our latest results on plasmonic molecule formation by hybridization of spiraling plasmons on metallic nanowires, experimentally measured near field distributions of plasmonic supermodes, plasmonic hot?spot generation used nanotip fibers, large extinction?ratio band gap guidance and mid infrared supercontinuum generation using chalcogenide?silica fiber.

8961-27, Session 7

Fibers design with a bend-compensated cladding for distributed wavelength filtering

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Fiber designs are proposed that allow distributed wavelength filtering far more selective than conventional designs, and which is consistent with conventional fiber fabrication. By including a gradient that pre-compensates the bend perturbation in the cladding, the proposed designs overcome the usual tradeoff between mode area and wavelength selectivity. Simulations shows that the resulting fiber performance enables delivery of multi-kW signals over long distances with modest net Raman gain, using bend-resistant fibers of convenient core size.

8961-28, Session 7

Yb3+ doped ribbon fiber for high-average power lasers and amplifiers

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Diffraction-limited high power lasers in the region of 10s of kW to greater than 100 kW are needed for defense, manufacturing and future science applications. A balance of thermal lensing and Stimulated Brillouin Scattering (SBS) for narrowband amplifiers and Stimulated Raman Scattering (SRS) for broadband amplifiers is likely to limit the average power of circular core fiber amplifiers to 2 kW (narrowband) or 36 kW (broadband). A ribbon fiber, which has a rectangular core, operating in a high order mode can overcome these obstacles by increasing mode area without becoming thermal lens limited and without the on-axis intensity peak associated with circular high order modes. High order ribbon fiber modes can also be converted to a fundamental Gaussian mode with high efficiency for applications in which this is necessary [5][6]. We present an Yb-doped, air clad, optical fiber having an elongated, ribbon-like core

having an effective mode area of area of 600 μm? and an aspect ratio of 13:1. As an amplifier, the fiber produced 50% slope efficiency and a seed-limited power of 10.5 W, a gain of 24 dB. As an oscillator, the fiber produced multimode power above 40 W with 71% slope efficiency and single mode power above 5 W with 44% slope efficiency. The multimode M2 beam quality factor of the fiber was 1.8 in the narrow dimension and 15 in the wide dimension.

8961-29, Session 7

Low-loss hybrid fiber with zero dispersion wavelength shifted to 1 μm

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We propose a novel cylindrically symmetric hybrid fiber design that allows combining properties of the both fibers guiding light due to total internal reflection (low optical losses) and photonic bandgap fibers (anomalous dispersion at 1 um). Refractive index profile of these fibers consist of the only few layers: low-index core (ncore-nsilica>0) surrounded with one or more high-index ring layers (nhigh-ncore>0), a depressed layer (ndepress-nsilica<0) and silica cladding. Operating mode is one of the high-order modes (depending on high-index ring layers number) with intensity maximum at fiber axis. Because the other modes (including the fundamental mode LP01) are guided in the high-index ring layer(s) the hybrid mode can be easily excited by splicing hybrid fiber and standard single-mode (l~1um) step-index fiber with appropriate mode field diameter. Moreover method of achievement of asymptotically singlemode regime of light propagation (suppression of the high-index ring layer modes) has been proposed. The main idea of it is doping narrow strong absorbing layer where hybrid mode has intensity of electric field closed to zero. Furthermore we have considered possibility to increase anomalous dispersion of the hybrid fiber (up to 80 ps/nm km) by usage more complicated refractive index profile with two high-index ring layers.

In this work we have fabricated the technologically simplest hybrid fiber with the only one high-index layer. The hybrid LP02 core mode had dispersion of 13 ps/(nm*km) and optical loss of about 6 dB/km. Propagation of chirped pulses through the fabricated hybrid fiber allowed us to compress them from 8ps to 330fs.

8961-30, Session 8

3kW single-mode direct diode-pumped fiber laser

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Ytterbium-doped fiber lasers are well known for their capability of producing high power laser radiation at around 1-1.1?m wavelengths with excellent beam quality and high Electrical-to-Optical (EO) efficiency over 30%. CW single-mode fiber lasers have been scaled up to 10kW recently. Nevertheless, power scaling of single-mode fiber lasers is not straight forward mainly due to parasitic nonlinear effects in the fiber cavity and limited pump diodes brightness. Direct diode-pumped single-mode fiber lasers have been limited to 1-2kW. Scaling single-mode fiber lasers beyond 2kW has relied on tandem pumping by short wavelength fiber lasers. The tandem pumping scheme complicates the laser design and significantly reduces EO efficiency.

We present a 3kW single-mode fiber laser based on an Yb-doped LMA fiber operating at 1080nm. We have developed the capability of multi-kW single-mode operation through fiber process development of significantly lower numerical apertures, (0.04-0.05) than the generally accepted limit for chemical vapor deposition processes. The fiber core area is about two times larger than typical commercial LMA fibers used for kW single-mode laser operation. This larger effective area allows us to suppress detrimental nonlinear effects at higher powers while the low NA enables a larger coiling diameter, eliminating bend induced mode distortions which limit effective area scaling in LMA fibers. The large core also allows for larger cladding that relieves the requirement for brightness of pump diodes. The laser is pumped by 9xxnm diode bars stacks and believed to be the highest power direct diode pumped single-mode fiber laser oscillator to date.

8961-31, Session 8

146 W continuous wave Ytterbium-doped fiber amplifier at 1009 nm

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The power scaling of Ytterbium-doped fiber laser systems is limited by several effects especially nonlinearities and fiber induced thermal loads. Commonly Ytterbium-doped fiber lasers are pumped between 910nm and 976nm, the wavelength range where Ytterbium has high absorption and diodes with high power are available. In order to decrease the quantum defect and thus to reduce the thermal load the usage of longer wavelengths than 976nm is an advantage. Since the Ytterbium absorption is significantly reduced above the zero-phonon line high brightness sources are necessary to achieve the needed pump-absorption in a so-called tandem pumping setup. We demonstrate a single-mode continuous-wave laser amplifier with 146W of power at a wavelength of 1009nm. On one hand this experiments constitutes an extension of the wavelength range of high power fiber lasers, furthermore, emission-wavelength well below 1030nm find use for efficient high-brightness tandem pumping of high-power fiber amplifiers. The wavelength and bandwidth of the seed-oscillator are defined by a pair of fiber-bragg-gratings. This seed is amplified in a two-stage Ytterbium-doped rod-type amplifier to 146W with a high slope-efficiency of 64%, an excellent beam-quality and stability and an ASE-suppression as high as 63dB. This is to our knowledge the highest power in fundamental-mode operation obtained at this wavelength so far. Suppression of ASE plays an important part in the amplification of short wavelength amplification because of the much higher gain in the 1030 nm region. Thus, the presented amplifier is an excellent pump source for tandem-amplification, potentially also for ultra-short pulse tandem amplification.

8961-32, Session 8

Yb-free Er-doped all-fiber amplifier cladding-pumped at 976 nm with output power in excess of 100 W

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Power scaling of Yb-free Er-doped fiber lasers cladding-pumped at 976 nm is extremely challenging due to low Er ion absorption cross-section and growth of unbleachable loss at high Er concentrations because of clustering effects. Hence, usual double-clad Er-doped fibers suffer from low efficiency. We present an efficient high power all-fiber amplifier based on our newly developed Yb-free Er-doped fiber.

Proper core composition and relatively low Er3+ concentration mitigates clustering effect. Furthermore, large single-mode core diameter of 34 um increases the pump absorption and decreases the fiber length.

Our amplifier consists in the specialty Er fiber pumped through a commercially available pump combiner by means of 6 pigtailed multimode diodes (D=105 um, NA=0.15, input pump power of 275W). The signal source is a low power continuous wave fiber laser spliced to the amplifier. Therefore we built truly all-fiber laser without any free space coupling.

We obtained 103 W of amplified signal limited only by the available pump power. Pump conversion efficiency is as high as 37 %. To the best of our knowledge this is the highest power ever demonstrated for Yb-free Er-doped lasers pumped at 976 nm. This power level is to that obtained in resonantly pumped Er-doped fiber lasers

8961-33, Session 8

>450W gain-switched-diode-seeded, single-polarization, picosecond fiber MOPA

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High-power lasers operating in the picosecond regime are currently in demand for a number of applications including laser micro-machining, material processing and the pumping of parametric oscillators. Picosecond fiber lasers offer great advantages in terms of compactness, efficiency, hassle-free operation and thermal management as compared to their bulk laser counterparts. By exploiting a master oscillator power amplifier architecture, seeded by a gain switched laser diode generating pulses of 28ps pulse duration, we have demonstrated a single polarization, monolithic all-fiber system at 1040nm delivering a record 455W of average power in a diffraction-limited output beam. The polarization extinction ratio was measured to be 17dB and the M2 < 1.2. The pulse repetition frequency was 214MHz, yielding an estimated pulse energy of 2.1µJ and a corresponding peak power of 76kW. Although an SRS peak at 1090nm was clearly observable at the maximum operating power (at -30dB relative to the signal) it contained only 0.38% of the total optical power. Moreover no roll-over in output power with respect to the launched pump power was observed indicating that further power scaling should be possible in due course with a brighter pump source/improved pump coupling. The spectral bandwidth of the seed laser broadened from 0.12nm to 2.4nm at 455W of output power due primarily to SPM. It should therefore be possible to compress the pulses substantially towards the femtosecond regime and to achieve MW peak power levels in due course.

8961-34, Session 8

Investigation of a large core 976 nm Yb fiber laser for high brightness fiber-based pump sources

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We present three level laser operation at 976 nm of a large-core Yb-doped aluminosilicate fiber, which is fabricated by powder-sinter technology and shows a very homogeneous refractive index profile. The investigated fiber has a core diameter of 125 µm and a numerical aperture (NA) of 0.18, well-matched to standard fiber coupled pump diode. The core composition has been optimized to reduce photodarkening effects. Multimode operation around 976 nm is observed delivering about 5 W output with a slope efficiency of 70%. In addition we present a tapered resonator containing a Fiber Bragg grating to realize single mode operation with multiple Watts output power. This fiber laser source could be useful to realize high brightness fiber coupled pump sources.

8961-66, Session PTue

High-brightness, fiber-coupled pump modules in fiber laser applications

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High-power, high-brightness, fiber-coupled pump modules enable high-performance industrial fiber laser systems with simple system architectures, multi-kW output powers, excellent beam quality, unsurpassed reliability, and low initial and operating costs. We report recent development of single-emitter-based, 60 W and 120 W, 9xx nm pump modules coupled into 105 µm fiber with a 0.14 NA beam. This combination of high power and high brightness translates into improved fiber laser performance, e.g., simultaneously achieving high nonlinear thresholds and excellent beam quality at kW power levels. We discuss how the pump performance influences the design of the active fiber, enabling an increase in system efficiency and/or threshold for nonlinear processes such as stimulated Raman scattering and stimulated Brillouin scattering. We report spatial beam combination of the pump modules using fused-fiber combiners with very low loss, enabled by the low NA of the pumps. We demonstrate the use of volume holographic gratings in spectrally stabilized pump modules and characterize the wavelength-locking current and temperature ranges; 976 nm wavelength-stabilized pumps are of particular interest for power scaling of diffraction-limited fiber sources. Finally, we show results of extensive reliability tests of both chips and fiber-coupled pumps under accelerated and real-world operating conditions, and we discuss the high overall fiber laser system reliability enabled by the pump performance.

8961-67, Session PTue

Experimental study of SBS suppression via white noise phase modulation

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Power scaling of narrow linewidth high-power optical fiber lasers is limited due to the onset of stimulated Brillouin scattering (SBS). Many

techniques have been created to broaden the linewidth of a seed laser and increase the SBS threshold. One technique, white noise source (WNS) phase modulation, has found useful applications in the construction of high power fiber amplifiers. Theoretical models have been developed to describe the effect of white noise phase modulation as a function of linewidth and fiber length on the SBS enhancement factor , but have yet to be experimentally validated.

To produce the WNS phase modulated optical signal, we use an RF WNS to generate a uniformly random distribution of voltage fluctuations over a broad range of frequencies. This RF signal is amplified and filtered with low-pass filters before being applied to an electro-optic phase modulator (EOM), where the optical signal of a seed laser is modulated, broadening the line width of the seed laser. We amplify this modulated signal up to 90 W using an ytterbium-doped fiber with a core diameter of 10 µm and a cladding diameter of 125 µm. The output power is then used in a cut-back experiment to study the SBS threshold in a passive 10/125 PM fiber spliced onto the Yb-doped amplifier. Detailed studies describing SBS enhancement factors as functions of linewidth and fiber length will be presented. In addition, the experimental results will be compared to phase modulation models of the SBS process in optical fibers.

8961-68, Session PTue

High-energy, high-average and peak-power phosphate-glass fiber amplifiers for 1micron band

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High energy fiber amplifiers have seen tremendous advances over the past decade. Common silica fibers can not be doped at high concentrations of rare earth ions due to prohibitive side-effects. Therefore, the fiber length has to be increased for efficient amplification (usually 5-10m). This is undesirable due to nonlinearities that grow with length. In contrast, phosphate-glass based fibers can be highly doped without any side-effects, and hence can provide high gain in short lengths (less than 0.5m). This enables an ideal pulsed fiber amplifier that maximizes the energy extraction and minimizes the nonlinearities.

For SBS dominated transform-limited long pulses (> ~20ns), with a ~0.25m Yb-doped phosphate-glass fiber amplifier, we have initially achieved greater than 1kW peak power, 100µJ energy, and 1W average power at 1.06µm (10kHz , 100ns). The amplifier fiber was inherently single transverse mode (SM) and polarization-maintaining (PM).

For nanosecond and picosecond (short) pulse widths, SRS and CHI3 nonlinearities such as SPM are dominant. For direct amplification and CPA of 10ps-1ns pulses, the B-integral has to stay below ? to maintain the fidelity of the pulse shape and spectral phase (i.e. compressibility for CPA). In this regime, we have initially achieved greater than 45kW peak power, 90µJ energy, and 32W average power at 1.06µm (0.2-1MHz, 2ns) with a ~0.45m phosphate amplifier, again with inherent SM and PM operation.

These initial results were limited by the seed and pump powers, and not by nonlinearities. We will present our latest results on long and short pulse regimes at the conference.

8961-69, Session PTue

Coherent combining of SHG converters through active phase control of the fundamental waves

Anne Durécu, Cassandra Aubert, Guillaume Canat, Julien Le Gouët, Laurent Lombard, Pierre Bourdon, ONERA (France)

Coherent beam combining (CBC) by active phase control has proven to be an efficient and scalable way to increase the output power delivered by fiber laser systems. This study investigates the potential of this technique when applied to another type of laser sources: nonlinear optical frequency converters.

Given that the efficiency of nonlinear conversion processes, here Second Harmonic Generation, relies on a phase-matching condition between the fundamental and the harmonic waves, an indirect control of the phase of an SHG beam through the fundamental wave is theoretically possible.

This paper experimentally demonstrates such indirect phase control and its application to CBC of frequency converters. Two continuous-wave 1.55-µm fiber amplifiers are frequency doubled in PPLN crystals to generate 775-nm beams. These SH beams are coherently combined using frequency-tagging active phase control. A standard fibered electro-optic modulator (EOM) is used to control the phase of one of the 1.55-µm fiber amplifiers. This EOM provides both phase modulation for frequency-tagging and proper phase shifts to compensate for the phase fluctuations of the other 1.55-µm amplifier. The SH beams generated in a tiled-configuration are overlapped in the far-field. Collection of the intensity in one lobe of the far-field interference pattern provides the feedback signal necessary to close the phase-locking loop.

Efficient coherent combining of the two 775-nm beams is successfully achieved through phase control of one of the 1.55-µm fiber amplifiers. A lambda/19.5 residual phase error is measured. Finally, the limits of CBC applied to frequency converters are discussed.

8961-70, Session PTue

Actively Q-switched single-frequency fiber laser at 978nm using highly ytterbium-doped silica fiber

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A single frequency actively Q-switched DBR all fiber laser at 978 nm was developed by using a 2-cm long commercial ytterbium-doped silica fiber and a pair of silica fiber Bragg gratings. The Q-switching is enabled by the stress-induced polarization modulation in the short linear fiber laser cavity. The laser generates actively Q-switched single-frequency laser pulses with a pulse repetition rate ranging from tens of kilohertz to hundreds of kilohertz. This is, to our best knowledge, the first demonstration of a single frequency all-fiber Q-switched laser below 1 ?m using commercial highly ytterbium-doped silica fiber.

8961-71, Session PTue

Ho-doped fiber for high-energy laser applications

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Ho-doped fiber lasers are of interest for directed energy applications because they operate in the eye safer wavelength range and in a window of high atmospheric transmission. Because they can be resonantly pumped for low quantum defect operation, thermal management issues are anticipated to be tractable. A key issue that must be addressed in order to achieve high efficiency and minimize thermal issues is parasitic absorption in the fiber itself. Hydroxyl contamination arising from the process for making the Ho-doped fiber core is the principal offender due to a combination band of Si-O and O-H vibrations that absorbs at 2.2 ?m in the Ho3+ emission wavelength region. We report significant progress in lowering the OH content to 0.16 ppm, which we believe is a record level. Fiber experiments using a 1.94 ?m thulium fiber laser to resonantly pump triple clad Ho-doped core fibers have shown a slope efficiency of 62%, which we also believe is a record. Although we were pump-power limited, the results of these studies demonstrate the feasibility of power scaling Ho-doped fiber lasers well above the currently-reported 400-W level.

8961-72, Session PTue

Mitigation of photodarkening in Yb-doped lasers based on Al-silicate fibers

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In this paper, we investigate the impact of visible radiation on photodarkening generation in Yb-doped fiber laser. Simultaneous photodarkening and photobleaching effects induced by 976 nm and blue and red radiations respectively were investigated in a 1070 nm laser and compared to the loss induced in an irradiated active fiber. We observed a significant photobleaching effect due to 405 nm radiation but not complete recovery. A strong absorption of the 405 nm radiation by the excited ions (ESA) was also observed and could be the limiting factor for the bleaching performance. We also observed for the first time, to the best of our knowledge, ground-state absorption induced photodarkening in pristine fiber irradiated at 405 nm.

This effect could generate additional residual losses in the laser system.

8961-73, Session PTue

All-fiber Raman oscillator for the generation of radially and azimuthally polarized beams

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Many applications such as material processing, optical tweezers and microscopic setups will benefit from radially and azimuthally polarized beams due to their unique non-uniform polarization characteristic and doughnut-shaped beam profiles. Here we demonstrate a Raman fiber oscillator for the generation of radially and azimuthally polarized beams consisting of a high NA fiber and two Fiber-Bragg Gratings (FBGs). Due to the high NA of the fiber, the radially and azimuthally polarized modes are guided with their own effective refractive indexes and, in this case, the FBGs reflect these modes at different wavelengths. By controlling the coupling lens and the polarization of the pump beam, the mode that will oscillate can be selected. However, at the output of the fiber oscillator a non-circularly symmetric intensity profile as a consequence of a slightly elliptical fiber core is observed. Consequently, the influence of elliptical cores on the lifting of the polarization degeneracy has been analyzed in detail. In order to compensate for the elliptical core we applied a transverse force on the last few cm of the fiber. With this force the waveguide characteristic of the fiber is changed in such a way that a radially or azimuthally polarized doughnut-shaped beam profile is observed. Thereby an output power of 480mW (400mW) was reached for the azimuthal (radial) polarization. The presented concept is wavelength independent and suitable for all-fiber microscopic setups, especially for STED-microscopy.

8961-74, Session PTue

Optimization of laser fibers for high pump light absorption

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For the implementation of novel fiber laser concepts, such as extra-large mode area (X-LMA) fiber lasers or multi-core fiber lasers alternative manufacturing processes for highly-doped silica glasses and the laser fibers created from it are required. For efficient laser operation a high efficiency of absorption of pump power in the active fiber core is a necessary condition. To increase the pump light absorption the fiber development aimed at the preparation of laser-active and adapted passive single-large core fibers up to multi-core structures with 7 large cores showing broken circular fiber symmetry. The optimization of the optical fibers which will be shown in detail is based on the combination of several innovative manufacturing methods such as the powder sintering technology (REPUSIL), the preform preparation by stack-and-draw technique and the fiber drawing process. The described procedure is particularly suitable to produce multifilament glass preforms resp. laser fibers with large cores in which the radial and lateral indices of refraction can be adjusted homogeneously and reproducibly. Due to the realized increase of the laser-active core volume in these fibers the pump light absorption could be considerably increased and the shorter fiber length that results from it allows the use of fibers with a moderate residual attenuation. The results concerning the characterization of materials science and the optical aspects e. g. the dopant concentration distributions and related refractive index profiles as well attenuation and pump absorption spectra will be presented. Furthermore, the photodarkening behavior of the developed laser fibers will be discussed.

8961-75, Session PTue

Completely monolithic linearly polarized high-power fiber laser oscillator

Steffen Belke, Frank Becker, Benjamin Neumann, Stefan Ruppik, Ulrich Hefter, ROFIN-SINAR Laser GmbH (Germany)

We have demonstrated a linearly polarized cw all-in-fiber oscillator providing more than 500W of output power and a polarization extinction ratio (PER) of 18,6dB. The design of the laser oscillator is simple and consists of an Yb-doped polarization maintaining large mode area (PLMA) fiber and suitable fiber Bragg gratings (FBG) in matching un-doped PLMA fibers. Pump power is delivered via a high power 6+1:1 pump coupler. A QBH fiber optic cable as standard for high power laser ensures a safe delivery of the beam to external optics. The design enables power scaling beyond the kW regime and increased PER above 20dB maintaining the electro/optical efficiency of approximately 30%, which is in the range of non-polarized fiber lasers. Higher power levels will be investigated in the nearest future.

Choosing an adequate bending diameter for the Yb-doped PLMA fiber suppresses one polarization mode as well as higher order modes, resulting in a compact and robust linearly polarized high power single mode laser without external polarizing components. To be suitable for industrial use, this fiber laser oscillator is fitted into a 19” rack unit.

Linearly polarized lasers are well established for one dimensional cutting or welding applications. Using beam shaping optics radially polarized laser light can be generated to be independent from the angle of incident to the processing surface. Furthermore, high power linearly polarized laser light is fundamental for nonlinear frequency conversion of nonlinear materials.

8961-76, Session PTue

Vector modulation instabilities in high-energy narrow-bandwidth nanosecond pulsed polarization-maintaining ytterbium-doped single-mode fiber amplifier

Emmanuel Hugonnot, Commissariat à l'Énergie Atomique (France); Pierre Calvet, Commissariat à l'Énergie Atomique (France) and Univ. des Sciences et Technologies de Lille (France); Arnaud Mussot, Univ. des Sciences et Technologies de Lille (France); Guillaume Tison, Agnes Mahe, Eric Freysz, Univ. Bordeaux 1 (France)

Ytterbium fiber laser technologies have proven their capability to deliver high-power and high-energy pulses. However, non-linear effects occurring inside the core of the fiber represent the principal limitation for pulse peak power. Along this line, we have recently observed wavelength conversion of the nanosecond amplified pulse to non-traditional colours at the output of polarization-maintaining large-mode-area fiber amplifiers. We will show that these phenomena recorded in the forward and backward direction can be associated to modulation instability.

To investigate the vector modulation instability occurring when both polarizations of the fiber are excited, we performed numerical study combining coupled-mode generalized nonlinear Schrödinger equations for propagation and rate equations for ytterbium amplification. In agreement with experimental observations, our results show that after amplification and propagation of a nanosecond pulse injected on the slow axis of the amplifying fiber, two MI sidebands are clearly obtained at 800 nm and 1580 nm on the fast axis. When the laser wave is injected on the fast axis, there is no sideband and when it is injected at 45° of the axis, we obtain MI sidebands close to the laser wavelength. Since, we find no way to obtain phase matched process in the backward direction; we considered the reflexions occurring at the output of fiber amplifier. Even if these backward pulses are less powerful, this leads to an optical parametric amplification process. Our numerical simulations indicate that this process can indeed account very well for the MI instabilities recorded in the backward direction.

8961-77, Session PTue

Single-crystal, rare-earth doped YAG fiber lasers grown by the laser-heated pedestal growth technique

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1. Introduction

Traditional fiber lasers are made of glass. Glass fiber lasers typically involve a double-clad structure in which the core glass has been doped with a variety of rare-earth ions. While conventional glass fiber lasers deliver very high power there are some limitations to power scaling of these fibers which results from laser damage to the small cores, low stimulated Brillouin scattering (SBS) thresholds, and low thermal conductivity. In contrast to glass fiber lasers, single-crystal (SC) fiber lasers made from rare-earth doped crystalline materials such as YAG afford the possibility of delivering extremely high powers. That is, SC fiber lasers would be scalable to much higher power levels compared to their glass counterpart.

2. Fabrication

The approach we have used to fabricate SC fibers is Laser Heated Pedestal Growth (LHPG). In this well-established technique, the tip of a 1-mm diameter ceramic or rare-earth doped SC YAG source rod is melted with a CO_2 laser and an SC fiber is pulled from the molten oxide[1,2]. Figure 1 shows a sketch of the LHPG apparatus. The SC fibers that we have grown to date are as long as 1 m with diameters ranging from 150 to 330 ?m.

3. Measurements and Results

The spectral loss for an SC YAG fiber is given in Fig. 2. The peak at 4.7 ?m is an intrinsic multiphonon absorption seen in all YAG crystals. We have also measured the losses in our pure YAG SC fibers at a few key laser wavelengths. The losses measured using a cutback method were 1.3 dB/m and 1.1 dB/m at 1.06 and 2.94 ?m, respectively. These fibers were grown from high purity SC source rods and we have also grown SC fibers starting with high quality ceramic YAG bars which yield similar results.

The SC fibers that we have grown to date include, 0.5% and 50% Er:YAG, 0.5% Ho:YAG, and 6% Tm:YAG. The longest length of doped YAG fiber has been about 50 cm. We have also measured the emission spectrum of our Er^{3+} doped YAG fiber. Again, these fibers are unclad. The fiber was end-pumped by a 975 nm laser diode and the amplified spontaneous emission (ASE) spectra under different incident pump power levels are shown in Fig. 3. The emission peaks at 1617 nm and 1645 nm are the strongest and correspond to the lasing wavelengths in low doped Er:YAG lasers.

4. Summary and Conclusion

Erbium, holmium, and thulium doped single crystal YAG fibers were grown using the laser heated pedestal growth technique. The radial distribution of erbium ions was uniform and the near-infrared ASE spectra of the fiber were measured. By engineering the ion concentration radially we are hoping to clad the doped SC YAG fiber and, therefore, to make a true SC fiber laser. A clad SC fiber laser should be able to deliver significant laser power and be an excellent alternative to glass fiber lasers.

5. References

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8961-78, Session PTue

Design and characterization of a polarizing microstructured optical fiber with large mode area for single-mode operation at 1064 nm

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The single-mode (SM) ytterbium-doped fibers with large mode area (LMA) have attracted much attention to increase the power of fiber lasers and amplifiers. The power level of pulsed fiber lasers in the range of a few tens of watts to multi-kilowatts have been demonstrated but still need to be enhanced for industrial applications. A major limitation to the development of higher output power is nonlinear effects, which can be overcome by using LMA fibers in order to maintain an acceptable output-beam quality. Compared to conventional fibers, microstructured optical fibers (MOF) provide much better control of numerical aperture to values as low as 0.02, which allows a core diameter greater than 100 µm while keeping SM operation. Furthermore, the possibility to insert stress rods able to modify the polarization properties of MOFs is of great interest for those applications, which require the use of polarization maintaining

(PM) or polarizing fibers. However, weak guidance makes LMA MOFs very bend sensitive, forcing them to be kept straight for core diameters above 45 µm. Recently, a promising fiber design with better bending loss performance has been reported by Dong et al. Theoretical studies of these fibers relate only to non-PM fibers. In this work, we numerically investigate the influence of stress-rods on bending losses of guided modes in passive LMA MOFs at 1064 nm, using a method based on the finite element method. Experimental performances of fabricated 50-µm core diameter polarizing fiber are also presented.

8961-79, Session PTue

Passive mitigation of mode instabilities

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The onset of mode instabilities in high power fiber amplifiers once that a certain threshold power is reached has quickly become the most limiting effect for the further power scaling of this technology. This effect has its roots on a thermally induced index grating ultimately created by the modal interference between the fundamental mode and a higher-order mode. Mode instabilities are particularly damaging because they demote one of the main advantages of fiber technology: its extremely high beam quality.

In this work we propose two concrete passive mitigation strategies: the first one is based on the reduction of the heat load in the fiber, whereas the second one is based on the reduction of the pump absorption. As mentioned above, it is widely accepted that mode instabilities are rooted on the heat load generated in the amplification process. Therefore, reducing this heat load should lead to an immediate increase of the instability threshold. One way of doing this is by reducing the wavelength separation between the signal and the pump. In this work we analyze the consequences of either moving the signal wavelength while leaving the pump wavelength constant or vice-versa. In both cases an increase of the threshold is expected.

The second approach consists on reducing the pump absorption of the active fiber by increasing the pump core diameter. In this case weaker, more homogeneous thermally induced gratings are expected, that should result in a higher threshold. The dependence of the threshold on the pump core diameter and on the fiber length is analyzed.

8961-80, Session PTue

Fabrication of microstructured fibers from preforms with sealed top-end holes

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Theoretical aspects of microstructured fibers fabrication from preforms with sealed holes at the top end are discussed. Dependences of the holes blowing degree on their diameters, on a ratio of the preform top end temperature to temperature in the center of a furnace and on other parameters are estimated.

Experimental results of different microstructured fibers drawing in such a regime are presented. We have drawn the simplest microstructured fiber with one hole from a tube with outside diameter 6.2 mm and inner diameter 4.4 mm (capillary drawing). Also we have drawn MSFs from preforms with 6 and 60 small holes. To check the results of the theoretical analysis we have prepared a preform with different size holes and then drew it into a fiber. In all cases experimental results are in good agreement with theoretical estimations.

Thus this method of fabrication gives the possibility to manufacture long length microstructured fibers with stable internal structural parameters, high reproducibility, ease of controlling and changing the fibers parameters and opportunity to make structures with holes of different sizes. The observed changes of the holes blowing degree in our experimental samples can be easily compensated with the help of additional heating of the preform top end. Besides, such heating makes it possible to control and change the holes blowing degree, particularly during the fibers drawing process.

8961-81, Session PTue

Dual-wavelength fiber mode-locked laser based on graphene-saturable absorber

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We present an all-fiber Tm- and Er-doped fiber laser simultaneously mode-locked by a common graphene saturable absorber. The graphene layers were fabricated by CVD method, characterized by Raman spectroscopy and transferred onto the fiber connector end. The laser consists of two loops resonator with one common branch, which contains the graphene SA. The 1.55 µm loop is based on in-line polarization controller (PC), isolator and a highly Er-doped fiber, pumped by a 980 nm laser diode via a wavelength division multiplexer (WDM). The light is coupled out from the 1.55 µm cavity through a 20% coupler. The 2 µm loop is designed analogously to the Er-laser. It is based on a 1.5 m long piece of Tm-doped fiber pumped by a 1573 nm laser diode (beforehand amplified in an Er/Yb-doped fiber amplifier. Both signals are combined and split by a 1570/2000 nm WDMs. The stable mode-locked operation was obtained in both loops after careful adjustment of PCs and above pump power thresholds of 30 mW and 160 mW for erbium and thulium loop, respectively. The laser loops have slightly different lengths, which results in repetition frequencies of 20.19 MHz for the Er-laser and 18.43 MHz for the Tm-laser. The soliton spectra were centered at 1565 nm and 1944 nm with FWHM of 4.2 nm and 3.9 nm, respectively. Pulse durations and output powers were at the level of 930 fs, 1.03 ps and 0.5 mW, 3 mW at 1.5 µm and 2 µm, respectively.

8961-82, Session PTue

The effect of polarization in passive coherent beam combining of fiber lasers

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An external-cavity fiber laser was constructed using a ytterbium-doped dual-core double-clad polarization-maintaining fiber. The optical path-length difference (OPD) between the two doped cores was minimized during the fiber fabrication process. The residual OPD was further reduced by bending the fiber. The lasing bandwidth was restricted by a Littrow grating to a few nanometers, ensuring that changes in operational wavelength would have a negligible effect on the differential phase delay between the two cores. The lasing modes of the two doped cores were passively combined using a home-made Dammann grating. The relative phase between the two doped cores could be tuned by lateral translation of the Dammann grating. By injecting a probe laser beam into both arms of the laser cavity and observing the phase shift of the interference fringes between the two arms, we were able to measure the optical path change (measured phase error) induced by the Kramers-Kronig (KK) effect. Our experiments have shown that the K-K effect is capable of compensating for induced cavity phase errors when the fiber is pumped at sufficiently high power. This is evident from the staircase-shape total cavity phase error that we observe while we introduce additional cavity phase error continuously using the Dammann grating. However, these results have been seen to be a function of the polarization state, with a very different response observed in the orthogonal state. In this paper, we explore the role of polarization and K-K phase shifts in passive coherent beam combining.

8961-83, Session PTue

Novel technique for suppression of self-pulsing in Yb fiber lasers

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Although fiber lasers are used in a number of application areas nowadays due to its excellent laser performance, the self-pulsing phenomenon that happens in most of the rare-earth-doped fiber lasers has been one of the main problems to achieve robust fiber laser operation since the high peak power generated by self-pulsation may cause catastrophic damage of the fiber itself as well as severe output instabilities. Self-pulsing is known to be caused by several mechanisms such as sustained relaxation oscillation, self-mode-locking due to the saturable absorption in an unpumped part of the fiber and the nonlinear optical processes (SBS, SRS), etc. Much effort has been devoted for the last decade and various techniques have been suggested to suppress it, including splicing a passive fiber over a few kilometers to the active fiber, resonant pumping near the lasing wavelength, a ring cavity fiber laser configuration, and so on. In this paper, we suggest an alternative technique for achieving stable fiber laser operation by suppressing the self-pulsing completely. By coupling an optimized two-mirror Fabry-Perot cavity to an Yb doped fiber laser resonator externally, we could obtain very stable laser output without self-pulsation at all power levels up to ~20W. Investigation on laser characteristics has revealed that suppression of the self-pulsing behavior in our configuration can be achieved by forcing the operating longitudinal modes in the fiber laser resonator. We report on the results of this study in detail and discuss the prospects for further improvements of our technique.

8961-84, Session PTue

kW average power from a Yb-doped rod-type large-pitch fiber

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Ytterbium-doped rod-type fibers can be considered as an enabling fiber technology that has been achieved several performance records in pulse operation, i.e. in the nanosecond to femtosecond pulse regimes. These fibers combine very large-mode areas and short fiber lengths to effectively mitigate detrimental nonlinearities. However, the existence of higher order transverse modes combined with the high thermal load that these short fibers have to withstand can lead to the observation of mode instabilities. We show that, independently of mode instabilities, the average output power in such a system can be scaled well beyond the threshold of this effect with high slope efficiency. We present a record output power of 1 kW extracted from a 1 meter long rod-type fiber with a core diameter of 90 µm. The corresponding beam quality is M2~3.5 at the highest power value. Hence, by solving mode instabilities or by lifting the threshold, the rod-type fiber concept will become an excellent platform for further performance scaling of pulsed fiber lasers.

8961-85, Session PTue

Fiber laser seeded by 1030 nm gain-switched laser diode for supercontinuum generation

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We demonstrated simple two stage MOPA fiber laser for super continuum generation. The pump MOPA laser was operating at 1030 nm with 100 ps pulse duration and repetition rate of 1 MHz. One of the key element was a seeder based on laser diode and high speed/ high power driver. The laser diode was standard butterfly packaged Fabry-Perot laser diode operating at 1030 nm in gain switched mode. The driver was specifically made with the output up to 50V/1A at repetition up to 2MHz and pulse duration in sub-ns region. Directly from the diode a 100 ps pulse duration was achieved and peak power of 1 W. By using two stages fiber amplifier the peak power was boosted up to 16 kW. For the super continuum generation we used PCF endlessly single mode fiber. As the system was fully integrated it represents highly robust and simple design

8961-86, Session PTue

980-nm random fiber laser directly pumped by a high-power 938-nm laser diode

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A random lasing based on Rayleigh scattering (RS) and Raman gain in a passive fiber directly pumped by a high-power laser diode (LD) has been demonstrated for the first time. Owing to the RS-based random distributed feedback (RDFB) the low-quality LD beam (938 nm) is converted into the high-quality laser output (980 nm). Because of the relatively low excess above the threshold with the available LD, the RDFB laser output is limited in power by 0.5 W level. In the used gradient-index (GRIN) fiber the output beam has 4.5 lower divergence as compared with the pump beam thus demonstrating radical improvement in beam quality at relatively high pump-to-laser power differential efficiency. This result offers a challenge in development of new type of high-power fiber lasers based on passive fibers without a cavity directly pumped by high-power LDs. Using of passive fibers without cavity reflectors has some principal advantages over conventional high-power fiber lasers based on active fibers with resonators, such as lower quantum defect, longer lifetime due to the elimination of reflectors destruction and absence of photo-darkening effect that becomes more important at shorter wavelengths. Opportunities to form all-fiber configuration as well schemes providing lasing at <900 nm and tunable operation of the proposed RDFB fiber laser are discussed. A comparison with LD-pumped Raman fiber laser based on the same GRIN fiber with linear cavity based on multimode fiber Bragg gratings (FBGs) is performed.

8961-87, Session PTue

Gain-switched all-fiber sources at 2 µm

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Gain-switching is the simplest way of generating pico- and nanosecond pulses at variable repetition rates. We investigate a gain-switched diode and fiber laser as a seed source for the 2 µm spectral range.

The gain-switched laser diode with a central wavelength of 1.95 µm is amplified by a core-pumped fiber amplifier stage and is filtered with narrowband fused WDMs. The seed source produces approximately 100 ps pulses at variable repetition rates ranging between 2.5 MHz and 40 MHz with an average power of 17 mW at 40 MHz repetition rate. The

source has a monolithic all-fiber set-up, is very stable constructed what makes it a very interesting alternative to mode locked and Q-switched sources.

Moreover, we investigate gain-switched fiber laser pumped with a picosecond Raman laser operating at 1.2 µm with various repetition rates. The fiber source is wavelength stabilized with a fiber Bragg grating at a central wavelength of 1.98 µm.

To confirm the suitability of both sources in high power applications they are amplified in high power fiber amplifiers made out of Thulium-doped large mode-area step-index fibers and thulium doped photonic crystal fibers.

8961-88, Session PTue

16 W pulsed green laser based on efficient frequency conversion of an Yb-doped fibre laser externally modulated by a semiconductor optical amplifier

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High power green lasers find applications in material processing, medical treatments, laser projection, or pumping of optical parametric amplifiers. Pulsed green lasers with versatile properties such as adjustable repetition rate or pulse duration are of great interest. In this paper we propose a pulsed green laser based on efficient frequency conversion of an Yb-doped fibre laser externally modulated by a semiconductor optical amplifier (SOA). The SOA-based modulation allows us varying both the repetition rate and the pulse duration in a wide range. The laser architecture is composed as follows. An Yb-doped fiber laser is amplified and modulated by a SOA. Optical pulses are then generated with pulse durations in the range 3-40 ns and repetition rates in the range 50-800 kHz. This signal is pre-amplified by 3 stages of polarization-maintaining Yb-doped amplifiers and injected in a booster amplifier stage using in a commercially available flexible microstructured polarizing double-clad Yb-doped fiber with a mode field area of about 650 µm2. At the output of the booster, the beam is collimated and focused in a thermally-controlled LBO crystal for second-harmonic generation. For the 50 kHz / 40 ns regime, we have obtained a maximum value of 250 µJ for the pulse energy at 532 nm. For the 250 kHz / 8 ns regime, a maximum value of 16 W at 532 nm has been obtained and a maximum value of the conversion efficiency of 66 % is reached which is one of the best conversion efficiency of the state of the art.

8961-89, Session PTue

Spatially resolved 3D-measurements of long-period gratings written by fs-laser inscription in large mode area fibers

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Long-period gratings (LPGs) are fiber devices that couple specific forward-propagating core modes to forward-propagating cladding modes. They can be used to fabricate band-rejection filters in order to suppress non-linear processes that limit power scaling of fiber lasers, including stimulated Raman (SRS) scattering, the most important limiting process for industrial fiber lasers. LPGs are fabricated by modulating the refractive index in the core via heat diffusion using a CO2laser or arc discharge or via multi-photon absorption using a fs laser. High-power fiber sources employ large-mode-area (LMA), double-clad (DC) fiber. Fabricating and characterizing LPGs in LMA DC fiber introduces challenges beyond those for standard single-mode fibers, including mode-dependent effects and guidance of rejected modes in the inner cladding. We investigated the influence of different inscription methods for writing an LPG in LMA DC fiber using a three-dimensional, spatially resolved measurement of the refractive-index change. We report, to the first of our knowledge, direct measurements of the induced index change in an LMA DC fiber and the influence on LPG performance. In our experiments we investigated the relationship of the refractive-index change and the LPG characteristics using fs-laser inscription for different writing conditions (pulse energy, writing velocity, and writing path along the fiber). We discuss implications for SRS suppression in kW-class fiber lasers using LPGs.

8961-90, Session PTue

Ultra-low noise optical phase-locked loop

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The relative phase between two fiber lasers is controlled via a high performance optical phase-locked loop (OPLL). Two parameters are of particular importance for the design: the intrinsic phase noise of the laser (i.e. its linewidth) and a high-gain, low-noise electronic locking loop. In this work, one of the lowest phase noise fiber lasers commercially available was selected (i.e. NP Photonics Rock fiber laser module), with sub-kHz linewidth at 1550.12 nm. However, the fast tuning mechanism of such lasers is through stretching its cavity length with a piezoelectric transducer which has a few 10s kHz bandwidth. To further increase the locking loop bandwidth to several MHz, a second tuning mechanism is used by adding a Lithium Niobate phase modulator in the laser signal path. The OPLL is thus divided into two locking loops, a slow loop acting on the laser piezoelectric transducer and a fast loop acting on the phase modulator. The beat signal between the two phase-locked lasers yields a highly pure sine wave with an integrated phase error of 0.0012 rad. This is orders of magnitude lower than similar existing systems such as the Laser Synthesizer used for distribution of photonic local oscillator (LO) for the Atacama Large Millimeter Array radio telescope in Chile. Other applications for ultra-low noise OPLL include coherent power combining, Brillouin sensing, light detection and ranging (LIDAR), fiber optic gyroscopes, phased array antenna and beam steering, generation of LOs for next generation coherent communication systems, coherent analog optical links, terahertz generation and coherent spectroscopy.

8961-91, Session PTue

Performance of kW class fiber amplifiers spanning a broad range of wavelengths: 1028~1100nm

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We present results on the amplifier performance and characteristics of Yb-doped Single Mode fiber amplifiers spanning a broad range of wavelengths from 1028 nm to 1100 nm. Both PM and non-PM amplifiers are discussed, with emphasis on the use of polarization

controllers in intrinsically non-PM amplifiers to obtain high Polarization Extinction Ratios (PER). In general, outside the 1064nm region, there has been relatively little discussion or work towards developing high power fiber amplifiers for operation at either 1030 nm or 1100 nm with narrow line-width and high brightness, primarily due to amplifier design and architecture issues related to strong re-absorption, amplified spontaneous emission and non-linear effects. Here we address key fiber and amplifier design characteristics aimed at mitigating these issues while highlighting performance attributes and challenges for operation near either end of the above defined spectral range.

8961-92, Session PTue

Power scaling through narrowband ASE seeding in pulsed MOPA fiber systems

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Master Oscillator Power Amplifier (MOPA) fiber systems are the most straightforward way for power scaling. In pulsed nanosecond MOPAs where no special requirements regarding narrow (kHz) spectral bandwidths are needed, the seeder of choice is the Fabry-Perot semiconductor laser with a few nanometers of spectral width envelope. However, the multi-mode characteristics of the laser diode can have a deleterious effect on dynamic performance, and spontaneous emission noise can trigger the side modes to oscillate under the intensity modulation condition. In fact, random backscattered short duration pulses with large amplitude compared to the Rayleigh scattering can be originated, beyond the damage limits of optical components, seed laser or even the fiber itself, leading to catastrophic failures. The phenomena can be attributed to stimulated Brillouin scattering (SBS), being a limiting factor for power scaling. We propose the use of a narrowband ASE source as seeder in high power pulsed MOPA configurations in order to overcome the limitations imposed by the use of modulated Fabry-Perot lasers, since no longitudinal modes or sidebands are present. Its low coherence and clean spectrum suppresses the risk of triggering SBS in comparison to the Fabry-Perot semiconductor laser. We present results of a double-clad fiber MOPA system using a Fabry-Perot laser operated in CW and then externally modulated with an acousto-optic modulator (AOM), as well as operated through direct current modulation. The results are compared with those using an externally modulated narrowband ASE source in the same system.

8961-93, Session PTue

Development of narrow-linewidth Yb- and Er- fiber lasers and frequency mixing for ArF excimer laser seeding

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An injection seeding of an ArF excimer laser by using solid-state lasers is crucial not only for further narrow-linewidth operation but also for lower energy consumption. A fiber-laser based seeding pulse generation at 193 nm is a promising candidate for this purpose since fiber lasers are robust, compact, and stable. High-energy pulse generation with narrow linewidth from both Yb and Er fiber lasers is still challenging.

We propose the 193-nm generation with several wavelengths mixing of Yb and Er-fiber lasers. The 4 th harmonic generation of Yb fiber laser and the successive two-stages of SFG with Er-fiber laser would generate 193 nm pulses by using CLBO crystals. Here we report on watt-level nanoseconds narrow-linewidth Yb- and Er-doped fiber lasers operating at 6 kHz. Watt-level average powers are necessary for both Yb and Er fiber lasers with about 10-ns pulses, corresponding to about 150-?J pulse energy.

Yb-fiber system consists of a pulsed DFB or ECDL as an oscillator, a preamplifier, an AOM for pulse picker, and a power amplifier. We found that the pulsed ECDL can generate almost transform-limited pulse with 10-ns pulse duration, while pulsed DFB laser has much broader linewidth. Er-fiber system consists of CW DFB laser as the oscillator, an SOA for pulse generator, and some stages of amplifiers. In both cases, no obvious SBS and SPM were observed. Higher power amplifier by using Yb-doped solid-state crystal and some-stage of optical-frequency conversion are under construction, which would realize an efficient seeding for ArF laser.

8961-94, Session PTue

Polarization maintaining, high-power and high-efficiency (6+1)x1 pump/signal combiner

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We have developed an all-glass, fusion spliceable polarization maintaining (6+1) 1 pump/signal combiner for fiber lasers and amplifiers. We utilize a conventional tapered fiber bundle technology for multimode pump channels and a vanishing core fiber for the singlemode polarization maintaining large mode area (PLMA) signal channel. The signal channel of the combiner is optimized to match a double clad PLMA fiber with 20 micron core and 400 micron glass cladding and with 0.065 numerical aperture (NA). The multimode pump channels are 200 micron core and 240 micron cladding fibers with NA of 0.22 designed to deliver high power 980 nm pump light. The same double clad PLMA fiber is used as both the signal input channel and the combined output for the device. Polarization axes of the input and output PLMA fibers are aligned during the fusion splices to achieve low polarization crosstalk. Utilizing this approach, we have achieved coupling loss of ~0.3 dB for the signal channel, as measured from the input PLMA to the output PLMA at 1060 nm wavelength and coupling loss of ~0.2 dB for all pump channels, as measured from the multimode fiber input to the double clad fiber output at 974 nm. Low signal and pump losses result in high efficiency lasing or amplification at over a kW of pump power for high power applications, where a singlemode, high polarization extinction ratio output is required.

8961-95, Session PTue

Effect of resonant and Kerr nonlinearities on passive phase-locking of a multi-stable regenerative fiber amplifier array

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In this presentation, we show that the transmission characteristic of a bidirectional regenerative fiber amplifier with Kerr and resonant nonlinearities is a multivalued function of the intensity of the incident radiation, analogous to a nonlinear passive etalon (Felber et al, Appl. Phys. Lett. 28,731(1976)). Subsequent application to a random-length, externally-coupled, N-element amplifier array, predicts a similar multi-valued output, in which highest power solutions are associated with the greatest degree of phase-locking. Saturation is found to suppress break-a-way (“rogue”) lasing by individual amplifiers. This is verified through a rigorous analytical results for c-w externally globally-coupled regenerative amplifier arrays that demonstrate clearly the contribution of Kramer-Kronig and Kerr nonlinearities. We present results of the array order parameter (approx. Strehl ratio) as function of out-coupler reflectivity in which the effect of multiple resonant (Kramer-Kronig) and Kerr contributions are clearly distinguished.

8961-96, Session PTue

Rod fiber amplifiers under high thermal load leading to transverse mode instability

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Recent increases in extracted output power from rare-earth doped rod fiber amplifiers has led to observations of transverse mode instability (TMI) above a system and fiber dependent average output power threshold [1-5]. TMI results in rapid beam fluctuations on a ms timescale, typically between the fundamental mode (FM) and the first higher order mode (HOM), since very large mode area fibers support HOMs for high average power operation of hundreds of watts. TMI onset significantly degrades beam quality and constitutes a significant impediment of future power scaling efforts utilizing fiber amplifiers. The quantum defect heating of the gain medium results in a form of intermodal stimulated thermal Rayleigh scattering (STRS) related to the inversion profile and signal intensity.

In this work we investigate the thermally induced longitudinal waveguide perturbations which yield power transfer from the FM to the HOM by an associated long period grating. The transfer of power results from a nonlinear gain, which depends on the FM-HOM frequency shift as well as the position along the fiber. The nonlinear gain increases along the fiber with increasing heat load due to the thermo-optic effect, since the temperature increment yields increased mode overlap. We take temperature and mode profile evolution along the fiber into consideration to engineer rod fiber design parameters in order to increase the TMI threshold and achieve operation stability at higher average powers as well as higher peak powers.

8961-97, Session PTue

Thermo-optical effects in Tm-doped large mode area photonic crystal fibers

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In recent years performances of fiber lasers have been greatly increased in term of output power, beam quality and efficiency. The major contribution to this advance was due to the development of large mode area fibers combined to photonic crystal fiber technology, that allow to obtain high power operation with a good output beam, mitigating non-linear effects. The most considerable efforts in fiber laser research have been focused on 1?m lasers which are preferred due to the ytterbium excellent properties. However, many applications, such as medical ones, remote sensing or pumping of mid-IR lasers, require to operate at an eye-safe wavelength longer than 1.4?m. Thulium-doped fiber lasers, working in a band located around 2?m, are suitable for such uses. The main issue about the use of thulium in fiber lasers is related to its quantum defect, that causes a significant thermally induced index change, higher than ytterbium fibers, which lead to output power limitation, beam degradation and modal instability. In this work some well-known fiber designs, a large pitch fiber and a 19-cell fiber with thulium doped core, have been investigated using a finite element method based numerical approach, evaluating the impact of thermo-optical effect on the modal properties. Results have shown that, by modifying the design parameters such as core index and holes diameter, it is possible to obtain a good overlap of the fundamental mode with the doped region , while effectively suppressing the higher order modes.

8961-98, Session PTue

Effect of gain saturation on the mode instability threshold of high-power fiber amplifiers

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The recently discovered phenomenon of transverse mode instability (TMI) constitutes a major impediment to the further power scaling of large-mode-area rare-earth doped fiber amplifiers. TMI causes a periodic or chaotic fluctuation, on a ms timescale, of the signal between the fundamental mode (FM) and the first few higher-order modes (HOMs) when the average signal power reaches a fiber and system dependent threshold, and thus leads to a severe degradation of the output beam quality. The cause of TMI has been identified as a form of intermodal stimulated thermal Rayleigh scattering, in which the mode beating of the FM and HOMs gives rise to a thermally induced long period grating (LPG), which leads to transfer of power between the modes. Theoretical work has so far been based on either a numerically intensive beam propagation method (BPM), or a simplified coupled-mode model which does not take gain saturation effects into account.

In this work, we formulate a simple coupled-mode model of TMI, which takes the effects of gain saturation into account. Gain saturation is shown to diminish the strength of the thermally induced LPG, leading to a higher TMI threshold. The model is numerically very efficient, and we use it to investigate the effects of various fiber design parameters on the TMI threshold. We also investigate the influence of different pumping schemes.

8961-99, Session PTue

Intense supercontinuum generation in a nanosecond nonlinear all-PM-fiber power amplifier

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Nonlinear photonic crystal fiber (PCF) can provide high nonlinearity and flexible dispersion control using air-silica microstructure with tapers or non-silica material. For high power all-fiber-structured supercontinuum (SC) source, the difficulties will arise from mode coupling, endfacet damage, heat management, restricted interaction length, and the lack of high power SC drivers. Recently, the concept to combine laser amplification and nonlinear conversion can not only simplify the configuration, but regenerate the driving power to compensate the negative influences such as large fiber core and small nonlinear coefficient [9]. An active LMA DC silica fiber can avoid the difficult mode matching and preserve the compactness by coiling. For a nonlinear fiber power amplifier in a chain, the versatile SC source can be optimized for different purposes.

In this paper, we present a linearly-polarized nanosecond all-fiber-structured SC source spanning from 0.98 to >1.6 ?m with the effective peak power over hundred watts and corresponding energy in millijoule level at averaged power at tens of watt in a nonlinear fiber power amplifier using all-normal-dispersion diode-seeded MOPA configuration Such a SC source composed of a intense 1064-nm pump and the broad sideband seed could realize an efficient and compact broadband tunable optical parametric amplification (OPA) free from timing jitter and bulky optical delay line, which is so-called the SCOPA able to be used in biophotonics applications. Furthermore, the maximum SCOPA efficiency may be improved by adaptive pulse shaping owing to diode seeding.

8961-100, Session PTue

Effective suppression of stimulated Raman scattering in high power fiber amplifiers using double-pass scheme

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High gain and high efficiency can be simultaneously achieved by regenerative amplification in a high power fiber amplifier using double-pass scheme with a low power input seed [1]. However, the scheme with double interaction length was rarely adopted in high-power laser amplifier because of possible excitation of SRS. In order to overcome the deterioration of power scaling caused by SRS, some methods of suppressing SRS in fiber amplifier have been proposed, e.g. the special fiber designs by distributing spectral filters [2], exploring the ring-type fiber [3] and adopting the photonic band-gap fibers [4] et al. However, the maximum core sizes of the active fiber limits the applications of these methods based on special fiber designs. The distributed spectral filters were then proposed to filter the Raman Stokes wave and inhibit the signal depletion induced by SRS during the amplification [5-6].

In the study, we propose a scheme to combine the double-pass fiber amplifier with a wavelength selective reflector at opposite fiber end under the proper pumping configuration for mitigating SRS onset. The amplified signal is almost totally reflected by the reflector and most co-propagating Raman Stokes wave is transmitted at the fiber end. Furthermore, the Raman strippers can be inserted into the active fiber with double-pass scheme for effectively suppressing SRS. Raman stokes wave is continually removed from the fiber core by distributed strippers during propagating in fiber. Therefore, energy/power scaling and efficient suppression of SRS can be achieved by the compact structure using double-pass scheme.

8961-101, Session PTue

New optical fiber designs for beam shaping applications

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A large number of power delivery applications for optical fibers require beams with very specific output intensity profiles; in particular applications that require a focused beam typically image the near field intensity distribution at the exit surface of an optical fiber. In this work we discuss new optical fiber designs that shape the output beam profile to more closely correspond to what is required in many real world industrial applications. Specifically, we present results demonstrating the ability to transform kW-level pure Gaussian beams to shapes required for industrial applications, with very specific BPP (beam product parameter) values. We also present results of simulations whereby a pure Gaussian beam is transformed to a beam with a specified BPP as a function of core characteristics. Finally, fiber loss and output beam shape variability are discussed as a function of fiber design parameters.

8961-102, Session PTue

Adjustment of double resonance in short cavity Brillouin fiber lasers

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Among Brillouin fiber lasers, single-longitudinal mode lasers are based on fiber configurations with so-called doubly-resonant cavities. The Brillouin radiation in such lasers is generated with short fiber ring cavities that are simultaneously resonant for pump and Stokes waves.

In order to achieve double-resonance operation in the ring fiber cavity, we have to provide precise and reliable coincidence of the pump laser frequency with one of the cavity resonant modes. Second, we have to be sure that the Stokes wave generated in the cavity by the resonating pump is also resonant to the cavity, i.e. the peak of the Brillouin gain spectrum induced by the pump in the cavity fiber coincides with one of the cavity resonant modes. Generally, it is not precisely the case, especially, for short cavities of several meters. At the resonance, the Brillouin threshold power is minimal. Therefore, commonly used techniques are based on piece-by-piece cutting of the ring fiber with intention to minimize the Brillouin threshold. Such procedure is boring, time-consuming, and gives rather rough approach to the resonance. Here we report a procedure for precise setting of the ring fiber cavity to the Brillouin resonance for any preselected pump laser wavelength: experimental tracing of the cavity Brillouin response to a frequency scanning pump laser allows to measure FSR precisely and calculate the excess ring cavity length that must be removed from the ring to shift the Brillouin resonance immediately to the right position.

8961-103, Session PTue

Mode coupling in few-mode large-mode-area fibers

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We present an experimental study on mode coupling characteristics of few-mode large-mode-area (LMA) fibers, which are widely used in high power fiber lasers.

The modal power allocation is measured by modal decomposition of the near-field intensity profile of the output beam. The refractive index profile (RIP) of the fiber under test is measured for calculating the eigenmodes of the fiber. Modal decomposition is performed by reconstructing the near-field output intensity profile with a linear combination of the eigenmodes and minimizing the residues. The modal power content of each mode is then obtained.

Most of the power is excited with the fundamental mode at the input end. Cut-back measurement is performed to reveal the modal power content at different positions along the fiber.

Several commonly used fiber types with different geometries are measured, and the results are compared. The influences of fiber geometry, bending and stress on mode coupling is analyzed. And the impact on the beam quality of fiber lasers is discussed.

This study will provide additional understanding on the beam quality of the LMA fibers and fiber lasers.

8961-104, Session PTue

Frequency conversion through spontaneous degenerate four wave mixing in large mode area hybrid photonic crystal fibers

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Frequency conversion utilizing the nonlinear response of silica has been investigated thoroughly for different nonlinear processes, such as Raman scattering (RS) and four wave mixing (FWM). A fundamental limitation of conversion through RS exists, since the gain is decided by vibrational modes of silica which may not be suitable in all cases. In principle conversion to any frequency can be achieved through FWM, if energy conservation and phasematching of the interacting frequency components is fulfilled. Phasematching is often the limiting factor, and requires high control of fiber parameters, in particular dispersion properties. The dispersion properties can be controlled in photonic crystal fibers (PCFs) by core scaling. For high-power applications FWM processes in large-mode-area (LMA) fibers are required, but in LMA PCFs material dispersion dominates. Therefore a different mechanism than core scaling is needed to control the dispersion properties.

In this work, frequency conversion through spontaneous degenerate FWM in LMA single-mode hybrid PCFs is considered. Both high- and low-index inclusions are present in the fiber cladding, combining index and photonic bandgap guidance. The high-index inclusions give rise to large values of normal and anomalous dispersion near the edges of a photonic bandgap, enabling control of the dispersion properties. The frequencies of the FWM products can thereby be determined independently of fiber core size, allowing for power scaling of the process. In this work, the polarization dependence of the parametric gain and the dynamics of having both RS and FWM present in the PCFs are investigated experimentally.

8961-105, Session PTue

Brillouin-gain spectra of a monolithic counter-pumped single-frequency fiber amplifier

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The development of monolithic high power single-frequency ytterbium-doped fiber amplifier systems for gravitational wave detection and coherent beam combination has gained much interest in recent years. An already successful approach is the application of the counter-propagation pumping (CPP) scheme instead of co-propagation pumping. The benefit of CPP with respect to the stimulated Brillouin scattering (SBS) threshold is the strong temperature gradient and the exponential progression of the power along the active fiber. However, for all-fiber counter-pumping it has to be considered that the length of the passive signal feedthrough fiber (SFF) of the pump combiner has to be chosen as short as possible to avoid an increase of the SBS-threshold. In addition, the Brillouin-frequency shift of the passive SFF in comparison to the Ytterbium-fiber and, consequently, the interplay of the Brillouin-gain spectra (BGS) have to be taken into account. Thus, we measured the BGS of the passive SFF of our in-house developed pump combiner and of the Ytterbium fiber up to an output power of 215 W. The BGS were measured with a Fabry-Perot interferometer for different SFF lengths. With these results and additional information on the active fiber temperature, determined by thermography, design rules for efficient SBS mitigation and, consequently, further power scaling of monolithic counter-pumped single-frequency amplifiers can be achieved.

8961-106, Session PTue

Time-frequency-domain dispersion measurement in rare earth doped large effective mode area multicore fibers

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Ytterbium doped multicore fibers are recently employed in the field of high power and Quasi-Gaussian beam lasers to design truly single-mode multicore fiber lasers. The special design of these fibers offers low bending loss even for compact high power lasers and amplifiers. Moreover, the Multi-core fiber amplifier possesses a large effective mode area which results in a significant decrease of the related nonlinear effects.

In the paper, modal resolved group-velocity dispersionmeasurements in active multicore fibers are performed using time-frequency-domain white-light interferometry. A Mach-Zehnder-type interferometer with dual-channel detection in the spectral range from 0.4 ?m up to 1.7 ?m and a home-made Supercontinuum source are used. Temporally resolved spectrograms recorded at distinct delay positions enable the detection of interference fringes for the equalization-wavelength. By applying a Sellmeier polynomial fit to the wavelength dependent differential group delay function, the group-velocity dispersion can be derived. The dispersion parameters for several fiber modes in a 19-core Yb-doped fiber are investigated over a broad spectralrange of about 1.3 µm.

The measured 19-core Yb-doped fiber was finally implemented in a fiber amplifier setup. The measured M? factor of the amplified beam has found to be 1.3 at a pulse energy gain of 6.6 dB. Compared to a conventional LMA fiber the 19-core fiber possesses a significant decrease of spectral broadening at equate laser system parameters.

8961-108, Session PTue

All Yb-based CPA high-repetition rate femtosecond fibre laser with CEP stabilisation for strong field physics

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Chirp Pulse Amplification Fibre Lasers (CPA-FL) are revolutionising Strong Field Physics, opening new routes for ultra-fast phenomena studies with unprecedented repetition rate as we recently demonstrated [1]. CPA-FL [2, 3] have provided first designs based on few-cycles 800nm oscillator frequency shifted toward 1030nm by soliton generation in photonic crystal fibre (PCF), subsequently stretched to ns level, amplified and compressed. The state of art CPA-FL delivers 1030 nm, 100 W, 100 KHz and sub ps pulses capability compressible down to few 10's of fs via hollow core fibre compression stages at the expense of the throughput energy [4].

At Imperial College London we developed an all Yb femtosecond CEP stabilised high repetition rate CPA-FL for the purpose of our attosecond science activities. Our system consists of an Yb oscillator delivering 1030 nm, 2W, 90 fs laser pulses at 70 MHz repetition rate with a CEP stabilisation below 140 mrad. The repetition rate can be chosen from 100 KHz up to 350 KHz. The pulse is stretched to ns level using an Öffner configuration and amplified in LMA Yb fibre stages pumped with high mode quality 976 nm diode lasers towards the µJ level. The pulses are then compressed down to few 100's of fs using transmission gratings compressor with ~80% efficiency. Our system is unique in this regard and comprises as well mechanical stability schemes to maintain CEP for attoscience applications.

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8961-109, Session PTue

Effective NIR gain-switched fiber laser

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We report on experimental investigation of NIR fiber laser operating in gain switched mode. The active fiber is double clad single mode doped by Yb active ions. The optical setup is based on single stage fiber laser. One of the key elements is the specifically made pump system with feedback control and having fast switching time. Its rise/fall times are in range of few tens of ns and peak power reaches several 100 W. We demonstrated experimentally that with adequate optimization the output from the laser can exceed 1.7 kW peak power and pulse duration can be shorter than 40 ns without hindering the simplicity of the setup. According to our knowledge this is the report of shortest pulse obtained from single stage gain switched fiber lasers operating at 1µm wavelength range and being directly pump by laser diodes. The output pulse parameters are practically independent on repetition rate from 10 kHz to several 100 kHz. Polarization extinction ratio and spectrum width make the laser output ready for frequency doubling. All above mentioned properties makes such type of laser a possible candidate for some specific application in micro-processing especially in the case where only moderate peak power or pulse energy is required.

8961-110, Session PTue

Switchable dual-wavelength erbium-doped fiber laser covered in C-and L-bands with wide tunability and fast response time

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Fiber lasers have been much attention because of their various applications, such as wavelength division multiplexed (WDM) communication systems, performance testing of optical component, optical fiber sensor system, and optical signal processing over the last decades. Especially, in wavelength-routed WDM network using optical cross-connects (OXC), high-resolution spectroscopy, and passive component test, tunable and switchable lasers can be considered as the useful sources to reduce channel cross-talk and enhance the functionality of WDM communication systems. To realize the tunable and switchable lasers, various methods have been utilized. The most important key component is a wavelength selective filter, such as fiber Bragg gratings (FBGs), long-period gratings (LPGs), nonlinear optical loop mirror (NOLM) and interferometers. Recently, broad-band lasers covering both C-and L-band have now become one of the most promising future network elements, satisfying the ever-increasing capacity demand of wavelength-routed WDM network. However, there has been a lack of accumulated research reports on optical switching between C-and L-band. In the previously reported switching techniques between C-and L-band, the wavelength switching range was less than 30 nm, which did not cover the whole range of in C-(1530 to 1560 nm) and L-band (1560 to 1620 nm) such as LPGs on a polarization-maintaining fiber (PMF), FBGs on a PMF and high-birefringence fiber loop mirror. In this paper, we propose a widely tunable and switchable dual wavelength erbium-doped fiber laser with a wide operation range of 80 nm covering both C-and L-band by a fiber Fabry-Perot tunable filter (FFP-TF) and inserting the SLPG as the lasing wavelength-selective element in the concatenated cavities of the dual-wavelength EDFL operated. The proposed laser has a signal to noise ratio of greater than 50 dB during the whole switching and tuning processes. The dual-wavelength lasing output was effectively switched from C- to L-bands and a fast switching response time of 250 us was obtained.

8961-111, Session PTue

Optical characterization, luminescence properties of Er3+ and Er3+/Yb3+ co-doped tellurite glasses for broadband amplification

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In the present paper, optical absorption and emission spectra and luminescence decay lifetimes of different concentrations, 0.1, 0.3, 0.5, 0.7 and 1.0 mol% of Er3+ and 0.1Er3+/0.5Yb3+ co-doped tellurite glasses (TeO2-Bi2O3-ZnO-Nb2O5) were reported. Judd-Ofelt intensity parameters were determined and used to calculate spontaneous radiative transition probabilities (Arad), radiative lifetimes (?R), branching ratios (?) and stimulated emission cross-sections for certain emission transitions. NIR emission at 1.5?m and up-conversion spectra of Er3+ and Er3+/Yb3+ co-doped tellurite glasses were measured under excitation wavelength of 980 nm. The absorption, emission and gain cross-sections for 4I13/2?4I15/2 transition are determined. The peak emission cross-section of this transition is found to be higher (9.95?10-21 cm2) for 0.1 mol% of Er3+ and lower (6.81?10-21 cm2) for 1.0 mol% of Er3+ doped tellurite glasses, which is comparable to other oxide glasses. The larger peak emission cross-section for lower concentration of Er3+ is due to the high refractive index of glass matrix (2.1547), relation established from Judd-Ofelt theory. The observed full-width at half maxima (FWHM) for lower and higher concentration of Er3+ is 64nm and 96 nm. The larger values of FWHM and peak emission cross-sections are potentially useful for optical amplification processes in the design of Erbium doped fiber amplifiers (EDFs). Under 980 nm excitation three strong up-conversion bands were observed at 530nm, 546nm and 665nm. The pump power dependent intensities and mechanisms involved in the up-conversion process have been studied. The luminescence decay profiles for 4I13/2 level were reported for all glass matrices.

8961-112, Session PTue

Photonic crystal fiber pump combiner for high-peak power all-fiber thulium lasers

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Similar to ytterbium-doped fiber lasers at 1 µm, photonic crystal fibers (PCFs) are extremely attractive for use in high energy and high peak power thulium-doped fiber laser operating at 2 µm. The combination of long wavelength, ultra-large mode area, and virtually single-mode beam quality make Tm:PCFs advantageous, particularly for use in ultrashort pulse laser systems. In order to make such systems robust, it is highly desirable to integrate the entire system using an “all-fiber” configuration to avoid free-space propagation. Utilizing an advanced all-fiber pump combiner/mode-field adaptor, similar to a design used for a 1-kW Yb:PCF laser system, we report on the performance of a prototype for use with Tm:PCF. We characterize the amplifier performance of the integrated system to that of the Tm:PCF in a free-space signal/pump launch configuration. As we ultimately hope to use this integrated amplifier in an ultrashort chirped pulse amplification laser system, we carefully characterize spectral/temporal modulation resulting from multimode interference between fundamental and higher order transverse modes in the amplifier. For this, we couple and amplify a broadband ASE source based on single-mode step-index Tm:fiber. The ASE source includes a fiber-coupled polarization-dependent optical isolator, so that the ASE signal is polarized to enable splicing to the amplifier. This is compared to free-space coupling to Tm:PCF as well as free-space and integrated coupling to step-index large-mode area Tm:fiber.

8961-114, Session PTue

Spectral and temporal phase measurement by optical frequency-domain reflectometry

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The capability of measuring the spectral and temporal phase of an optical signal is of fundamental importance for the advanced characterization of photonic and optoelectronic components, biochemical sensors, structural monitoring sensors and distributed sensor networks. To address this problem, several techniques have been developed : frequency-resolved optical gating (FROG), spectral phase interferometry for direct electric-field reconstruction (SPIDER), stepped-heterodyne technique, laser Doppler vibrometry (LDV) and Doppler optical coherence tomography (OCT). However, such techniques often lack of versatility for the mentioned applications. Swept-wavelength interferometric techniques and, among these, optical frequency-domain reflectometry (OFDR) are flexible and highly sensitive tools for complete characterization of amplitude and phase of target devices.

In this work we report on the spectral and temporal phase measurement capabilities of OFDR. Access to spectral phase information is demonstrated by retrieving the phase shift introduced by an amplitude and phase programmable optical filter (Finisar Waveshaper 1000S/X). Results show accurate retrieval of group delay (GD), group delay dispersion (GDD) and discrete phase shift produced by the Waveshaper, as well as filter attenuation profile. In addition, we demonstrate the detection by OFDR of small temporal (i.e. dynamic) phase modulations, induced by the microscopic mechanical movement from a target in the direction of the probe beam. The technique, unlike LDV and Doppler OCT, allows the simultaneous retrieval of the instantaneous position of several reflecting target along the beam path. Such features make OFDR suitable for the study of static and dynamic aspects of photonic components and sensors, and for the assessment of strain in materials.

8961-115, Session PTue

Effect of linewidth enhancement factor in actively mode-locked ring laser

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Fundamental performance of swept-source optical coherence tomography (SS-OCT) system is defined by its wavelength-swept laser. Especially narrower instantaneous spectral linewidth of the laser is advantage in deep-range tomography. We have demonstrated narrow-linewidth actively mode-locked ring lasers (AMLL), employing anomalous dispersion configuration. The linewidth of an AMLL is determined by anomalous dispersion and self-phase modulation (SPM) in the semiconductor optical amplifier (SOA). For such soliton-like phenomenon of AMLLs, both of large dispersion and small SPM makes the linewidth narrower. Since the larger dispersion, however, restricts wavelength sweeping range of AMLLs and results in decline of axial resolution of OCT, too large dispersion cannot be used. To weaken SPM effect, low linewidth enhancement factor ? of quantum-dot SOA (QDSOA) is desirable.

In this study, we employ a QDSOA as a gain medium in an AMLL and also use a quantum-well SOA (QWSOA) for comparison. The spectra of the AMLL are evaluated using an optical spectrum analyzer (OSA). The spectral peak of QDSOA-AMLL with relatively small dispersion of -0.06 ps2/m is narrower than that of the QWSOA-AMLL with dispersion of -0.128 ps2/m . The linewidth of the QDSOA-AMLL is 0.04 nm in full-width half-maximum.

We also experimentally measured interference signals using a Fourier transform spectrometer and theoretically calculated the interference signals. For the entire depth range, the coherency of the QDSOA-AMLL is competitive with the QWSOA-AMLL. In addition the calculated interference signals for ? = 1 and ? = 5 correspond with the experimental signals.

8961-116, Session PTue

Fiber modes in non-confocal cavities

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The overlap of a single frequency laser beam with a pure TEM00 mode can be analyzed by coupling it into a non-confocal ring cavity. This method is of great interest for applications where only the power in the fundamental mode can be used (e.g. Gravitational Wave Detectors). However – especially when using delivery fibers or fiber amplifiers – it is not trivial to draw unambiguous conclusions about the origin of the imperfect overlap, because the fiber eigenmodes slightly differ from the TEM modes. Here, we show a theoretical analysis linking the observed cavity modes with the fiber modes. Moreover, we show that to achieve 98% TEM00 mode overlap a single mode fiber is not necessarily required.

In order to do this, we used the theoretical fiber modes to calculate the overlap with the complete TEMnm mode set numerically. We simulated the cavity alignment process by adapting the position and mode size to optimize overlap with the TEM00 mode. Allowing for a slight cavity misalignment, we were able to reproduce the data obtained from the measurements.

As long as the fundamental fiber mode can be predominantly excited, the higher order fiber modes can be compensated by alignment. On the other hand if the relative phase between the two modes is time dependent (for example due to a frequency offset between the modes or movement of the fiber), their impact on the TEM00 modal decomposition becomes much stronger. Overall the model is consistent our measurements of different fiber designs and different power levels.

8961-117, Session PTue

Influence of zero dispersion wavelength on supercontinuum generation in near infrared, visible, and UV range for a series of microstructured fibres

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Nonlinear phenomena in microstructured fibers (MSFs) is defined by dispersive properties of a fiber. Zero dispersion wavelength (ZDW) and pump source wavelength play an important role in estimating the nonlinear effects and thus are subject of wide investigations. Multiple nonlinear processes like: four wave mixing (FWM), cross phase modulation (XPM), cannot be very efficient without phase matching which is achieved when a fiber is pumped in anomalous dispersion region. On the other hand, other nonlinear processes, such as self-phase modulation (SPM) and Raman scattering (RS), profit from pumping fiber in normal dispersion region. Thus the efficiency of supercontinuum (SC) generation in a fiber is dependent on its chromatic dispersion properties, which can be tailored by the proper fiber geometry design, and by the pump source wavelength.

In our paper we present experimental analysis of SC generation obtained for a series of nonlinear MSFs. Our fibers have different ZDW and therefore when pumped by the same pump source, different nonlinear

effects contribute to the SC generation. We analyze and explain the influence of ZDW on nonlinear effects. Comparisons of nonlinear interactions for fibers pumped in anomalous and normal dispersion regimes are provided.

In our silica MSFs an ultra short UV radiation was obtained by nonlinear processes estimation. We provide experimental analysis of MSFs geometrical parameters influence on UV conversion efficiency. Our studies present effective SC generation in near infrared, visible and UV ranges. Unique information about the influence of MSFs geometry on UV generation efficiency gives possibility to increase its application potential.

8961-118, Session PTue

Analysis of supercontinuum generated with endlessly single-mode new type of microstructured fibre series with near-visible zero-dispersion wavelength

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Fundamental properties of pure silica microstructured fibres (MSFs) can be determined by their geometrical cross-section design. Investigation of nonlinear effects was widely evaluated in diverse types of MSFs with exactly defined dispersive properties. Proper design of Zero Dispersion Wavelength (ZDW) strongly influences generation of nonlinear processes resulting especially in supercontinuum generation (SC). ZDW shift to short wavelengths together with high nonlinearity (small effective mode area) can be obtained by dramatic decrease of microstructured fibre pitch and increase of air-filling ratio. Fibre geometry must be properly scaled preserving technological tolerances to obtain precisely defined position of ZDW near visible range. Additionally, higher air-filling ratio results in multimode guiding regime.

Therefore, in the paper we present studies of novel type of fibre geometry with ZDW near visible range together with endlessly single mode propagation regime. Chromatic dispersion measurements and ZDW analysis are performed with use of interferometric method. Presented MSFs series (the same structure type, but different ZDW position) is manufactured by stack and draw method. Proposed MSFs geometry enables fabrication of desired chromatic dispersion characteristic while respecting all technological tolerances, which is very difficult in case of manufacturing typical photonic crystal fibres for supercontinuum generated with 780 nm wavelength pulses from titanium-sapphire laser. Additionally, proposed endlessly single mode operation provides high quality white light output beam, simultaneously with stable and flat SC source. Paper also reports on the SC generation with pumping in the anomalous and normal side of chromatic dispersion with femtoseconds and picoseconds pulses.

8961-119, Session PTue

Spectroscopic properties of Ho3+, Tm3+, and Ho3+/Tm3+ doped tellurite glasses for fiber laser applications

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Several papers were reported on spectroscopic properties of rare earth doped different host glasses. A complete knowledge of fluorescence properties of rare earth ions in laser materials is necessary to achieve efficient, compact and cheap sources of laser radiation for NIR and mid-IR region. Tellurite glasses are potentially useful for generation of NIR and mid-IR laser radiation due to its special features such as lowest phonon energy (750 cm-1) among oxide glasses, reasonably wide transmission region (0.35 - 5?m), good glass stability, good rare earth ion solubility, high linear and non-linear refractive index. In the present work, authors prepared Ho3+ and Tm3+ singly doped and Ho3+/Tm3+ co-doped tellurite glasses using conventional melt-quenching method. Spectroscopic measurements and analysis of energy transfer process in Ho3+, Tm3+ and Ho3+/Tm3+ co-doped glasses pumped with 785nm and 451 nm excitation wavelengths have been performed. There are some spectroscopic properties are important to understanding and modeling of rare earth doped laser materials. Using Judd-Ofelt theory, radiative transition rates (Arad), radiative lifetimes (?R), branching ratios (?) were estimated for certain excited states of Ho3+ and Tm3+ doped tellurite glasses. The emission cross-sections and gain coefficients have been determined from the absorption spectra of Ho3+ and Tm3+ ions in glasses. The energy transfer process such as ion cross-relaxation, Tm3+-Ho3+ energy transfer and energy transfer up-conversion were studied and identified to specific candidate for laser operation.

8961-120, Session PTue

Effect of mode locking technique on the filtering bandwidth limitation in all normal dispersion femtosecond fiber laser

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The spectral bandwidth plays an important role on the stability and the width of the generated pulses in all normal dispersion femtosecond fiber lasers. The narrower the spectral filter, the shorter the pulse width. In this manuscript, the dependence of the lower limit of the spectral filter's bandwidth on the mode locking technique is numerically and experimentally elucidated. It is found that nonlinear polarization evolution (NPE)-based mode locking can support narrower filtering bandwidth compared to semiconductor saturable absorber mirror (SESAM)-based and hence shorter pulse width can be obtained using NPE. In simulation, the narrowest spectral bandwidth of stable mode locked pulse is plotted as a function of both the length and small signal gain of Yb+3 fiber. To verify the concept experimentally, two set ups were implemented, one employs the SESAM and another employs NPE. Stable pulses are obtained using 7 nm spectral filter in both two cavities; SESAM and NPE. However by using 2 nm spectral filter no stable pulses were observed in SESAM-based cavity while quite stable pulses were observed in NPE-based cavity.

8961-121, Session PTue

Highly stable carbon nanotubes mode locked fiber laser

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We demonstrate a highly stable mode locked fiber laser based on single wall carbon nanotubes. A short segment of a microfiber was embedded in the carbon nanotubes and polyvinyl alcohol composite acting as a saturable absorber. The operation is based on the evanescent field interaction of the propagating light with carbon nanotubes. The pulse widths were 359fs?96fs? 66fs, to the best of our knowledge, 66fs was the shortest pulse in the carbon nanotubes mode locked fiber laser. The

output pulses are monitored for 100h to find that there is no significant degradation of the spectral width.

8961-122, Session PTue

Automated image magnification for CO2 laser glass processing system

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Precise and accurate alignment of optical fiber and fiber based components is critical to optimizing fusion splice performance. A CO2 laser heating system enables a wide range for fiber processing, from a few microns to a few millimeters. Thus, alignment requirements for specialty fibers and components are unique in that many require a large field of view (>2500um) for the edge alignment and a high magnification for micron or submicron features – such as single or multiple cores, stress applying members, or structured air holes. Currently available glass processing systems have attempted to solve this issue by allowing the user to install a lens into the imaging path to achieve either the field of view or the magnification but not both, which is both time consuming and not automated. In our novel automated magnification system, the optics can zoom in or out based on fiber size and process requirement.

As examples, 2mm to 125um fiber cladding alignment can be accomplished at zoom-out position and 20/400 LMA fiber core alignment can be performed at zoom-in as shown in Figure 1. For PCF (Photonic Crystal Fiber), the air hole pattern is identified and rotationally aligned with the higher optical magnification as displayed in Figure 2. The chart in Figure 3 illustrates the improvement in splice performance when utilizing the automated magnification system for splicing SMF as well as a stabilized feedback of the CO2 laser.

8961-123, Session PTue

Gauss modulated of burst gauss-pulses by a pulse shaper from an erbium q-switched fiber laser

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A Q-switched erbium fiber laser is used to generate burst gauss-pulses which amplitude is also modulated by a big gauss pulse. Inside the laser cavity we use a bulk acousto-optic modulator (AOM) that permits fast and reliable controlling of the cavity Q-factor. If the AOM rise-time is less than the cavity round-trip, the q-switch pulses consist of a number of sub-pulses separated by an interval equal to the cavity round-trip. Also if we use a two steps pulse to modulate the AOM, the active fiber with the AOM works as a pulse-shaper. So in this way we use the AOM modulated by two steps pulse to generate Gaussian-sub-pulses. To modify characteristics of amplitude modulation of the burst Gaussian-pulses in a big Gaussian pulse we use an attenuator inside the cavity. In a previous work we have shown the influence of cavity loss upon performance of a q-switched erbium-doped fiber laser. Also behind our experimental results a distributed model that takes into account two contra-propagating laser waves also works in this complex experiment. So we compared both results from the experiment and from the model.

8961-124, Session PTue

Effects of the gain property on the efficiency of the strongly pumped fiber laser

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The tandem-pumping technology, successfully used in the IPG's single-mode 10-kW fiber laser, makes the option of the pumping wavelength more flexible. Note that the gain property (e.g., the absorption and emission cross sections, represented as ?a(?) and ?e(?), respectively) of the fiber laser changes with the pumping wavelength. In this paper, aiming at optimizing the pumping wavelength, the effects of the gain property on the efficiency of the fiber laser are studied. We take the quantum efficiency ? (?=Po(Lopt)?s /(Pp?p), where Po(Lopt) is the output power with the optimum length Lopt, Pp is the pump power, and ?s/?p is the lasing/pumping wavelength) as the diagnoses parameter of the laser efficiency. By analytic studying the model given in [IEEE J. Quantum Electron. 34, 1570], we find that, although ? increases monotonically with the term [N*?p*?a(?p)](where N is the dopant concentration and ?p is the pump fill factor), there is a critical value of [N*?p*?a(?p)] beyond which ? increases with [N*?p*?a(?p)] slowly. It means that [N*?p*?a(?p)] should be larger than the critical value to obtain high efficiency. The analytic expression of the critical value is also given in this paper.

Due to the limitation of the analytic study caused by the unavoidable approximation, we also carry out numerical studies. The results indicate that the efficiency of the laser should be improved by reducing [?e(?p)/?a(?p)] or increasing [?e(?s)/?a(?s)]. It is found that [?e(?p)/?a(?p)] should be less than 2 to ensure that the drop of ? is smaller than 0.1. It is also illuminated that ? increases slowly when [?e(?s)/?a(?s)] should be larger than 5. We believe that these results are helpful for designing the fiber lasers.

8961-125, Session PTue

High-power fiber amplifier with adjustable repetition rate for use in all-fiber supercontinuum light sources

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In recent years the use of supercontinuum light sources has encouraged the development of various optical measurement techniques, like microscopy and optical coherence-tomography. Some disadvantages of common supercontinuum solutions, in particular the rather poor stability and the absence of modulation abilities limit the application potential of this technique.

We present a directly controllable all-fiber laser source with appropriate parameters in order to generate a broad supercontinuum spectrum with the aid of microstructured fibers.

Through the application of a laser seed-diode, which is operated by a custom built controller to generate nanosecond pulses with repetition rates in the MHz range in a reproducible manner, a direct control of the laser system is enabled. The seed-signal is amplified to the appropriate power level in a 2-step amplification stage. Broad supercontinuum is finally generated by launching the amplified laser pulses into different microstructured fibers.

The system has been optimized in terms of stability, power-output, spectral width and beam-quality by employing different laser pulse parameters and several different microstrctured fibers.

Finally, the system as a whole has been characterized in reference to common solid state-laser-based supercontinuum light sources.

8961-126, Session PTue

Numerical aperture measurement system for microstructured fibres and tapers analysis in a broad wavelength range

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Numerical aperture (NA) of an optical fiber is a dimensionless number which characterizes the range of angles over which the fiber can accept or emit light. In classical optical fibers light is guided in material on the base of differences between refractive index in core and cladding. Numerical aperture in that type of fibers is negligibly dispersive in the whole spectrum thus it is enough to measure it only for single wavelength. On the contrary in microstructured fibers (MSF), where light is guided on the base of fiber geometry, NA is significantly increasing with wavelength. Proper identification of this fundamental fiber property determines the ability of efficient light coupling into the fiber, capability of low loss splicing with other fibers. Furthermore it is essential to monitor the change of NA in fiber tapers, which strongly depends on the taper diameter. In this paper we present a novel system for NA measurements of classical and microstructured fibers as well as tapers on both of these fiber types. In opposite to traditional methods of NA characterization, our system can specify the dispersive properties of NA in a very broad wavelength range from 450 nm up to 2400 nm. Moreover, in fibers without circular symmetry the NA can change not only with wavelength, but also with the angular orientation. Therefore our set-up has the capability of rotating the fiber around its axis. Additionally, the presented setup can be applied for determination of refractive index (RI) of a broad range of materials, with which the MSF air-holes can be filled with. The RI can be calculated from the difference of the NAs of a filled and unfilled fiber.

8961-127, Session PTue

Stimulated Brillouin scattering suppression with a chirped laser seed: comparison of dynamical model to experimental data

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When scaling CW single-mode fiber amplifiers to high power, the first nonlinear limitation that appears for narrow-linewidth seed lasers is stimulated Brillouin scattering (SBS). Since the SBS threshold scales as the inverse of the interaction length, any method that reduces this will increase the threshold. We present a dynamical simulation of Brillouin scattering in a Yb-doped fiber amplifier that numerically solves the differential equations describing the laser, Stokes and pump waves, the inversion, and the local density fluctuations that seed the scattering process. We compare the model to experimental data, and show that a linearly chirped seed laser is an efficient form of SBS suppression; specifically, in comparison to a random phase modulated seed and long delivery fibers. The frequency chirp decreases the interaction length by chirping through the Brillouin resonance faster than the fiber transit time. The seed has a highly linear chirp of 1e14 – 1e16 Hz/s at 1064 nm while preserving a well-defined phase relationship in time. This method of SBS suppression retains a long coherence length, while at high chirps appears to the SBS as a large linewidth increasing the threshold. For chirp repetition periods longer than the fiber transit time an increase in fiber length increases the laser bandwidth within the fiber making the interaction length independent of delivery fiber length for large enough chirp rates. The parameters in the model are fitted to 300 W experimental data and then used to predict chirp requirements for multiple kW amplifiers and tens of meters of delivery fiber.

8961-35, Session 9

Bursting for enhanced ablation of materials *(Invited Paper)*

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A significant enhancement in the rate of material removal is demonstrated using a nanosecond UV fiber laser in multi-pulse burst mode, as compared to the case without bursting. Percussion drilling and thin-film scribing tests show that, in general, laser bursts with increased pulse count and reduced pulse spacing show higher material removal rates. Results to be presented are for mono-crystalline silicon, indium tin oxide (ITO) thin films on glass, sapphire, and copper.

It is well known that operating a nanosecond-pulsed laser at higher energy pulses accelerates material removal rates, but degrades machining quality. Additionally, operating at a higher pulse repetition frequency is recognized to deliver fast material removal, while still maintaining machining quality. Alternatively, multi-pulsing (bursting) is emerging as a more effective technique for accelerated material processing. In this report, we demonstrate that operating the laser in burst mode is superior to operating the laser in single-pulsed mode with uniform pulse distribution. Primarily this is because multi-pulsing minimizes thermal diffusion as the delivered energy ablates the material. The uniformly spaced pulse distribution case corresponds to the condition of maximum thermal diffusion in the substrate.

8961-36, Session 9

High peak- and average-power, pulse shaped fibre laser in the ns-regime applying step-index XLMA gain fibres

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In more and more laser based industrial applications the cw and pulsed fibre lasers became the tool of choice mainly because of their robustness, compactness, high brightness, high efficiency and reasonable costs. However to further increase the productivity with those laser types there is a great demand for even higher laser output power.

In this context we demonstrate a pulsed high peak- and average power fibre laser in a MOPA configuration with selectable pulse durations between 1 ns and several hundred nanoseconds. To overcome fibre nonlinearities as SRS and SPM, flexible extra large mode area (xlma) step index fibres, prepared by novel powder-sinter technology, have been used as gain fibres. As an example, for 12 ns pulses, a pump power limited average laser output power of more than 400W with simultaneously peak powers of more than 3.5 MW (close to self-focussing-threshold) have been achieved in save operation and with negligible nonlinearities. To the authors´ knowledge it is the first time that this type of gain fibres has been applied in real high power pulsed laser-amplifiers. The potentials of this laser system have been further explored towards longer pulse durations in order to achieve pulse energies more than 100 mJ by means of pulse shaping techniques. In addition, investigations have been done with reduced pulse energies and repetition rates up to 500 kHz and average powers of more than 500 W. Finally, the scalability of our system for average powers in the kW range has been studied.

8961-37, Session 9

High-peak power, flexible-pulse parameter, chirally coupled core (3C®) fiber-based picosecond MOPA systems

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We demonstrate flexible performance in a fiber MOPA system based on nLIGHT's PFL seed laser platform and chirally coupled core (3C®) fiber. The 33um core, 27um MFD 3C fiber used in these demonstrations is fabricated in volume at nLIGHT's Finland facility. A variety of pulse formats are amplified to nonlinearity limited >300kW peak power, including single pulses in the <50ps regime and >500ps regime at a variety of repetition rates from 10's of kHz to several MHz. Despite lack of internal stress inducing elements, 3C fibers demonstrate high polarization extinction ratios (PER >15dB) which remain stable over environmental perturbation. Beam quality in these 3C based MOPAs is exceptional with M2<1.15 and circularity >95% at all power levels. Beam pointing often evident in other LMA fiber technologies due to higher order mode content is immeasurable in these fiber MOPAs. Burst mode operation of the seed laser system using flexible burst repetition rates (10's of kHz to several MHz) and adjustable pulse-to-pulse spacing within bursts (<10ns to 100ns) is demonstrated and amplified in the same 3C fibers. Bursts of up to ten 50ps pulses amplified to total energies exceeding 160uJ are demonstrated at 200kHz burst repetition rate and 32W average power at high efficiency (74% slope). Bursts of up to five 500ps pulses are also amplified to up to 360uJ total energy. In both cases, the varying degree of saturation of pulses within a group and possible mitigation paths are reviewed. Progress of development of further core size scaling will be covered.

8961-38, Session 9

An all-fiber high-energy cladding-pumped 93 nanosecond Q-switched fiber laser using a fiber saturable absorber

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We report an experimental demonstration of an all-fiber passively Q-switched fiber laser using large mode area (LMA) step-index and photonic crystal Yb+3-doped fibers as the gain element and single mode step-index Yb+3 fiber as a saturable absorber. Conjoined tapered fibers are used to couple the amplified spontaneous emission (ASE) between a large mode area Yb3+-doped fiber pumped at 915 nm and an unpumped single-mode Yb3+-doped fiber saturable absorber. The tapered fiber sections are structured to match the estimated mode field diameters of the fundamental mode of the tapered large mode area gain fiber and the expanded LP01mode of the single mode fiber. The comparatively high intensity of the ASE in the single mode unpumped fiber saturates the absorption, making the fiber transparent, before the onset of gain depletion in the LMA fiber. Thus, the unpumped single mode Yb3+-doped fiber acts as a saturable absorber in the same manner as traditional bulk saturable absorbers such as Cr+4:YAG. Using this scheme, we demonstrate a 32 ?J 93 ns Q-switched oscillator at 1030 nm. The associated peak power is more than two orders of magnitude larger than previous studies using unpumped Yb+3 fiber as a saturable absorber. We further demonstrate amplification to 0.230 mJ through the addition of an Yb+3 fiber master-oscillator power-amplifier (MOPA) to the fiber oscillator without compromising the all-fiber architecture.

8961-39, Session 9

High-power monolithic fiber amplifiers based on advanced photonic crystal fiber designs

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For multi kW fiber laser applications where near diffraction limited beam quality and sub GHz linewidths are required. The Photonic Crystal Fiber has many advantages in that it represents a "digital" fiber fabrication technology in that since the fiber is made up of many individual fibers, the properties of the fiber can be modified in many different ways. In this paper we report on our efforts to design, fabricate and operate kW level fiber lasers based on completely monolithic PCF designs. The PCF fibers consist of 40um core fibers with large (530um) air clad pump regions. The core consists of a micro-segmented acoustic tailored region with 133 sub core "pixels", made up of 3 different types of index matched glass (2 Yb doped, one undoped). In addition a mode selecting side core (MSS) structure is used to filter higher order modes from the fiber. A 6+1 to 1 Etched Air Taper combiner was fabricated with over 96% pump efficiency and integrated with the PCF fiber. Initial tests with 470W of pump yielded 381W output with no observation of either SBS or Modal instabilities. Low loss PCF to PCF splices and end caps were also created. Efforts to scale the power to over 1.5kW of pump will also be reported.

8961-40, Session 10

Plasma outside deposition (POD) of fluorine doped silica for high-power laser applications *(Invited Paper)*

Andreas Langner, Gerhard Schötz, Heraeus Quarzglas GmbH & Co. KG (Germany)

The plasma outside deposition (POD) process is the basic technology for production of large core multimode silica fibers with highly fluorine doped cladding. Due to the all silica fiber construction such fibers can transmit several kW of power even with a core of 100 µm or less. An overview of the current capabilities and trends in high power laser applications will be presented, including very large fibers, shaped core and cladding designs, fibers with multiple claddings or multiple cores, and designs for pulsed lasers. These concepts can be applied to the transmission fibers as well as the fiber lasers. Heraeus is supporting these new developments by offering a growing number of materials, preforms and services.

8961-41, Session 10

The Yb-doped aluminosilicate fibers photodarkening mechanism based on the charge-transfer state excitation

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The photodarkening (PD) of Yb-doped aluminosilicate fibers under

continuous NIR-pumping (915?975 nm) is a critical limiting factor in the design of amplifiers based on such fibers. It now seems clear that PD nature is generally associated with aluminium oxygen-hole centers (Al-OHC) visible absorption bands. In this paper we report the main origin of the Al-OHC formation due to the NIR-pumping irradiation. We have performed comparative studies of the absorption and luminescence spectra of Yb-doped fiber preforms and YAG crystal samples. The UV-absorption bands associated with a divalent and trivalent ytterbium ions (Yb^2+ and Yb^3+) in the aluminosilicate glass network were described in details. We have confirmed the similarity of NIR-pumping (915 nm) and UV (193 nm) quanta influence to the colour-center formation processes: the NIR-pumping or UV irradiation has resulted in creation of the Yb^2+ and Al-OHC in the glass network. We have revealed the complete absence of Al-OHC UV (3.2 eV) and visible (2.3 eV) absorption bands in the hydrogen-loaded preform samples irradiated with a 915 or 193-nm light. The presence of room-temperature stable Yb^2+ in the NIR-pumping and UV irradiated preform samples was evidenced by registration the corresponded for Yb^2+ UV-absorption bands (3.7 and 5.8 eV) and the visible “yellow” luminescence (~2.3 eV). We suggest that the origin of Yb^2+ formation is generally connected with the Yb^3+ photoinduced excitation to the “charge-transfer state” (CTS). We have found and described the CTS-related transitions in Yb-doped aluminosilicate fiber core glass relying on the previously published ideas for YAG:Yb. In general, the “one-photon” (UV) or “cooperative” (NIR-pumping) excitation of CTS can be considered as a most likely mechanism of Yb^3+ to Yb^2+ conversion following the Al-OHC formation – i.e. as the main mechanism of PD.

8961-42, Session 10

Intrinsically low Brillouin- and Raman-scattering optical fibers

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It has recently been shown that parasitic optical process, such as Stimulated Brillouin scattering (SBS) can be significantly reduced through a combination of novel fiber fabrication methods and proper compositional tailoring. More intriguing was the identification of a composition where the Brillouin gain coefficient (BGC) could be zero by properly controlling the photoelastic properties of the material. Here, a similar approach to the suppression of SRS in fiber systems is described and demonstrated. As conventional optical fibers are mainly comprised of silica, the primary method in realizing low-SRS fibers, as with low-SBS fibers, is to displace large amounts of silica with a material with lower Raman gain, if the replacement material has a Raman spectrum overlapping with that of silica. In this work, for the first time, Raman and Brillouin gain spectra are reported for three all-glass Yb:YAG crystal-derived optical fibers. It is shown that fibers derived from YAG have both a reduced Brillouin gain, which has been reported previously, and also reduced Raman gain relative to that of pure silica. This latter finding is due partly to a significant broadening of the silica Raman lines, and also partly due to yttria and alumina possessing lower gain than that of silica. Such a designer-materials approach to the suppression of stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS) can enable future high-energy and high-peak-power fiber laser systems. Measurements of the Raman gain spectra for several other compositions will also be presented.

8961-43, Session 10

Fabrication and characterization of a phosphosilicate YDF with high Yb absorbance and low background loss

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We report fabrication and investigation of ytterbium-doped phosphorsilicate fiber (P co-doped YDF) with high Yb content, low numerical aperture, and low background loss. The P co-doped YDF is fabricated by MCVD using the vapor sources of Yb, SiCl4, AlCl3, and POCl3, and by the gas-phase doping method. The optical properties of this P co-doped YDF are compared with Al co-doped and Al:P co-doped YDFs with low background losses. The minimum background loss of the P co-doped YDF, in the spectral range from 1100 to 1380 nm, is as low as ~3 dB/km. This is nearly independent of the Yb and P contents because soot deposition and collapsing conditions are properly optimized. The excess loss induced by PD, for the P co-doped YDF, was dramatically reduced compared to both Al do-doped and Al:P co-doped YDFs. The optical slope efficiency of the P co-doped YDF is about 80%, depending on the pumping wavelength and fiber length. The fiber colors during pumping are blue for both the P co-doped and Al:P co-doped YDFs. Based on the results from a prolonged test, the output power of the P co-doped YDF is highly stable, with an initial degradation of 2-3%; which demonstrate improvement in PD resistivity with P incorporation into the glass, compared to the Al:P co-doped YDF with degradation above 15%.

8961-44, Session 11

Fiber lasers at 3 microns and beyond: status and perspectives *(Invited Paper)*

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We will present an overview of our recent results pertaining to the development of monolithic fiber lasers operating around 3 µm and beyond. Specifically, we will describe a double-clad highly erbium-doped fluoride glass all-fiber laser operating in the vicinity of 3 µm, its power scalability up to several tens of watts in cw mode, as well as its various pulsed operation modes. The first chalcogenide glass based all-fiber laser operating beyond 3 µm will also be presented.

8961-45, Session 11

Development of high-power holmium-doped fibre amplifiers

Alexander V. Hemming, Nikita Simakov, Alan Davidson, Michael Oermann, Len Corena, Dmitrii Stepanov, Neil Carmody, John Haub, Defence Science and Technology Organisation (Australia); Robert Swain, Sub-Micron Engineering Corp. (United States); Adrian L. Carter, Nufern (United States)

The development of high power fibre laser sources at 2 um has been dominated by thulium fibre lasers. More than 1 kW of output power in a near diffraction limited output beam [1], and 608 W of narrow line-width output power [2] have been demonstrated. Holmium doped devices have advantages for a wide range of applications due to the atmospheric transmission benefits of operating at wavelengths beyond 2.1 µm in comparison to thulium based sources.

We have previously demonstrated an efficient resonantly cladding-pumped holmium-doped fibre laser producing 407 W from a robustly single mode fibre [3]. This demonstration is the highest output power produced by any holmium-doped laser. Further advances in the power scaling of holmium fibre sources are expected to take the form of high power fibre amplifiers. An amplifier architecture will allow the realisation of the narrow line-width operation required for applications such as coherent and spectral beam combination.

We have demonstrated a polarised resonantly core pumped holmium fibre laser. The laser produced 27 W of output power in a single-mode beam. This device demonstrates the potential for developing monolithic devices using this fibre architecture and has wide applicability to the

development of master oscillators and amplifiers suitable for further amplification to address a wide range of remote sensing, scientific and defence applications. This paper will present power scaling results of this amplifier architecture.

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[2] G. D. Goodno, et. al., Opt. Lett. 34, 1204-1206 (2009)

[3] A. Hemming, et. al., CLEO: 2013, paper CW1M.1

8961-46, Session 11

Efficiency improvement in Thulium-doped fibers via excited state pumping

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Thulium fibers hold a great potential for many applications in the fields of biology, medicine, environmental sensing, and defense just to mention a few. Furthermore, Thulium fibers bring several advantages for pulsed operation such as the extremely broad amplification bandwidth and the significant reduction of non-linear effects due to the long operation wavelength. Unfortunately thermal problems plague Thulium-doped fibers to the extent that they limit the power scalability of high-pulse energy high-average power fiber systems. These thermal problems come from the large quantum defect present in Thulium systems pumped at 793nm and emitting around ~2µm, and by the inability to efficiently exploit cross-relaxation mechanisms in most silica based fibers. Moreover, the large quantum defect also results in a relatively low efficiency of the amplification process (typically ~30%).

In this contribution we propose a new way to simultaneously increase (almost double) the amplification efficiency and reduce the thermal issues of Thulium-doped fibers. This technique is based on pumping the excited state of the Thulium fiber, in order to bring the ions from the pump level to the upper laser level via stimulated emission instead of via phononic relaxation processes. This way the transition between the pump level and the upper laser level occurs in a radiative way significantly reducing the overall heat load of the fiber. According to our simulations, in a 4m long 10µm core Tm-doped fiber pumped with 100W at 793nm, this technique would allow reducing the temperature in the core from ~400°C to ~160°C while simultaneously increasing the output power from ~37W to ~76W.

8961-47, Session 11

3.8 W supercontinuum all-fiber source at 1.9-3.1 µm

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We report a novel robust and reliable all-fiber laser source generating supercontinuum in Mid-IR. The emission of an all-fiber picosecond Tm-doped silica-based fiber laser mode-locked at the wavelength of 1960 nm (44 MHz repetition rate) utilizing a SESAM semiconductor mirror was amplified in a 4 m piece of a silica-based Tm-doped double-clad fiber diode-pumped at the wavelength of 793 nm. Optical supercontinuum of 5.3 W optical power expanded from 1.9 to 2.5 µm was already generated in this amplifier with a slope efficiency of 21%. Then the amplifier output was spliced with a germanate fiber piece of 35 cm length and 9 µm core diameter using commercial electrical fusion splicer. The laser generated supercontinuum in the range of 1.93-3.06 µm at -10 dB level with optical power of 3.8 W and about 70% slope effeciency. The supercontinuum was represented by a stable pulse train of 44 MHz repetition rate. Its spectral maximum corresponded to the wavelength of 2.9 µm. The peculiarity of the supercontinuum was that it was generated in the region of anomalous dispersion both in the amplifier and in the germanate fiber due to the Raman solitons generation process. As to our knowledge, it is the first oxide-glass based all-fiber solid-spliced laser which emission extended beyond 3 µm. Thus, this novel supercontinuum generation technique is particularly attractive for practical applications, such as optical coherence tomography, optical clocks, trace gas sensing, and military applications.

8961-48, Session 12

2.1mJ, 210W femtosecond fiber CPA system

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Coherent combination offers a way to overcome limitations of a single laser amplifier. These include the average power, which is often limited by thermal-effects, and the pulse energy andpeak power where nonlinearities and damage thresholds are the limiting factor. Fiber amplifiers are especially suitable for this concept due to their excellent beam quality and reproducible output modes, which are two crucial requirements to achieve a high combination efficiency. In this contribution, we report on a femtosecond fiber laser system based on this approach in conjunction with the chirped-pulse amplification (CPA) technology. The pulses coming from a mode-locked oscillator are first stretched to about 1.5 ns before passing through three pre-amplifiers. The beam is then split into four sub-beams for the four main-amplifiers. They consist of four large-pitch (LPF) fiber amplifiers in a parallel configuration. They posses a mode-field diameter of 80 µm each. The splitting and combination is realized by using polarization dependent elements like beamsplitter cubes and thin-film polarizers. Together, they form a Mach-Zehnder type interferometer. Additionally, an active stabilization system based on the Hänsch-Couillaud approach is employed to stabilize the path-lengths in the amplifier arms with sub-wavelength precision. With these components, we could achieve a combined average power of 210 W at a repetition rate of 100 kHz. This corresponds to a pulse energy of 2.1 mJ. The autocorrelation traces and spectra show a good match of the different channels, thus resulting in a high combination efficiency of 88 %.

8961-49, Session 12

High-pulse energy and average-power ultrashort laser pulses via nonlinear compression of coherently combined fiber CPA system

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Coherent combining applied to state-of-the-art femtosecond fiber CPA systems has recently opened the route towards high energy and average power laser systems. We demonstrate the combination of four main amplifier channels in such a system to 2.1 mJ, 320 fs at an average power of 119 W (56 kHz). These pulses are then coupled to a 1.1 m long hollow-core fiber with an inner diameter of 250 µm, which is filled with 1.5 bar of argon gas. The noble gas provides the nonlinearity that leads to spectral broadening via self-phase modulation inside the waveguide structure. Subsequently, the pulses are compressed in a chirped mirror compressor that has a group delay dispersion of -1600 fs2. After the compressor the pulses have an energy as high as 1.05 mJ, which corresponds to an average power of 58 W. The pulse duration after the compressor is measured to be only 42 fs leading to an estimated peak power of ~18 GW, which is the highest ever reported for a fiber based system. Besides this high energy operation regime the average power scalability of this approach is discussed and underpinned with experiments. Under different conditions 580 µJ, 26 fs, 11.6 GW, 135 W (250 kHz) pulses are achieved with the same system. This unprecedented combination of average power, pulse energy and ultrashort pulse duration will be beneficial for a variety of applications, e.g. the generation of coherent extreme ultraviolet radiation or laser particle acceleration.

8961-50, Session 12

High average power and energetic femtosecond fiber laser using chirped- and divided-pulse amplification

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A very efficient way of scaling the energy of amplified femtosecond pulses was provided by the chirped-pulse amplification (CPA) method. Although CPA is used in virtually every amplified femtosecond system, its implementation is increasingly difficult and costly when the desired stretched pulse duration is greater than 1 ns. The divided-pulse amplification (DPA) idea was proposed more recently and is similar to CPA in the sense that it also consists in redistributing the pulse energy over a time interval larger than the initial pulse width to reduce the peak power. In this scheme, a train of several orthogonally polarized delayed pulse replicas is generated and amplified before final recombination. In this Letter, we propose and demonstrate a femtosecond fiber amplifier that uses both concepts simultaneously to scale the output energy of a tabletop femtosecond fiber system. Because the CPA stretched-pulse duration is of the order of hundreds of picoseconds, the DPA delay is induced using freespace interferometers with reasonable arm lengths of up to 0.3 m. A passive architecture is demonstrated where a single interferometer is used for both replica generation and recombination, avoiding the need for active stabilization systems. With two replicas we thus generate 320 fs, 450 ?J pulses at a repetition rate of 100 kHz, corresponding to 45 W average power, using a distributed mode filtering rod-type large-mode area fiber with a combining efficiency of 94%. Temporal and spatial limitations are also investigated as a function of delay between pulse replicas in the amplifier.

8961-51, Session 12

Spectral synthesis to overcome gain-narrowing in femtosecond fiber amplifiers

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Fiber chirped-pulse amplifiers (F-CPA) are now widely recognized as a powerful tool for producing high average power and energetic pulses. However the linear character of chirped-pulse amplification implies that gain narrowing limits the available pulse duration at the output of such systems to several hundreds of femtoseconds, typically around 350 fs. In this contribution we demonstrate a solution to circumvent such problems and allow the generation of ultrashort sub-200 fs pulses, even operating at high gain values. Femtosecond pulses emitted by an ultrashort oscillator are separated into several beams, each carrying a different spectral slice of the pulse to be amplified. After amplification in independent fiber amplifiers, the spectral parts are coherently combined to reconstruct an amplified spectrum that can be larger than in standard linear F-CPA configurations. The experimental set-up starts with a 270 fs mode-locked oscillator which is spectrally broadened to tens of nanometers and spectrally separated, through a dichroïc mirror, in two parts which are amplified in two different Yb-doped fiber photonic-crystal fiber. The outputs of these amplifiers are then spectrally recombined and sent in a compressor. Coherent combining is ensured through active stabilization of the relative optical phase based on frequency tagging (LOCSET technique). In this configuration we are able to generate 145 fs pulses at 35 MHz with an average power of 3 W, corresponding to a total cumulated gain of more than 600. The coherent combining process, stabilization loop and gain narrowing with and without spectral synthesis are also investigated.

8961-52, Session 12

High-energy booster using a core-pumped Yb-doped fiber chirped-pulse amplifier

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Fiber amplifiers have proved to be an efficient and reliable technology to produce high energy ultrafast pulses as well as high average power. Tremendous work is still under progress to further scale the pulse energy by limiting the accumulated amount of Kerr nonlinearity which results in pulse temporal distortions and lower peak power. Over the years, various techniques have been developed to limit the self-phase modulation (SPM) impact, such as chirped-pulse amplification (CPA), passive and active coherent combining or divided pulse amplification, usually used in combination with large-mode-area fibers. All these methods aim at keeping the laser intensity below the SPM induced pulse splitting threshold by temporally or spatially spreading the pulses energy prior to amplification. In this contribution, we investigate single mode core pumping as a way to drastically reduce the amplifier length in order to lower the B-integral and further increase the pulse energy. The output of a fiber amplifier with moderate B-integral is seeded in a 30 cm long 40/200 µm PCF core-pumped by a single-mode 976 nm Yb-doped fiber laser. This short booster provides a total gain of 4.5 allowing the generation of 155 µJ pulses before compression with low nonlinear phase accumulation. After compression, 110 µJ 350 fs pulses were obtained at 20 kHz. Experiments as well as numerical simulations confirm that the core pumping configuration allows extraction of more than twice the energy achievable with a traditional cladding pumped fiber amplifier.

8961-53, Session 12

Normal dispersion femtosecond fiber optical parametric oscillator

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We propose and demonstrate a synchronously pumped fiber optical

parametric oscillator (FOPO) operating in the normal dispersion regime. The FOPO generates chirped pulses at the output allowing significant pulse energy scaling potential without pulse-breaking. The output average power of the FOPO at 1600nm was ~60mW (corresponding to 1.45nJ pulse energy) and ~55% slope power conversion efficiency. The output pulses directly from the FOPO were highly chirped (~3ps duration) and they could be compressed outside of the cavity to 180fs by using a standard optical fiber compressor. Detailed numerical simulation was also performed to understand the pulse evolution dynamics around the laser cavity. We believe that the proposed design concept is very useful for scaling up the pulse energy in FOPO using different pumping wavelengths.

8961-54, Session 13

Nonlinear optics in gas-filled hollow core fibers *(Invited Paper)*

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We review the recent development in inhibited coupling (IC) hollow core photonic crystal fiber HC-PCF) that enabled a dramatic reduction in transmission loss and the optical power overlap. This advance generates a new paradigm in high-field nonlinear optics such as ultra-low loss guidance and compression of high power and high energy ultra-short pulses.

8961-55, Session 13

High-gain, Ytterbium-doped, Ge-pedestal, large-pitch fiber

Christian Gaida, Florian Jansen, Hans-Jürgen Otto, Fabian Stutzki, Jens Limpert, Cesar Jauregui-Misas, Friedrich-Schiller-Univ. Jena (Germany); Andreas Tünnermann, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

Large mode area rod-type fibers have enabled amplification of ultra-short pulses to mJ pulse energy and MW peak powers. For very large mode field areas, fibers have to be designed as rigid rods with typical fiber lengths of around 1 m for efficient operation. A shorter fiber length can be desirable to reduce the packaging size of commercial systems and to decrease the impact of parasitic nonlinear effects for peak-power scaling. The fiber design presented here is based on a modified large-pitch fiber with a higher ytterbium concentration that leads to an increased refractive index of the doped area. To achieve index matching the cladding index needs to be changed. In this contribution we propose to co-dope the passive host material with germanium to match both indices and to obtain a higher Yb-concentration within the active core. Compared to standard LPF the ytterbium doping concentration of this novel germanium-pedestal LPF is doubled. A detailed numerical and experimental investigation shows that with short fiber lengths <40cm is feasible to achieve output powers beyond 100W with 10W seed. Significantly higher gains, of nearly 30 dB, can be achieved for fiber lengths in the order of 60cm. A similar gain can be expected in a conventional LPF with 1.20 m length. In conclusion, we demonstrate a fiber design for significantly enhanced energy storage per fiber length and improved pump absorption. This concept will notably reduce the footprint of ultra-short fiber laser systems.

8961-56, Session 13

Double-clad large mode area Er-doped fiber for high-energy and high-peak power amplifiers

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The use of double-clad fibers for short pulses amplification requires high active ions concentration in order to keep the active fiber length short. In the case of Er-doped fibers an increase of concentration leads to a significant drop of efficiency due to Er ions clustering. We have demonstrated through numerical simulation that efficiency of amplifiers based on double-clad P2O5-Al2O3-SiO2 (PAS) Er-doped fibers decreases slower with Er-concentration growth if compared with standard Al2O3-SiO2 fibers. In this paper, we present single-mode large-mode-area heavily Er-doped double-clad fiber based on PAS glass matrix for short pulses amplification. The developed PAS fiber has a 36 ?m single-mode core and a small signal cladding absorption of 3 dB/m at 980 nm leading to an optimal fiber length in range of 5-8 m depending on the central wavelength. At first, an all-fiber nanosecond MOPA at 1560 nm was built using our PAS fiber as the final amplifier. We obtained 28 W of average output power (efficiency of 25 % with respect to the launched pump power at 976) limited by amplified spontaneous emission. Pulse energy of 1.5 mJ was achieved at pump power level of ~120 W. We believe that it is the first demonstration of mJ-energy level single-mode nanosecond fiber system. Then, direct amplification of 100-fs source was performed using this fiber. We obtained 12 nJ pulse energy and 100 kW of peak power from the fiber which is close to the record value for Er-doped fiber amplifiers

8961-57, Session 13

Single-mode fibers with antireflective surface structures for high-power laser applications

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High laser power transmission through optical fibers is often limited by Fresnel losses that not only reduce transmission but, due to back reflections, can also cause significant laser instability and potential damage to lasers at high optical power. Conventional antireflective (AR) coatings can be impractical, due to delamination problems as well as their tendency to damage under high power laser irradiation. In addition, cleaning the AR coatings can be difficult due to their fragility. We have recently demonstrated new methods to directly imprint the end faces of IR fibers with an antireflective surface microstructure (ARSS), sometimes called "moth eye" surface that has been successfully used for oxide bulk materials. However, such a process will not work for silica fibers due to their high softening temperatures. Conventional methods using lithography and etching are also impractical, especially for single mode fibers with small end faces. We report on results for reduced Fresnel

losses using reactive ion etching of a microstructured surface on the end faces of silica fibers, where the features are random (or quasi-periodic) and have variable heights, known as random ARSS (rARSS). We will also report laser damage test results at 1.06 µm on these fiber end faces with random ARSS, showing damage thresholds as high as 750 J/cm^2, as well as for silica glass, which shows > 5x higher laser damage thresholds than a conventional AR coated sample. In addition we present results showing that surfaces with rARSS can be cleaned like normal optics without any resultant damage.

8961-58, Session 13

Breaking the symmetry for enhanced higher-order mode delocalization

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All very large mode area fiber designs have to deal with the suppression of higher-order modes. Large-pitch fibers utilize the delocalization of higher-order modes, which increase the amplification and excitation of the fundamental mode and leads to a strong effective single-mode operation. Due to the non-resonant nature of the large-pitch concept it is very capable for high average power operations in combination with large mode field diameters, where the thermo-optical effect can no longer be neglected.

In this contribution we demonstrate that the symmetry of modes can be utilized to enhance the performance of the LPF design. To suppress the most disturbing LP11-like higher-order mode a mirror-symmetry can be avoided. A very strong suppression of higher-order modes can be accompanied by a spiral structure, which is very difficult to manufacture. Therefore, the vortex effect of the spiral structure can be transferred to a common hexagonal lattice. It is shown that the proposed spiral LPF can enhance the higher-order mode delocalization over a broad range of thermal loads in comparison to the classical LPF. Therefore, it is expected that such a fiber can enhance the diffraction-limited average output power of fiber laser systems with very large mode field areas.

8961-59, Session 14

Mid-IR combs pumped by fiber lasers *(Invited Paper)*

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We implement a simple method of down-converting frequency combs provided by well developed near-IR ultrafast fiber lasers to highly desirable yet difficult-to-achieve mid-IR range. The method is based on sync-pumped optical parametric oscillators (OPOs) that operate at the degeneracy point. Using PPLN OPO pumped by a 1560-nm Er fiber laser or GaAs pumped by a 2000-nm Tm laser, we achieve frequency combs with instantaneous spectral span of correspondingly 2.5-3.8 and 2.6 - 6.1 microns. High conversion efficiency (up to 40% in photons), low pump threshold (~ 10mW), and superior coherence properties make these comb sources very useful for molecular spectroscopy and metrology.

8961-60, Session 14

A scalable high-power yellow laser source based on frequency doubling of a combined Yb-Raman fiber amplifier

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The excellent beam quality, narrow linewidth, and multi-kilowatt output power levels of Yb-doped fiber lasers make them ideal sources for frequency doubled green lasers. However, building a robust, cost effective yellow laser has remained challenging because of poor performance of Yb-doped fiber amplifiers at wavelengths above 1100nm. Extending the wavelength range has been demonstrated in CW using Raman amplifiers, but power scaling in this configuration is limited by SBS and low peak powers demand the frequency doubling to be done in an optical cavity.

Here, we demonstrate a record of over 20W yellow light by frequency-doubling the output of a novel monolithic Yb-doped fiber source, built using commercially available components and well established LMA fibers.

Our scalable scheme is based on a combined Yb-Raman amplifier. A pulsed source in the wavelength range of 1060-1100nm is combined in a single-mode WDM with a narrowband CW seed the 1100-1180nm range, before amplification to high powers. The LMA Yb-Raman amplifier both amplifies the pulses to 10-20kW peak power (64W average), and using fiber nonlinearity, efficiently shifts the wavelength by SRS to that of the CW seed. While pulse width is determined by the pulsed source, the wavelength is set by the narrowband CW seed.

The high peak powers allow frequency-doubling in a single pass of an LBO crystal. Efficiency of 915nm pump light to yellow exceeds 25%.

The scheme can be used to efficiently generate scalable, high-power, cost effective robust sources in the 560-590nm range.

8961-61, Session 14

760 mW, nanosecond, single-frequency UV fiber laser at 325.3nm

Romain Dubrasquet, Johan Boullet, Marc Castaing, Simon Lugan, Gil Mery, Nicholas Traynor, Azur Light Systems (France); Eric Cormier, Centre d'Etude des Lasers Intenses et Applications (CELIA laboratory) (France)

We have demonstrated a single frequency 760mW class fiber laser emitting at 325 nm using a multistage Ytterbium doped fiber MOPA system to amplify an electronically modulated single frequency laser diode seeder at 976 nm. The seeder modulated at 100kHz and 5ns. Three amplifier stages are used to generate pulses of more than 100?J and a peak power of 20kW at 976 nm.

This high peak power allows us to generate a second harmonic power of 2.3W at 488nm and then third harmonic output power of 760 mW at 325.6 nm in two 20 mm long LBO crystals. The conversion efficiencies for the two stages are 38% and 6.8% respectively. The fundamental power is first focused on a waist diameter of 106 ?m in the first crystal (type I) and then second harmonic and fundamental residual power are both focused in the second crystal (type II) on a waist of 88?m and 62 ?m respectively. The large pulse duration should permit to conserve up to 50 cm long coherence length so this new high power laser source can be particularly interesting in stereo lithography but also in holography, biology and medicine.

8961-62, Session 15

Threshold power and fiber-degradation-induced modal instabilities in high-power fiber amplifiers based on large-mode-area fibers

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We report on two types of modal instabilities observed in high power Yb amplifiers based on Large Mode Area Fibers. The first is observed to occur at a Threshold Power, which we refer to as Threshold Power Modal Instabilities (TPMI). The modal instability is observed as a decrease in beam quality or reduced core light output as higher order modes leak into the fiber cladding. The second type of modal instability is observed for certain cases where the fiber degrades, leading to a similar behavior as the TPMI. We refer to the second class as Fiber Degradation Modal Instabilities (FDMI). We observe that fiber performance is unchanged below the critical power for fiber degradation. Experiments on degraded fiber show a wavelength dependent permanent change is created in the degraded fiber with a memory of the original operating wavelength. We propose a simple picture where modal interference periodically mediates photodarkening or other defect formation in the fiber material creating a grating structure that can then couple the fundamental mode to higher order modes at high thermal loading.

8961-63, Session 15

Raising the mode instability thresholds of fiber amplifiers

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In previous presentations we described how various physical effects influence the mode instability threshold powers of fiber amplifiers. In this presentation we add studies of saturation of the laser gain and show how it can significantly raise the threshold. We also describe spontaneous thermal Rayleigh scattering (sTRS) as the seed for the stimulated thermal Rayleigh scattering process (STRS) responsible for mode instability.

We will describe a new model of sTRS that computes the level of seeding due to scattering from LP01 into LP11 with the optimum frequency shift. The rate of scattering per beat length is nearly constant and is approximately 100 times as strong as the quantum noise level used as the seed previous modeling. The threshold using the larger seed is 5-10% lower than before. The sTRS scattering rate is also proportional to the square of the temperature, so cooling the input end of a fiber amplifier could raise the threshold by a few percent.

We will show that saturation of the laser gain reduces the strength of the thermal grating responsible for mode coupling and thus raises the threshold power. The fiber must be longer with a smaller core to cladding ratio to take advantage of this effect. However, even when taking SBS thresholds into account, the mode instability threshold can be raised by a factor of two or more. Confining the dopant to regions of high saturation can accentuate the threshold improvement.

8961-64, Session 15

Analysis of stimulated Raman scattering in cw kW fiber oscillators

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The threshold for Stimulated Raman scattering (SRS) is analyzed experimentally and theoretically for monolithic LMA cw kW fiber oscillator. Experimental it was found that the threshold depends on the spectral width of the out coupling FBGs, which is not yet understood completely. With a smaller spectral width the threshold decreases, where the threshold is determined by a fixed power content above 1.1 µm relative to the total power. Interestingly, with a broadband reflex by a cleaved fiber end, the threshold is lowest, even if the Raman signal is reflected as well. Attempts to describe such lasers by simulations are based on the nonlinear Schrödinger equation supporting spectral broadening of cw-fiber laser, rate equation gain as well as broadband Raman gain. Spectral broadening of the laser as experimentally obtain can be reproduced and the influence of the spectral with on Raman threshold can be predicted for different designs of the complete fiber laser cavity. In addition we investigate strategies to prevent SRS by fiber integrated filters, e.g. long-period gratings, which are analyzed by their required properties and influence on laser output parameters. The latter the latter is critical in order not to attenuate the signal while increasing the SRS threshold and thereby the total achievable output power. This is true especially because the filters would have to be applied in the passive signal delivery fibers, where the full power is propagating and the attenuation has to be balanced against the benefit of the filter vs. the exponential Raman gain.

8961-65, Session 15

Numerical analysis of modal instability onset in fiber amplifiers

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Numerical analysis of the onset of modal instability in fiber amplifiers is presented. Specifically calculations of the evolution of the intensity fluctuation spectrum along an amplifier for sampling points offset from the core center are presented for different instability onset conditions. These include seeding with LP01 only, seeding with LP01 and LP11 at the same frequency, and seeding with LP01 and LP11 at offset frequencies. Seeding with LP01 only resulted in the onset of instability at a threshold of about 850 Watts establishing the upper limit determined by numerical noise in the model. The intensity spectrum in this case exhibited a single broad peak. Seeding with 10 Watts of LP01 and 1.0E-16 Watts of LP11 at a frequency offset of -600 Hz resulted in an instability threshold of 400 Watts and the preferential amplification of the offset LP11 component resulting in strong frequency lines at multiples of 600 Hz. Seeding with 9.5 Watts of LP01 and 0.5 Watts of LP11 at the same frequency resulted in an instability threshold of 300 Watts with a spectrum that exhibits an interesting structure and broadens significantly in the last centimeters of the fiber. All spectra were calculated after turn-on transients had decayed. The significantly different position dependent spectra suggest distinct instability mechanisms for these cases.

8962-1, Session 1

Kinetics of an optically pumped metastable Ar laser *(Invited Paper)*

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An optically pumped metastable Ar laser has been demonstrated using CW diode laser pumping of discharge excited Ar/He mixtures. Key elements of the lasing kinetics have been investigated using computational modeling.

8962-2, Session 1

Laser excitation dynamics of argon metastables generated in atmospheric pressure flows by microwave frequency microplasma arrays

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The optically pumped rare-gas metastable laser is a chemically inert analogue to diode-pumped alkali (DPAL) and alkali-exciplex (XPAL) laser systems. Scaling of these devices requires efficient generation of electronically excited metastable atoms in a continuous-wave electric discharge in flowing gas mixtures at elevated pressure. This paper describes on-going investigations of the use of linear microwave micro-discharge arrays to generate metastable rare-gas atoms at atmospheric pressure in optical pump-and-probe experiments for laser development. Each array consists of a set of microstrip transmission line resonators with a small (25-100 micron) gap to ground in which the microplasma is ignited. Power requirements to ignite and sustain the plasma at 1 atm are low, <30 W. We report on the laser excitation dynamics of argon metastables, Ar (4s, 1s5), generated in flowing mixtures of Ar and He from 20 Torr to 1 atm. Tunable diode laser absorption measurements indicate Ar(1s5) concentrations as high as 1e13 cm-3 at 1 atm. The metastables are optically pumped by absorption of a focused beam from a continuous-wave Ti:S laser, and spectrally selected fluorescence is observed with an InGaAs camera and an InGaAs array spectrometer. We observe the optical excitation of the 1s5 ? 2p9 transition at 811.5 nm and the corresponding laser-induced fluorescence on the 2p10 ? 1s5 transition at 912.3 nm; the 2p10 state is populated by collisional energy transfer from 2p9. We will discuss spatial distributions of the discharge-produced metastables, the spectroscopy of the plasma and laser-pumped emission, and determinations of optical gain.

8962-3, Session 1

Optical pumping of Ar metastables in a high pressure CW discharge

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CW operation of an optically pumped rare gas laser requires methods for sustaining relatively high concentrations of metastable excited atoms under high pressure conditions. Inductive and capacitively coupled discharges have been examined for Ar/He mixtures. Lasing of the Ar metastables has been demonstrated using pulsed optical excitation.

8962-4, Session 2

Experimental study of the diode pumped alkali laser (DPAL) *(Invited Paper)*

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A small-scale Cs DPAL apparatus has been developed for fundamental researches. A commercially available laser diode (LD) with volume Bragg grating (VBG) outcoupler is used to pump the gain cell longitudinally. Both windows of the gain cell is set at Brewster's angle so that the minimum loss and the maximum durability are achieved. Therefore, pump and laser beams has the same polarizations and they are separated by dichroic mirrors. Real-time observation of the power absorption enabled us the verification of our numerical model. Output coupling coefficient is continuously variable from 13% to 85% by the use of the slanted quartz plate oriented to the s-polarization. Pump beam diameter has been varied and output characteristics of the DPAL are observed. It is presumable that the thermal index distortion has significant effect on the output stability of our DPAL apparatus. A smaller pump beam diameter than that of the TEM00 mode of the resonator shows the minimum distortion effect. A 2.3 W cw output with optical to optical efficiency of 57% (based on the absorbed power) has been achieved.

8962-5, Session 2

Optical gain and multi-quantum excitation in optically pumped alkali atom: rare gas mixtures

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Diode-pumped alkali laser (DPAL) technology offers a means of achieving high-energy laser output through optical pumping of the D-lines of Cs, Rb, and K. The exciplex effect, based on weak attractive forces between alkali atoms and polarizable rare gas atoms (Ar, Kr, Xe), provides an alternative approach via broadband excitation of exciplex precursors (XPAL). We have developed an approach for measuring both spectrally and spatially resolved optical gain in these systems, based on tunable diode laser absorption/gain spectroscopy. In XPAL configurations, we have also observed multi-quantum excitation within the alkali manifolds which result in infrared emission lines between 1 and 4 um. The observed excited states include the 4-2F-J states of both Cs and Rb, which are well above the two-photon energy of the excitation laser in each case. We have observed fluorescence from multi-quantum states for excitation wavelengths throughout the exciplex absorption bands of Cs-Ar, Cs-Kr, and Cs-Xe. The intensity scaling is roughly first-order in both pump power and alkali concentration, suggesting a collisional energy pooling excitation mechanism. Observations of branching ratios of side fluorescence from Cs(7-2S-1/2) also indicate the possibility of stimulated emission for some conditions. Collisional up-pumping appears to present a parasitic loss term for optically pumped atomic systems at high intensities, however there may also be excitation of other lasing transitions at infrared wavelengths.

8962-6, Session 2

The role of adiabaticity in alkali atom fine structure mixing

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As an alkali atom in an excited electronic state collides with another atom or molecule, the nuclear dynamics of the collision will couple with the electronic degrees of freedom. This non-adiabatic dynamics will cause the alkali atom to undergo a non-radiative transition between the electronic states. In DPAL systems, this is the mechanism responsible for establishing a population inversion and is a rate-limiting step in the performance of these systems.

A review of the rates of transition between the spin orbit split states in alkali vapor induced by collisions with rare gases is developed, including the temperature dependent scaling. For the heavier alkali atoms the spin orbit splitting is larger and the rates are slow, consistent with previous adiabaticity arguments. The higher relative speed of the lighter rare gases shortens the collision duration and increases the rate. The rates dramatically increase for higher lying states and the lighter alkali atoms. By employing a semi-classical, time dependent perturbation calculation, a robust scaling law is developed. By including a centrifugal barrier, a modification based on polarizability allows for a strong correlation with more than 100 observed rates. Comparison with quantum mechanical scattering calculations for the lowest lying P states further supports the scaling law.

8962-7, Session 2

An experimental high pressure line-shape study of the rubidium D1 and D2 transition with helium

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An essential metric for modeling diode pumped alkali lasers is the determination of the pump rate to generate excited state rubidium atoms. The line-shape of the absorption cross-section for rubidium is a primary component to determine the overall pump rate as a function of the frequency of the pump diodes. Typical Diode Pumped Alkali Laser (DPAL) models utilize a simple Lorentzian when at pressures over an atmosphere, but at high pressures (up to 5000 Torr) the first resonance lines of rubidium have been observed to broaden asymmetrically by absorption spectroscopy employing a white light source and a 1.33m spectrometer. This asymmetry has been predicted using Anderson-Talman theory, which takes the Fourier Transform of theoretical potential energy surfaces. Using this skewed line-shape, a rate for the growth of the asymmetry has been measured for helium. Additionally, the corresponding broadening and shift rate have been determined and compared nicely with the previously measured low pressure results. The addition of the asymmetry parameter to the line-shape plays a critical role in the prediction of absorption of high pressure diode pumped alkali lasers. The absorption cross-section has been modeled using this asymmetry and has been extrapolated up to approximately 30 atm for comparison to a typical Lorentzian line-shape.

8962-8, Session 3

Semi-analytical and 3D CFD DPAL modeling: feasibility of supersonic operation *(Invited Paper)*

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Extensive studies of diode pumped alkali lasers (DPALs) have been carried out in the past few years [1,2]. Static and flowing-gas DPALs have been investigated. Modeling of these devices has been conducted as well [1,3-8] and fluid dynamics and kinetic processes have been taken into account, but for flowing-gas DPALs only subsonic velocity of the gas was considered. In this presentation we explore the feasibility of operating DPALs with supersonic expansion of the gaseous laser mixture, consisting of alkali atoms, He atoms and (frequently) hydrocarbon molecules. The motivation for this exploration stems from the possibility of fast and efficient cooling of the mixture by the supersonic expansion.

We have recently [9] reported on semi-analytical modeling for a supersonic Cs DPAL with parameters similar to those of the 1-kW flowing-gas subsonic Cs DPAL [4], the maximum power, Plase, for the former is larger than that for the latter by 25%. Optimization of He/CH4 buffer gas composition and flow parameters shows that for the resonator parameters of Ref. 4, extremely high power and optical-to-optical efficiency, 21 kW and 82%, is achievable in the supersonic device. For the supersonic K DPAL Plase, 43 kW, is 70% larger than for subsonic with the same resonator and K density at the inlet, the maximum optical-to-optical efficiency being 82%. A three-dimensional (3D) computational fluid dynamics (CFD) modeling of supersonic DPALs which is currently in progress will be reported in detail.

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8962-9, Session 3

Multi-dimensional modeling of classic DPAL

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The diode pumped alkali laser (DPAL) system has received considerable attention in the last decade as a viable high power gas laser system driven by high efficiency diode lasers. A number of modeling studies have been performed for DPAL [1-5]. In this paper, high-fidelity, time–dependent and steady-state (cw) simulations of a cylindrical closed cell DPAL system are presented using the new BLAZE-VI multiphysics simulation model [6]. BLAZE-VI is a highly scalable parallel finite–volume model that includes transport, thermal, kinetic, and optical effects appropriate for the simulation. The model equations and solution scheme are described in detail and a structured tessellation of the relevant physical domain is described as an appropriate grid for the required simulations. Simulations of two classic DPAL experiments are presented and compared to data.

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8962-10, Session 3

Simulation of deleterious processes in a static-cell diode pumped alkali laser

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The complex interactions in a diode pumped alkali laser (DPAL) gain cell provide opportunities for multiple deleterious processes to occur. A key point of investigation is to determine whether these processes are significant within alkali lasers. Research into ionization and other deleterious processes is being done at the Air Force Research Laboratory (AFRL) utilizing physically detailed simulation of a static-cell DPAL.

8962-11, Session 3

Kinetic and fluid dynamic processes in diode pumped alkali lasers: semi-analytical and 2D and 3D CFD modeling

Boris D. Barmashenko, Salman Rosenwaks, Karol Waichman, Ben-Gurion Univ. of the Negev (Israel)

Operation of diode pumped alkali lasers (DPALs) [1] is based on the D1(n 2P1/2 ? n 2S1/2) transition of alkali atoms (where n = 4, 5, 6 for K, Rb and Cs, respectively) pumped via the D2(n2S1/2 ? n2P3/2) transition and followed by rapid relaxation of the upper to the lower fine-structure level, n2P3/2 to n2P1/2. At high power (> 100 W) the heat release due to the relaxation between the fine-structure levels results in a considerable increase of the temperature T in the pumped region [2], causing a decrease of the pump absorption. Ionization of the excited levels result in reduction of the density nX of neutral atoms participating in lasing and hence decrease of pump absorption and gain. Both the temperature rise and the loss of atoms decrease the slope and the overall optical-to-optical efficiency.

To avoid the temperature rise and replenish the lost alkali atoms, flowing-gas DPALs are used [3]. We report on a semi-analytical [4-6] and three dimensional computational fluid dynamics (3D CFD) modeling of flowing-gas and static DPALs which take into account the influence of the aforementioned processes on the output power.

We first applied the model to Cs DPAL with static gas reported in [2]. Calculated values of Plase are in good agreement with the measured values. To further test the model, we applied it to the recently reported 1 kW flowing-gas Cs DPAL [3]. Results of 3D CFD modeling of this laser are in good agreement with the results predicted by the semi-analytical model.

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8962-12, Session 3

Mechanisms for plasma formation during high power pumping of XPAL

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During optical pumping of the Cs/Ar XPAL (Excimer-Pumped Atomic Laser) system, a large density of Cs(6p2P1/2,3/2) is produced which constitutes the upper laser levels. Similar resonance excitation of alkali vapor has been used to produce an efficient source of optically pumped plasmas in other systems. Seed electrons are generated by associative ionization of two excited states (or a high-lying state and a ground state) producing a dimer ion. Super-elastic relaxation of the atomic resonance states heat the seed electrons which then further ionize the atoms to form a plasma. Such processes in cesium vapor are well known and are likely an important consideration in XPAL.

In this paper, we report on global modeling of the Cs/Ar XPAL including the full range of electron and ion kinetics, and plasma formation. The model contains the conventional neutral mechanism for laser excitation of Cs/Ar, augmented by electron kinetics, including the solution of Boltzmann's equation for the electron energy distribution to produce self-consistent electron impact rate coefficients. The states in the model include Cs(6s, 6p2P1/2,3/2, 5d2D3/2,5/2, 7s2S3/2, 7p2P1/2,3/2) and a selection of lumped states for higher levels; Cs+, Cs2, Cs2*, Cs2+; Ar, Ar(1s4, 1s5, 1s3, 1s2, 4p, 3d, 5s, 5p, 4d, 6s), Ar+, Ar2+, and the ArCs excimers. Photoionization by the pump and laser is included. The knowledge base for Cs electron kinetics is being improved by performing ab-initio calculations of cross sections for electron impact on Cs atoms using the Breit-Pauli and Dirac B-spline R-matrix approaches. These cross sections when convolved with the electron energy distribution, provide rate coefficients for excitation, super-elastic collisions and electron collision mixing of excited states. Results from the model will be discussed for conditions that will likely produce plasma in XPAL operation, including scaling laws for laser operation.

Work was supported in part, by the National Science Foundation [PHY-1068140, PHY-1212450 (KB and OZ)] and the HEL Joint Technology Office (NB, MK).

8962-13, Session 4

Scalable pump source for diode pumped alkali lasers

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External cavity feedback can improve the output of diode pump lasers by providing tunable wavelength locking, spectral narrowing, and slow-axis mode reduction. Our prior work demonstrated the utility of a staircase-like array of mirrors to eliminate optical path length differences, allowing the several bars in a stack to become locked with an angled diffraction grating. In this paper we describe a series of new technical refinements that further increase the power, reduce the divergence, and narrow the spectral range of diode array pump lasers. The new architecture is configured with partially-reflective splitters that exchange power between an idler beam that is locked with the grating and several output beams oriented along a perpendicular direction. A single external cavity can lock the power of several tens of kilowatts. We describe the architecture of a 3kW prototype and report first results.

8962-14, Session 4

Narrow line diode laser stacks for DPAL pumping

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Diode pumped alkali metal vapor lasers (DPALs) offer the promise of scalability to very high average power levels while maintaining excellent beam quality, making them an attractive candidate for future defense applications. A variety of gain media are used and each requires a different pump wavelength: near 852 nm for cesium, 780 nm for rubidium, 766 nm for potassium, and 670 nm for lithium atoms. The biggest challenge in pumping these materials efficiently is the narrow gain media absorption band of approximately 0.01 nm.

Typical high power diode lasers achieve spectral widths around 3nm (FWHM) in the near infrared spectrum. With state of the art locking techniques, both internal to the cavity and externally mounted gratings, the spectral width can typically be reduced to 0.5 nm to 1 nm for high power stacks. More narrow spectral width has been achieved at lower power levels. The diode's inherent wavelength drift over operating temperature and output power is largely, but not completely, eliminated. However, standard locking techniques cannot achieve the required accuracy on the location of the spectral output or the spectral width for efficient DPAL pumping. Actively cooled diode laser stacks with continuous wave output power of up to 100W per 10mm bar at 780nm optimized for rubidium pumping will be presented. Custom designed external volume holographic gratings (VHGs) in conjunction with optimized chip material are used to narrow and stabilize the optical spectrum. Temperature tuning on a per-bar-level is used to overlap up to fifteen individual bar spectra into one narrow peak. At the same time, this tuning capability can be used to adjust the pump wavelength to match the absorption band of the active medium. A spectral width of <0.1 nm for the entire stack is achieved at >1KW optical output power. Tuning of the peak wavelength is demonstrated for up to 0.2 nm. The technology can easily be adapted to other diode laser wavelengths to pump different materials.

8962-15, Session 4

Oxygen atom density and thermal energy control in an electric-oxygen iodine laser

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Experiments with Electric Oxygen-Iodine Laser (ElectricOIL) heat exchanger technology have demonstrated improved control of oxygen atom density and thermal energy with minimal quenching of O2(a), increasing small signal gain from 0.26% cm-1 to 0.30 cm-1 [1]. Heat exchanger technological improvements were achieved through both experimental and modeling studies, including estimation of O2(a) surface quenching coefficients for select ElectricOIL materials downstream of a radio-frequency discharge-driven singlet oxygen generator (DSOG). Estimation of O2(a) quenching coefficients is differentiated from previous studies by inclusion of oxygen atoms, historically scrubbed using HgO [2-4] or AgO [5]. High-fidelity, time-dependent and steady-state simulations are presented using the new BLAZE-VI multiphysics simulation model [6] and compared to data.

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8962-16, Session 5

Active phase locking demonstration of low repetition rate, 100mJ class laser beams for medium size space debris removal application under cleanspace project

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Space debris removal of medium size debris thanks to ground-based high energy laser in safe and routine operations appears to be a promising and affordable system. Thanks to a European FP7 project called CLEANSPACE, a study of this concept is currently in progress.

The goal of this project is to define a global architecture for medium-sized debris removal around selected space assets.

The estimated laser specifications required for such a system are an Energy level >10KJ, a pulse length????t=10ns, repetition rate > 10Hz, M?<2.5 and a wavelength around 1.06µm. All these laser specifications put together lead to a very challenging laser system. In order to use relatively reasonable amplifying chain the CLEANSPACE project has investigated active phase locking of several pulsed laser beams coming from several amplifying chains of moderate energy.

The main goal of our study is to demonstrate efficient phase locking of up to nine amplified pulsed laser beams coming from a master oscillator. Due to too small pulse duration to achieve a classical active phase regulation on this signal, we propose to use a multiplexed CW wavelength shifted beam (1030nm) in order to be outside the gain bandwidth (1064nm). By analysing the interference pattern between a reference beam and all the disturbed beams, phase regulation is performed by using photodetectors, piezzo actuators and lock-in amplifiers. In a first step, we have recently demonstrated active phase locking of 3 amplified beams with a total energy of 250mJ, a repetition rate of 20Hz and a pulse duration of 15ns.

8962-17, Session 5

ELI-beamlines: extreme light infrastructure science and technology with ultra-intense lasers

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We will be giving an overview on the development of the "ELI-beamlines facility" [1] 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 [2]. 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 system will be delivering pulses with length ranging between 10 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 above 1022 Wcm2, 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. The design concepts and designs for different areas including building, lasers, beam distribution and secondary source beamlines for this new user's facility will be discussed. We will focus on experimental opportunities in plasma and high density physics that will be possible when combining both 10-Hz PW beamlines and the kilojoule beamline. The status and timelines of the project delivery will be presented.

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8962-18, Session 5

Focal zooming improvements to make fusion Ignition achievable

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Fusion has been achieved to some extent, however the energy output has not yet exceeded what input energy is needed to begin the process. A major issue hindering successful fusion is that, as the fuel target implodes the spot size of the laser beams must also decrease in unison with the target, this is called focal zooming. In order to make alterations to the zooming, new phase plates have to be manufactured and installed for each beam, which is not only expensive but time consuming. We will look further into alternative methods of Focal zooming, a pulse-shaping concept in which the focal properties of a laser pulse change with time, which improves the possibility of fusion energy as a power source. A small scale experiment will be built in which focal zooming of laser beam will be tested. We plan to modify beam spot size over various durations, using equipment and lasers at our school.

8962-19, Session PTue

Recent advances for temporal and spectral diagnostics of the LMJ front-end laser facility

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In lasers used for inertial confinement fusion (ICF) both temporal and spectral performances have to be controlled with accuracy. As commercial systems do not allow enough accurate measurements, we developed new diagnostics.

For spectral measurements, we developed an innovative highly resolving spectrometer. This system allows a 1GHz resolution measure of spectrum in single-shot operation.

For temporal shape measurement, we implemented upgrades and go on with the pre-industrial integration of our previous early design [1], in an all-in-one box system. This system enables real-time analysis of optical pulses shapes for wavelengths from 300nm up to 2?m. Thanks to an innovative optical-electro-optical (OEO) sub-converter, it is also possible to measure electrical pulses, with 60GHz bandwidth at 500Gs/s sampling rate and more than 8-bit dynamics range.

One of the most important specifications for ICF concerns the temporal Dynamic Extinction Ratio (DER) few tens of picoseconds before the pulse. LMJ need at least more than 50dB extinction. Commercial system permits no more than 20-30dB of direct measurement in single-shot experiment. We developed an all fibered system that allows direct measurement of temporal DER for pulsed laser in single shot operation. This device could be adapted to several wavelengths and allows achieving a measurement up to 60dB of DER with 1dB accuracy.

In brief, we will give an up-to-date description of some recent development in high precision diagnostics applied to LMJ front-end.

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8962-20, Session PTue

Near field angular filtering with volume Bragg gratings in photothermorefractive glass

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The coherent properties of laser beams make them very sensitive to spatial imperfections, such as dust, scratches, and impurities of the optical components, which will introduce spatial modulations and induce nonuniformity in the near field in the laser beams. Besides, the nonlinear effects in the laser systems also induce nonuniformities in laser beams. These modulations will grow in the laser systems, degrading the laser beam quality and resulting in damages in the laser medium and optical components, which is considered one of the main limitations in designing and building high-power laser systems, especially in inertial confinement fusion lasers that have higher intensities. Uniform near-field distribution is an important factor in building high-power laser systems, but diffraction of light by the imperfections disturbs the spatial homogeneity of the laser beams. To improve the near-field distribution in laser systems, the traditional spatial filter consisting of lenses and a pinhole located at the focus of the lenses is introduced to clean up the laser beam. This type of filter requires a vacuum chamber to eliminate breakdown at the focus and enough space or an aspherical lens in order to eliminate spherical aberration.

We propose and perform a near field angular filtering on the basis of volume Bragg gratings (VBGs) in a series connection for cleaning up a laser beam. The dependence between angular selectivity and VBG parameters is analyzed with the coupled wave theory. VBGs with the period of 0.9 micrometer and thickness of 2.5mm and 2.9mm recorded in PTR glass were used as the angular filtering element, and a collimated real laser beam with spatial modulation at the spatial frequency between 0.7 and 10mm-1 is used as the source beam to demonstrate the effects for angular filtering in two dimensions. The near-field modulation and contrast ratio of the filtered beam are found to be improved 3.2 and 44 times, which is important for high-power laser systems. In order to increase the bandwidth of the filtering, we also propose a broadband angular filtering by using volume Bragg grating and a surface grating pair in series connection, and the bandwidth of 60 nm is obtained.

8962-21, Session PTue

High contrast research in the Nd:glass laser system based on optical parametric amplification temporal cleaning device

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Owing to the development of chirped pulse amplification (CPA) technology [1] in the past two decades, laser power has reached petawatt level in Nd:glass system with the focus intensity beyond 1020W/

cm2 [2]. On this laser intensity condition, the temporal pulse contrast of higher than 1010 is required to prevent the possible target pre-ionization with the prepulses or the pedestal before the main pulse. Based on optical parametric amplification (OPA) pulse cleaning process, using the frequency doubled pulses to pump the fundamental frequency 1053nm signals from the common source, high contrast pulses exceeding 1010 is achieved by some researchers [3,4].

We report our recent progress on temporal pulse contrast research at 1053nm. Our high contrast demonstration is based on the Ti:sapphire-Nd:glass hybrid double CPA [5] scheme consisting of a Tisapphire CPA pump laser, a pulse temporal cleaning device and a small scale Nd:glass CPA laser. The first CPA stage is a 1kHz 3.2mJ/35fs commercial laser with ASE contrast ~108. The OPA pulse temporal cleaning device is used to generate 1053nm ~100uJ/46fs clean pulses with contrast higher than 1011 [6]. The pulses are injected in the next Nd:glass laser with a stretching energy of ~5uJ, and amplified further to 190mJ at 1Hz with a pulse energy gain of ~4?104. The compressed ~0.5ps pulse is about 154mJ with efficiency of ~81%. The ASE temporal contrast of amplified pulses measured by a third-order cross correlator is ~1011 before the main pulse ~170ps.

Therefore, a ~100mJ-level high contrast incident pulse will be enough for acquiring high contrast in a 1kJ/1ps PW level laser system with similar gain.

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8962-22, Session PTue

A single-filament schlieren method for flowing characteristic measurements in the pulsed gas lasers

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A fast pulsed discharge in gas laser usually gives rise to optical disturbance of gas medium in discharge region, which would affect the subsequent discharge quality at high pulse repetition frequency (PRF). Experimental investigations to acquire information of the flowing characteristics of a discharge-excited ArF laser were presented based on conventional schlieren method and single-filament schlieren method. The origin and development of shock waves and acoustic waves can be clearly visualized with the conventional schlieren method. The gas flow distribution in circulating system was obtained by fitting the movement of the centerline with time after digital image processing on schlieren images at different time delays. It was also found that some residual optical disturbance after the heated gas was removed from the discharge region. The simply-equipped single-filament schlieren method showed a higher sensitivity in measuring this weak disturbance. It gave a real-time measurement of the non-uniformity of gas medium in the discharge region. The measurement of flowing characteristics provided a detailed understanding of the operating state of the ArF excimer laser. Also these two methods can be successfully applied in other pulsed gas lasers.

8962-23, Session PTue

4kW coherent beam combination laser using self-controlled stimulated Brillouin scattering-phase conjugation mirrors for high-speed laser cutting

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The coherent beam combination laser using SBS-PCMs (Stimulated Brillouin Scattering-Phase Conjugation Mirrors) has various applications such as laser machining [1], laser peening [2], and large-area laser annealing [3]. In particular, the coherent beam combination laser can utilize a high speed 2D laser cutting by using a hologram. With the hologram, the laser cutting process can be done with any shape without scanning of the laser beam.

In this presentation, the authors will introduce 4kW coherent beam combination laser. The 4 kW laser output beam will be obtained from the 4 beam combination using SBS-PCMs, and it will be applied to laser machining of a micro SD RAM card by a hologram.

Figure 1 shows the schematic diagram of the 4kW (4 x 0.1J/10ns/10kHz) laser system. The front-end system produces a single frequency seed beam of 1064nm at a repetition rate 10 kHz. The average output power of the front-end system is 5W (5mJ/10ns/10kHz). The seed laser beam from the front-end system is amplified by a pre-amplifier from 5W (5mJ/10ns/10kHz) up to 200W (20mJ/10ns/10kHz). The pre-amplifier utilizes a Nd:YAG rod as its gain medium. After the amplification process, the laser beam is divided into 4 sub-beams by the coherent beam divider/combiner. The wave-front distortion of the each sub-beam is compensated by SBS-PCMs. After the reflection at the SBS-PCMs and after passing through the main amplifier module again, the sub-beams are combined by the coherent beam divider/combiner. Each sub-beam is amplified by the main amplifier module. As a result, the output power of each sub-beam is 1kW (0.1J/10ns/10kHz). The output power of the entire system is expected to be 4kW (4 x 0.1J/10ns/10kHz).

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8962-24, Session PTue

Layer formation of a target in laser ion acceleration

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Proton acceleration by using a 620-TW, 18-J laser pulse of peak intensity of 5x10^21 W/cm2 irradiating a disk target is examined using three-dimensional particle-in-cell simulations. It is shown that protons are accelerated efficiently to high energy for a "light" material in the target. In addition, using the best conditions for the target, one can generate a proton beam with an energy of 200 MeV.

Conference 8963: High-Power Laser Materials Processing: Lasers, Beam Delivery, Diagnostics, and Applications III

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8963-1, Session 1

Laser welding of XXL structures *(Keynote Presentation)*

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In the last 50 years laser material processing has successfully been established, especially in the area of thin materials. With the availability of more powerful laser sources it is now possible to process larger dimensions. The combination of a laser process with one or two GMA sub-processes to a hybrid welding process provides an application of brilliant laser radiation for conventional welding practices because of the increased gap bridgeability. Thus, material thicknesses up to 23 mm of steel grade X70 for pipeline applications are joined in flat position within a single process step over the whole thickness with a speed of about 1.5 m/min. For this purpose, a high-power disc laser source is used with a maximum output power of 16 kW. For plates of the aluminum alloy EN AW-6082-T6 with a thickness of 12 mm speeds of up to 6 m/min were used. By the use of an additional inductive preheating for welding of fine-grain structural steels with the grades S700MC, X70 and S690QL in a thickness range from 10 to 15 mm, it is possible to increase the welding speed and to obtain homogeneous mechanical properties near the welding seam. Other examined applications are the welding of large steel-aluminum foam sandwiches for shipbuilding and the high-rate deposition-welding process with a none-transferred arc which burns between two wire electrodes. For the latter, the laser is used to control the welding penetration in order to combine the high deposition rates of the arc process of up to 20 kg/h with a low heat input into the workpiece. In all the mentioned areas, with more applications being investigated, the laser offers the possibility to produce high quality joints at high speeds.

8963-2, Session 1

Dynamical behavior of laser-induced nanoparticles during remote processing

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Laser remote processing is used in a wide field of applications within industrial processing strategies. Among other things, it is characterized by flexible beam guidance in combination with high processing speeds. But in most cases assist-gas supply within the interaction zone is omitted. Thus it is difficult to influence the plume formation and all corresponding interaction mechanisms. As a result, a significant particle formation rate occurs. Hence due to the interaction between the incoming laser radiation and nanoparticles, the intensity fluctuates on the work piece surface.

Concerning to the formation of nanoparticles during the laser welding, the focus of previous experimental studies has been concentrated on the determination of the mean particle density and mean particle size within the vapor plume in relation to the welding time. In contrast to these studies and in order to get a more detailed understanding of the influence of nanoparticle formation on the laser remote welding, the presented work shows results of the analysis of the dynamical behavior of the particle density during the laser welding of stainless steel under remote conditions. Therefore, the beam of a 2 kW fiber laser is guided over the work piece surface. Three probe laser beams with various wavelengths are directed through the vapor plume and with the attenuated intensities the particle density is calculated. In addition, the relation between process instabilities and the temporal evolution of the particle density is investigated. The particle size distribution is determined by evaluating statistically images of nanoparticles using transmission electron microscopy.

8963-3, Session 1

Development of a double beam process for joining aluminum and steel

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Multi-material structures pose an attractive option for overcoming some of the central challenges in lightweight design. An exceptionally high potential for creating cost-effective lightweight solutions is attributed to the combination of steel and aluminum. However, these materials are also particularly difficult to join due to their tendency to form intermetallic compounds (IMCs). The growth of these compounds is facilitated by high temperatures and long process times. Due to their high brittleness, IMCs can severely weaken a joint. Thus, it is only possible to create durable steel-aluminum joints when the formation of IMCs can be limited to a non-critical level.

To meet this goal, a new joining method has been designed. The method is based on the combination of a continuous wave and a pulsed laser source. Laser beams from both sources are superimposed in a common process zone. This makes it possible to apply the advantages of laser brazing to mixed-metal joints without requiring the use of chemical fluxes. The double beam technology was first tested in bead-on-plate experiments using different filler wire materials. Based on the results of these tests, a process for joining steel and aluminum in a double-flanged configuration is now being developed. The double flanged seams are joined using zinc- or aluminum-based filler wires. Microsections of selected seams show that it is possible to achieve good base material wetting while limiting the growth of IMCs to acceptable measures. In addition, the results of tensile tests show that high joint strengths can be achieved.

8963-4, Session 1

Autogenous laser welding of Ti6Al4V in L-joint and T-joint configuration with Yb:YAG disk laser

Fabrizia Caiazzo, Univ. degli Studi di Salerno (Italy)

Mechanical assembly would be generally preferred in comparison with machining, because a reduction in waste material would be benefited, with consequent reduction of the buy-to-fly ratio, which is a measure of how much material is actually required to manufacture the final flying part.

The paper investigates the feasibility of the process of autogenous laser welding of Ti-6Al-4V alloy in L-joint and T-joint configuration using a Yb:YAG thin disk laser, as an alternative mean to machining.

A number of challenges must be addressed. First, a proper device for fixture must be developed in order to reduce the gaps; then, a system for bead protection must be employed as to prevent the oxidation of the weld pool.

The effect of power, welding speed, focus position and beam angle is discussed. In particular, the angle of buckling distortion is considered to evaluate the beads with respect to aerospace application. The mechanical strength of the joint is discussed with respect to phases as structures in the fused zone and in the heat affected zone.

8963-6, Session 1

Trends and basic investigations in high power laser materials processing *(Keynote Presentation)*

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Continuous application development in combination with advancements in laser sources and accessories enabled several trends in laser material processing. This paper will show investigations in process understandings based on modern process diagnostics like high speed videos. We will focus on applications related to thick sheet welding, welding with wobbling techniques, hot-forming materials and dissimilar materials. Additionally we link the gained process understandings to possibilities how to successfully introduce the knowledge in industrial applications.

8963-7, Session 2

Characteristics of the heat resistant FBG sensor under laser cladding condition

Akihiko Nishimura, Takaya Terada, Japan Atomic Energy Agency (Japan)

We have been developing heat resistant strain sensors by laser processing techniques. The application is aiming at the structural health monitoring for high temperature piping system. The situation requires extraordinary durability such as radiation resistance and noise isolation caused by nuclear reaction or electro-magnetic pulses. We proposed that the Fiber Bragg Grating (FBG) sensor made by femtosecond laser processing could be the best candidate. Combination with fabric reinforcement and heatproof adhesive mold successfully protected fragile optical fiber to install it on the surface of piping material [1].

To make the best use of the heat resistant characteristic, we fixed the FBG sensor by metal mold. A groove was processed to the surface of a SS400 plate with a grindstone. We used a Quasi-CW laser to weld a filler wire on the plate. An optical fiber was set under the filler wire beforehand. Then it was heated by the laser pluses with 10 joule energy and 10 ms duration, partially to be soaked in a weld pool. A series of weld pool formed a sealing clad on the groove. It was buried at 2 mm depth over the length of 1 cm. No degradation on the FBG reflection spectra was detected after the processing. The FBG sensor can detect the vibration of the plate caused by impact shocks. In this paper, Bragg peak shift of the FBG sensor under laser cladding condition will be discussed.

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8963-8, Session 2

Laser hardening of AISI 52100 bearing steel with a discrete fiber laser spot

Donato Sorgente, Ottavio Corizzo, Politecnico di Bari (Italy); Antonio Ancona, CNR-IFN UOS Bari (Italy); Leonardo Daniele Scintilla, Gianfranco Palumbo, Luigi Tricarico, Politecnico di Bari (Italy)

In this work hypereutectoid steel specimens (AISI 52100) were heat treated with a single discrete laser pulse with different power values, defocussing distances and interaction times. Optimal laser process parameters have been then achieved according to the desired hardness profiles. Experimental results highlighted that both the surface condition (in terms of roughness) and the initial temper (tempered and annealed) have great influence on the post-process hardness values and profiles.

8963-9, Session 2

Non-conventional laser surface hardening for baxisymmetric components

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The laser hardening of cylindrical surfaces, carried out exploiting the apparent-spot principles is reported in this paper. This process involves two phases: initially the component, subjected to the selective heating of the laser, rotates and reaches the austenitizing temperature in a ring of width dependent on the setting of the beam diameter, then the component or the source starts to translate and the whole area gradually achieve the same temperature. The possibility of avoiding the problem of tempering due to the overlap of the paths is the main advantage of this process related to a traditional laser hardening. In the present work this two processes have been compared and the hardness homogeneity reached with the apparent-spot method has been experimentally demonstrate. The difficulties connected to the achievement of this process regard the high number of variables involved, related to the source setting, the handling and the time of exposure. In order to verify the influence of each parameters on the resulting surface an accurate simulation campaign of the process has been developed. In order to determine the thermal properties of the steel subjected to the laser heat and validate the software, experimental tests have been carried out on real mechanical components and the reached temperature on the surface has been measured by a pyrometer. After the validation of the software, the simulations have guided the choice of the process parameters used on the experimental tests carried out to analyse the resulting microstructural properties.

8963-10, Session 3

Robust focusing optics for high-power laser welding

Blake McAllister, Edison Welding Institute (United States)

In the past few years, commercially available laser powers from both Fiber and Disk lasers has increased faster than at any other time in the history of industrial lasers. EWI has been fortunate to remain on the forefront of development for high-power laser welding capabilities.

As EWI's in-house laser capabilities increased, so did the need for robust beam delivery solutions. EWI, along with others in the high-power world, continue to encounter robustness issues with commercially available optics. As a result, nearly five years ago EWI developed its first high-power beam delivery solution for laser powers up to 10 kW. Since then, EWI has learned how to manage both process and optics related challenges that have allowed an even more robust beam delivery solution which has been tested up to 15 kW with exceptional performance.

EWI's new high-power reflective focusing optics (HPRFO) eliminates transmissive optics (fused silica, etc.) which has proven to be problematic as they are extremely sensitive to contamination in the presence of high laser power. This meant designing a fully-reflective solution using mirrors rather than lenses and windows to achieve the required, stable, focal

spot, while still protecting the delicate fiber end that delivers the high-power laser light. The patent-pending solution involves specialty mirrors and a flowing gas orifice that prevents ingress of contaminants into the optically sensitive region of the assembly. These mirrors also provide a unique solution for increasing the distance between the sensitive optics and the contamination-filled region at the work.

The HPRFO have demonstrated exceptional beam quality and minimal focal shift through the use of beam profiling tools. This solution has yielded remarkable results in a number of applications at EWI. One of which required deep-penetration welding using 13 kW and a weld time lasting nearly two minutes. A total of 132 feet of high-power, deep-penetration welding was performed without any degradation of quality. EWI believes that this optical solution will enable many high-power, laser welding applications to be developed without fear of an optical “weak link” in the overall system design.

8963-11, Session 3

Superior power handling in fiber optic cables for multi-kW lasers

Ola I. Blomster, Mats Blomqvist, Optoskand AB (Sweden)

Transmitting high power laser light through fiber optic cables has been used in industrial environments for years. With ever-increasing output powers from the laser sources and new applications where reflective materials are processed, the power handling of the fiber connector comes in focus. Designing fiber optic cables for industrial environments requires robust solutions that need to be small and should be able to handle high power losses without compromise either to process quality or to safety. Internal water cooling, where the optical fiber is in direct contact with water, in combination with an efficient cladding mode-stripper has got superior advantages handling high power losses.
To achieve robust properties and handling of high power losses it is necessary to use a design, which combines material with direct water cooling. In this paper we will present recent power-handling data for the new series of the well-known standards QBH and QD (LLK-D) fiber optic cables launched by Optoskand. The new series are designed with a combination of materials and internal water cooling, which gives a superior advantage when handling high power losses in the optical fiber connector.

8963-12, Session 3

Beamshaping for high-power lasers using freeform refractive optics

Roy McBride, Natalia Trela-McDonald, Matthew O. Currie, Duncan Walker, Howard J. Baker, PowerPhotonic, Ltd. (United Kingdom)

High power laser beamshapers based on lens arrays are widely used to generate square, rectangular or hexagonal flat-top far-field beam profiles. These devices can provide high efficiency and excellent brightness preservation, but offer a limited range of far-field profiles and can suffer from diffraction-related artefacts when used with spatially-coherent beams. Diffractive optical elements (DOE) offer a far wider range of far-field profiles, but bring performance trade-offs in terms of brightness, efficiency, scattered power and residual zeroth-order power.

Freeform refractive optics offer additional choices in the design of high power laser beamshapers. Freeform field mapping beamshapers can generate a range of application-specific beam profiles with high efficiency and, where required, minimal reduction in brightness, but with limited design freedom. More complex quasi-random freeform surfaces can act as fully-continuous phase screens, providing a level of design flexibility closer to that of DOEs, but without the related high-order scatter and zeroth order leakage.

We describe the design and implementation of these two types of freeform refractive beam shaper in fused silica, for use in high-power laser systems, where high damage threshold and low loss are essential. We compare and contrast the performance, benefits and limitations of both types of beamshaper, particularly with regard to efficiency, uniformity, brightness preservation and design flexibility, and outline which applications these design approaches are suited for.

8963-13, Session 3

Industrial performance analysis of the fast axis collimator lens

Martin Forrer, Hansruedi Moser, Dzelal Kura, Hans Forrer, FISBA OPTIK AG (Switzerland)

Micro optic components such as the fast axis collimator (FAC) are in widespread use in the high power diode laser industry. The requirement of high numerical aperture from diode laser and optical design and the pressure of cost to performance ratio have created convergence in the application to a planoacylinder high refractive index lens. The performance in power transmission and optical collimation of the FAC lens type are dependent on specific factors such as accuracy in form and refractive index, surface roughness and performance of the coating. We present a qualified method for measurement of the collimation efficiency and industrial analysis of the form error, of the surface roughness, of the AR coating as well as the result of a 1000h damp/heat test of the stability of the AR coating.

8963-14, Session 4

Monolithical aspherical beam expanding systems

Ulrike Fuchs, asphericon GmbH (Germany)

In complex laser systems, such as those for material processing, and in basically all laboratory applications passive optical components are indispensable. Matching beam diameters is a common task, where Galileo type telescopes are preferred for beam expansion. Nevertheless researches and customers have found various limitations when using these systems. Some of them are the complicated adjustment, very small diameter for the incoming beam (1/e?), fixed and non-modifiable magnifications. Above that, diffraction-limitation is only assured within the optical design and not for the real world set-up of the beam expanding system.

Therefore, we will discuss limitations of currently used beam expanding systems to some extent. We will then present a new monolithical solution which is based on the usage of only one aspherical component. It will be shown theoretically how the beam quality can be significantly improved by using aspherical lenses. As it is in the nature of things aspheres are working diffraction limited in the design, it will be shown how to combine up to five monolithical beam expanding systems and to keep the beam quality at diffraction limitation. Latest measurement data of the culminated wavefront error will be presented. Last but not least insights will be given how beam expanding systems based on aspheres will help to use larger incoming beams and to reduce the overall length of such a system.

8963-15, Session 4

Manufacturing process to improve roughness on aspheric surfaces

Sven R Kionkte, asphericon GmbH (Germany)

For a lot of applications like spectrometer and high power laser roughness as an important parameter has been discussed again and again. Especially for high power systems the surface quality is crucial for

determining the damage threshold and therefore the field of application. Every application has different needs with respect to the roughness, most of them have additional needs with respect to surface defects and waviness too.

For high power laser it is important to reduce absorption and scatter light. Because absorption increases the temperature of the elements which results in movement of optical focus (thermal lensing) or even worse the damage of the lens. In this paper roughness shall be in focus, especially because the specific roughness for aspherical elements is very different from spherical/plano surfaces.

Above that, it has often been difficult to compare roughness measurements because of different measurement methods and the usage of filters and surface fits. Measurement results differ significantly depending on filters and especially on the measured surface size.

Insights will be given how values behave depending on the quality of surface and the size of measured area. Most of these applications also require low roughness on aspheric surfaces. Because of small tool sizes in aspherics it has not yet been possible to achieve the same low level as for spheres and plano optics.

In addition, also results of a new manufacturing process will be shown allowing low roughness on aspheric even with remarkable departure from the best fit sphere.

8963-16, Session 4

New metric for the measurement of the quality of complex beams

Vadim Smirnov, OptiGrate Corp. (United States); Leonid B. Glebov, Christopher Lantigua, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); Julien Lumeau, Aix-Marseille Univ. (France) and Institut Fresnel (France) and CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

Measuring the quality of beams is a key problem in any laser-based system. While commonly accepted and used, the M2-metric presents numerous limitations that makes it quite often unreliable. We propose a new metric of beam quality, which is power in the slit, that we coin S2. This new metric offers useful advantages over the standard ISO M2 method for the measurement of beam quality regarding complex beams. The proposed S2 metric, like the M2 metric, is a ratio that relates the beam in question to that of a diffraction-limited Gaussian beam at the same wavelength. Unlike the M2 metric, which defines the width of a beam according to the second moment of the beam intensity distribution (D4?), the S2 method defines the width of a beam according to a power fraction of the beam (similarly to power in the bucket, but takes into account beam divergence). Thus, this new metric is less sensitive to small wings in the tails of the beam profile, which have a significant impact on the calculation of the second moment, and likewise on the resulting M2 value. We show that this new S2 metric is in good agreement with the standard M2 method for Gaussian beams, but offers an insightful perspective for complex beams, that have otherwise been deemed “poor quality” by the M2 method. Furthermore, we show that a complete understanding of the performance of a beam is possible with both the M2 and S2 metric, and that commercial systems for measuring M2 can be used for measurements of S2 too.

8963-41, Session 4

Intra-fiber mode combining schemes, demonstrating high power brightness preservation and coherent-coupling brightness enhancement

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We demonstrate intra-fiber couplers’ performance that approaches brightness preservation up to 3kW, and furthermore, showed few-Watts brightness enhancement when mutually coherent sources were used. In both cases a similar combining device is used: an adiabatic, fiber-only, mode coupling element that preserves the lowest spatial mode orders. By extracting the injected modes to the cladding and then compressing them to a tight cross section, brightness levels that approach the theoretical limits have been reached. Incoherent combination is shown for two three and seven combined elements. In addition, we show a solution for preserving the beam propagation factor of the coupler by using a specialty engineered core delivery fiber. Contrary to large step multimode core fibers, showing an output M? factor of ~100, the reported delivery fiber showed brightness improvement by two order of magnitude. It was also designed to support several kW signals. The device is fully fiber-integrated, i.e. it is free-space limitations proof. An overall optical transmission typically >95% was obtained. We estimate the fraction attributed to the coupler-delivery junction to be less than 0.5%. Consequently, low thermal load was measured at the combiner’s vicinity. In another operating regime, utilizing two mutually coherent sources, nearly a quadratic brightness factor was evident. Although no polarization preserving type fibers were used, it could achieve rugged ‘in-phase’ and polarized-matched mode-locking, allowing for a significantly simplified scheme compared to common coherent combining methods. Prospect on future trends related to nonlinearities and thermal load debugging are discussed.

8963-5, Session PTue

Laser-assisted friction stir welding of aluminum alloy lap joints: microstructural and microhardness characterizations

Sabina Luisa Campanelli, Giuseppe Casalino, Nicola Contuzzi, Andrea Angelastro, Antonio D. Ludovico, Politecnico di Bari (Italy)

FSW is a rapidly maturing solid state joining process that offers significant benefits over conventional joining processes. Extensive research has been carried out to improve this process. Researchers have explored different aspects of this process, namely tool design, weld microstructure, mechanical properties of the weld and many more.

This paper focuses on a new modification of Friction Stir Welding, the Laser Assisted Friction Stir Welding, which is a process that received the first attention in 2002. LAFSW is a combination of FSW and laser welding, with FSW being the dominant process and laser welding playing a supporting role with the aim of pre-heat the parts.

The presence of the laser beam introduces additional local heating, immediately ahead of the weld zone so that less mechanical energy, delivered through the tool, must be converted into heat.

An Ytterbium fiber laser with maximum power of 4kW and a commercial FSW machine were coupled. Both FSW and LAFSW tests were conducted on 3 mm thick 5754 aluminum alloy plates, in lap joint configuration, with constant tool rotation rate and with different feed rates in order to compare the two processes and to evaluate changes in the microstructure and in the microhardness of the welds due to the laser pre-heating.

8963-37, Session PTue

Analysis and design of supersonic deposition via a RE-doped fiber laser

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In this work, basic parameters such as intensity, BPP, spot size, average power and pulse energy are employed for designing an axicon lens-based RE-doped laser for supersonic deposition applications on metals. Furthermore, absorption and reflection of laser energy on metallic and plastic surfaces such as iron, steel, copper, acrylic, PVC, PET, widely used in various fields such as Metallization of non-metallic surfaces, Titanium coatings for aerospace and biomedical components and hard-facing for the tool manufacturing industry, will be analyzed using CO2, semiconductor and Ytterbium doped fiber laser analytic design data, for comparison. Full optical characterization and design of the proposed lasers will be included in the presentation.

8963-38, Session PTue

Detection of nanoscale defects in optical films by photothermal reflectance microscopy

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In high power laser applications, nanometer-sized defects (crack, scratch, impurity, contaminant, etc.) in optical materials can lower the laser-induced damage threshold (LIDT), leading to the materials breakdown. In this presentation, we demonstrate a novel technique for detecting nanoscale defects inside optical materials. This technique employs CCD-based photothermal reflectance microscopy (PTRM), which measures temperature-dependent optical reflectivity changes of the probe beam at the defect site due to pump-laser-absorption-induced heating of absorbing defects. For photothermal reflectance imaging of defects, an 808 nm laser beam with sinusoidal modulation is used to irradiate a transparent optical material. The thermo-optic response resulting from the laser beam absorption of defects in the material yields a periodic alteration in the reflectivity around defect sites. Such a time-varying thermoreflectance signal is probed with a 636 nm probe beam, and the amplitude of this signal is detected using a homodyne lock-in detection scheme, permitting enhancement of the defect contrast. The performance of the proposed system is studied on an optical material having absorbing inclusions (polystyrene beads and gold nanoparticles), showing that the photothermal reflectance image clearly reveals the local distribution of the nanometer-sized defects buried in the material.

8963-39, Session PTue

In-line process control for laser welding of titan by high dynamic range ratio pyrometry and plasma spectroscopy

Benjamin Lempe, Tobias Baselt, Christopher Taudt, Peter Hartmann, Westsächsische Hochschule Zwickau (Germany)

The production of complex titanium components for various industries using laser welding process has received growing attention in recent years. It is important to know whether the result of the cohesive joint meets the quality requirements of standardization and ultimately the customer requirements. Erroneous weld seams can have fatal consequences especially in the field of car manufacturing and medicine technology. To meet these requirements, a real-time process control system has been developed which determines the welding quality through a locally resolved temperature profile. By analyzing the resulting weld plasma the received data is used to verify the stability of the laser welding process. The determination of the temperature profile takes place by the detection of the emitted electromagnetic radiation from the material in the range of 500 nm to 1100 nm. As detectors, special high dynamic range CMOS cameras are used. Measuring the temperature is a problem because the emissivity of titanium depends on the wavelength, the surface and the angle of radiation. The special pyrometer setting using two cameras allows the compensation of these effects by calculating the difference between the respective pixels of simultaneously recorded images. Two spectral regions with the same emissivity are detected. Therefore the degree of emission and surface effects are compensated and canceled out of calculation. Using the spatially resolved temperature distribution the weld geometry can be determined and the laser process can be controlled. The active readjustment of parameters such as laser power, feed rate and inert gas injection increases the quality of the welding process and defective goods.

8963-40, Session PTue

New method of measurement laser beam on focal plane

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With the development of laser technology, higher requirement is presented on measurement technology of laser beam. The measurement technology of laser beam develops from the original Knife-edge method, Slit scanning method into the latter Shack-Hartmann method. The test index of laser beam also develops from originally testing power, wavelength into putting much value on the testing of wavefront, and characteristic value of a laser beam. In this paper, we go deep into study the method of measurement of laser beam and present a laser beam measurement method which is takes photos on focal plane to calculate the wavefront and the laser characterization. The difference between Shack-Hartmann method and this method is analyzed. And measurement performance is assessed by comparing wavefront and laser beam characterization, such as beam waist, beam divergence angle, the position of beam waist, in two methods. The results of experiment show that, this method is simple apparatus, and high precision, and it will be a development tendency on the laser beam measurement field, in the future.

8963-17, Session 5

Lasers for welding and their potential in production at GE *(Keynote Presentation)*

Marshall G. Jones, GE Global Research (United States)

Laser technology has been used in manufacturing in industry since the late 1960s. Industry and GE businesses have leverage laser welding for productivity gains, cost savings, and quality. The presentation will high-lights several laser-based welding applications, old and new. Applications will include the welding of refractory materials (e.g. Mo and Nb) for lighting products; 40 foot long fuel rods are welded with 2 kW fiber lasers for the nuclear business; head-liner welding for the diesel engine for locomotives (14 kW fiber laser replaced CO2 laser); and X-ray components are welded in a two-station 11kW fiber laser (EB welding replaced by laser). The three fiber laser applications were all transitioned into GE businesses during 2011 and it demonstrates the emergence of fiber laser welding being used in GE for manufacturing.

8963-18, Session 5

Laser beam drilling of metal-based composites

Harald Riegel, Markus Merkel, Hochschule Aalen (Germany); Andreas Oechsner, Univ. Teknologi Malaysia (Malaysia)

Laser drilling is a highly efficient technique to generate holes in almost any material. The relatively small amount of heat being involved during the process results in a small heat affected zone. This characteristic makes laser processing interesting for composite materials.

The drilling process has to be adapted to the special characteristics of the composite material. In this paper all investigations were performed at metallic hollow sphere structures, a relatively new group of advanced composite material. The experimental work was done by a CO2-laser. The used pulse duration is in the millisecond time regime with a mean power in the range of 100 to 400 mW. The percussion drilling has been used as drilling technique. Diameters of drilled holes have been evaluated as a function of the beam propagation. An image processing measuring technique has been developed to determine circularity and mean diameter as a function of the depth. The hollow sphere structures get melted and shrunk to bulk. The progression of the diameter as a function of the hole-depth is described by lines of constant intensity, the isophotes.

Numerical simulation was used to predict heat flux and temperature levels for different geometric parameters of the spheres (diameter, wall thickness) in order to optimize the drilling process. The numerical simulation allows a detailed analysis of the physical process in the zone that is influenced by the laser beam, which can hardly be analyzed by any measuring technique. The models for the static and transient finite element analysis consider heat conduction, radiation and convection.

8963-19, Session 5

CO2 laser heating for high reliability fiber component fabrication

Douglas M. Duke, Wenxin Zheng, Michael Harju, AFL (United States)

In recent years, increasingly higher optical power levels are used in a variety of bio-medical, fiber laser, and sensor applications. The higher power levels present significant challenges in terms of power management and the avoidance of power leakage with resultant localized heating. Robustness and reliability of high power assemblies is therefore a greater concern.

The use of a CO2 laser as a heat source has only recently become commercially available for optical fiber splicing and component fabrication. It offers unique benefits for fabrication of high-power optical components and assemblies, and also for splice strength.

CO2 laser heating is different from other heating methods in that the power from the CO2 laser beam is 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 a very well controlled process, with minimal vaporization and re-deposition of the glass itself.

Heating by a CO2 laser results in a contamination-free glass surface, with little surface damage or irregularity. Since the glass surface is very smooth and contamination-free, high power may be utilized in the component without localized surface hot spots, power leakage, loss of efficiency, and significant heat management problems. These same surface properties result in very high physical strength since crack sites are minimized. Splice strength results are therefore particularly impressive as shown in Figure 1.

8963-20, Session 5

Laser-dispersing of forging tools using AlN-ceramics

Christian Noelke, Laser Zentrum Hannover e.V. (Germany); Michael Luecke, Institut für Integrierte Produktion Hannover Gemeinnützige GmbH (Germany); Stefan Kaierle, Volker Wesling, Laser Zentrum Hannover e.V. (Germany); Ludger Overmeyer, Laser Zentrum Hannover e. V. (Germany)

Hot massive forging of aluminum work pieces is of particular interest due to the increased number of lightweight applications within the automotive and aircraft industry. Accompanied with the positive effects using aluminum parts, the specific attribute of aluminum to form cold welded spots during the forging process leads to limited process stability and parts quality. Forging tools damaged by adhesive wear need a replacement or if possible a refurbishment of the engraver. The achievement of extended live cycles and the prognosis of the remaining time until the next due date for a maintenance or tool change, offers a big potential to minimize break down times and additional expenses. Within this work laser-dispersed wear protection layers were applied on tool segments made of 1.2714 using ceramic AlN-powder particles. The applicability of these layers for the hot massive forging process and especially the potential of minimizing adhesive forces between tool surface and aluminum work piece has been evaluated. Comprehensive forging trials using work pieces made of EN AW-6082 T6 were done with varying parameter sets, regarding die temperature, work piece temperature and lubricant concentration. It could be shown that the laser-dispersed surfaces have less cold welding, beyond that the investigations have shown that there is a correlation between the intensity of cold welding/adhesive wear and the surface hardness of the corresponding tool segment.

8963-21, Session 6

High power beam analysis

Oren Aharon, Judith Aharon, Duma Optronics Ltd. (Israel)

Advances in manufacturing technology and the trends for faster and more accurate procedures opened the door for new metal welding and cutting applications based on high power lasers.

The demand for greater precision and high-performance applications dictates a need for better measuring tools. Compound measurements of power, beam profile and M square values on production floor will increase the use of these lasers as a higher quality more effective technology.

A laser propagating through space has a different width and spatial intensity distribution along its propagation path. This is continuously changing as a function of its laser divergence, interaction with optical elements and electronics driver characteristics. It is crucial for system designers, and laser manufacturers and end users to be able to accurately measure laser beam spatial propagation. There are two parameters that describe beams propagation at focal area one is one is M square value and the second is beam divergence and beam size product.

New technologies in the beam sampling area are emerging. Those technologies will allow direct measurement of high power laser beam in the focal point. We will discuss and analyze the thermal and optical implementation of high power measurement including fast real time measurement of caustic beam, beam profiles, position, and Z axis accuracy. It will allow direct measurement at the production floor, significantly increasing quality assurance. In this article we will analyze the implementation and impact of this technology on laser beam processing.

8963-22, Session 6

Cognition for robot scanner based remote welding

Ulrich Thombansen, Fraunhofer-Institut für Lasertechnik (Germany)

The strive for reduced cycle times in manufacturing has led to remote welding systems which use a combination of scanners for beam delivery and robots for scanner positioning. Herein, close coupling of both motions to a joint beam delivery requires good command of both motions. Especially the path precision of the robot plays a vital role in this set up.

A sensor system is being presented which allows tracking the motion of the laser beam against the work piece. It is based on a camera system which is coaxially connected to the scanner thus observing the relative motion. The acquired images are processed with computer vision algorithms from the field of motion detection. The suitability of the algorithms is being demonstrated with a motion tracking tool which visualizes the homogeneity of the tracking result.

The reported solution adds cognitive capabilities to manufacturing systems for robot scanner based materials processing to assist in optimizing the manufacturing process. It allows evaluation of the relative motion between work piece and the laser beam which can be used to adapt robot programming during set up or evaluate and correct the functionality of systems in production.

8963-23, Session 6

Tracking the course of the manufacturing process in selective laser melting

Ulrich Thombansen, Fraunhofer-Institut für Lasertechnik (Germany); Alexander Gatej, RWTH Aachen (Germany); Milton Pereira, Fraunhofer-Institut für Lasertechnik (Germany)

A manufacturing system for selective laser melting (SLM) has been designed under the objective to enable monitoring the SLM process. In this, the thermal emission from the melt pool and the geometric properties of the interaction zone are addressed by applying a pyrometer and a camera system respectively. The optical system is designed such that all three radiations from processing laser, thermal emission and camera image are coupled coaxially and that they propagate on the same optical axis. As standard f-theta lenses inevitably lead to increased aberrations and divergent optical axes for increased deflection angles, a fast z-shifter was used to implement a focusing unit which shapes the beam prior to passing the scanner.

The sensor system records synchronously the current position of the laser beam, the current emission from the melt pool and an image of the interaction zone. Acquired data of the thermal emission is being visualised automatically after processing which allows an instant evaluation of the course of the process on a per layer basis.

8963-24, Session 6

Simultaneous laser and seam tracking with texture based image processing for laser materials processing

Peter Abels, Alexander J. Drenker, Wolfgang Fiedler, Sebastian Kraemer, Fraunhofer-Institut für Lasertechnik (Germany)

This presentation deals with a seam tracking system for laser materials processing. The seam tracker is camera based. The digital high speed camera records interaction point and illuminated work piece surface. The camera system is coaxially integrated into the laser beam path. The aim is to observe interaction point and welding gap in one image for a closed loop control of the welding process. Especially for the welding gap observation new image processing method is used. Basic idea is to detect the work pieces and not the small nearly invisible gab. The texture based analysis of the work piece surface shows in compare to grey scale image processing more robustness and higher efficiency. This technique of image processing gives in some cases the opportunity for real cero gap seam tracking. In a condensed view economic benefits are simultaneous laser and seam tracking for self-calibrating laser welding applications without special seam pre preparation for tracking.

8963-25, Session 6

Fully automatic 3D laser processing

Logan G. Wright, Cornell Univ. (United States); Paul J. Webster, Cole Van Vlack, Laser Depth Dynamics, Inc. (Canada); Alison W. Kinross, Yang Ji, Christopher M. Galbraith, Queen's Univ. (Canada); Kevin D. Mortimer, Queen's Univ. (Canada) and McMaster Univ. (Canada); James M. Fraser, Queen's Univ. (Canada)

Hinged on their ability to deliver high energy density, lasers are poised to revolutionize manufacturing. However, precision in laser manufacturing is generally limited to two dimensions. Applications where 3D control is possible (e.g. nonlinear ablation using amplified ultrafast lasers) impose additional constraints, cost, complexity, expertise, and require extensive process development and manufacturing time. Laser processing depth control which relies on a priori assumptions about a material's response cannot precisely and reliably overcome a myriad of relatively mundane challenges encountered in heterogeneous materials or with complex plasma or fluid dynamics. Even in well-characterized materials, the approach breaks down if power-delivery is compromised or the nearby environment is altered, chemically or geometrically (e.g., high-aspect ratio cuts or material relaxation).

Inline coherent imaging (ICI) is a low-coherence interferometry technique which provides high dynamic range (> 60 dB), high speed, direct micron-resolution images of laser processing in situ. ICI's intrinsic spectral and temporal filtering makes it insensitive to process noise such as scattering of the processing laser, plasma and blackbody radiation. Imaging relies on static, CCD-based spectral-domain detection and suplerluminescent diode light sources. Its flexible, fiber-optic-based coaxial deployment ensures compatibility with any laser processing application.

We demonstrate the technique's versatility by fully-automatic, micron-scale 3D laser milling of uncharacterized, heterogeneous biological materials using ps pulses. Using nearly the same imaging system, we then achieve high-speed (>200 kHz), precise depth tracking of CW, kW laser welding. ICI is a prime candidate for fully-automatic, 3D laser processing in surgery and in current and emerging laser manufacturing applications.

8963-26, Session 6

Online NIR diagnostic of laser welding processes and its potential for quality assuring sensor systems

Friedhelm Dorsch, Holger Braun, Steffen Kessler, Dieter Pfitzner, TRUMPF Werkzeugmaschinen GmbH + Co. KG (Germany); Volker Rominger, TRUMPF Laser- und Systemtechnik GmbH (Germany)

On-axis observation of the laser welding zone by an NIR (near-infrared) camera allows characterizing the welding process and its result. It detects the thermal radiation and does not require any auxiliary illumination. Keyhole, weld pool and heat affected zone are imaged, the images are visualized and can be evaluated by real-time image processing regarding characteristic features and weld faults, like spatter, penetration depth and missing fusion.

The NIR camera (sensitivity 1200 to 1700 nm) is adapted to commercial TRUMPF welding heads for easy integration into industrial laser systems. The images are visualized and evaluated in respect to various features and aspects by a dedicated image processing system. The evaluation of different features can be combined to achieve a more robust detection of weld abnormalities.

Many examples of laser welding of ferrous materials under various processing regimes will be shown and the respective effects of the process parameters on the NIR-images are evaluated.

An NIR camera based sensor system can aid the user to setup his process in a controlled and repeatable way, it monitors and records the production process of every individual part, documents its characteristic features for full process data traceability, and will eventually serve as a key component in a closed-loop controlled laser welding system.

8963-27, Session 7

Cutting and drilling of carbon fiber reinforced plastics (CFRP) by 70W short pulse nanosecond laser

Peter Jaeschke, Laser Zentrum Hannover e.V. (Germany); Klaus Stolberg, JENOPTIK Optical Systems GmbH (Germany); Stefan Bastick, Laser Zentrum Hannover e.V. (Germany); Ewa Ziolkowski, Markus Roehner, JENOPTIK Laser GmbH (Germany)

Continuous carbon fibre reinforced plastics (CFRP) are recognized as having a significant lightweight construction potential for a wide variety of industrial applications. However, a today‘s barrier for a comprehensive dissemination of CFRP structures is the lack of economic, quick and reliable manufacture processes, e.g. the cutting and drilling steps. In this paper, the capability of using pulsed disk lasers in CFRP machining is discussed.

In CFRP processing with NIR lasers, carbon fibers show excellent optical absorption and heat dissipation, contrary to the plastics matrix. Therefore heat dissipation away from the laser focus is relatively fast and matrix is only heated indirectly by heat transfer from the carbon fibers. To cut CFRP it is required to reach the melting temperature for thermoplastic matrix materials or the disintegration temperature for thermoset systems as well as the sublimation temperature of the reinforcing fibers simultaneously. One solution for this problem is to use short pulse nanosecond lasers.

We have investigated CFRP cutting and drilling with such a laser (max. 7mJ @ 10 kHz, 30 ns). This laser offers the opportunity of wide range parameter tuning for systematic process optimization. By applying drilling and cutting operations based on galvanometer scanning techniques in single- and multi-cycle mode, excellent surface and edge characteristics in terms of delamination-free and intact fiber-matrix adhesion were achieved. The results indicate that nanosecond disk laser machining could consequently be a suitable tool for the automotive and aircraft industry for trimming and drilling steps.

8963-28, Session 7

Remote laser cutting of CFRP: Influence of the edge quality on fatigue strength

Johannes W. Stock, Michael F. Zaeh, Justinian P Spaeth, Technische Univ. München (Germany)

The additional weight of the batteries in electric cars can be compensated by using car-bon reinforced plastics (CFRP) for structural parts of the passenger cell. Various suitable machining processes for CFRP are currently subject of investigations.

Milling and abrasive waterjet cutting implicate fibre pull out or delamination and do not fully meet the requirements of mass production. However, laser beam cutting has a great potential in large scale cutting of CFRP and is a predominant research issue. Especially remote laser beam cutting provides a good cut surface quality. By now the correlation between cutting parameters and edge quality is sufficiently known. In particular, studies on the dynamic strength of remote laser cut parts are necessary: Therefore, fatigue testing was performed with specimens cut by laser radiation and compared with others made by milling and abrasive waterjet cutting. With these experiments a comparable study on the different methods of CFRP cutting is achieved. The influence both of the heat affected zone (HAZ) and of defects like micro-fissures on the fatigue strength were evaluated.

This study shows that remote laser cutting is suitable for dynamically stressed structural CFRP parts. The influences of the HAZ and micro-fissures on the fatigue strength were detected. Furthermore the laser is a wear free tool and offers great flexibility. Further work needs to be done on the implementation of this process for complex contours.

8963-29, Session 7

Modelling and simulation of a laser fusion cutting process

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An important part for laser cutting process optimisation is the use of simulation methods for visualizing and analysing local effects. Measurement techniques are often not sufficient to get space- and time-resolved information about the involved flow fields. A commercial CFD software package is used for simulating the complex laser fusion cutting process in order to obtain details of the cutting kerf depending on the laser beam characteristics. The model definition accounts for these characteristics as well as for temperature-dependent material behaviour (including phase changes) and for influences of the supersonic assist gas flow on the workpiece. Special attention is paid to modelling the solid phase of the workpiece using a fluid domain with internal momentum sources. The main challenges are the numerical stability of the simulation for automatic case studies, the optimization of the computational speed, and the validation of the simulation results with the aim of using numerical simulation as a tool for process optimisation. This paper includes an overview of the required modelling parts, some first simulation results, and an outlook for the next steps.

8963-30, Session 7

Highest performance in 3D metal cutting at smallest footprint: benchmark of a robot based system vs. parameters of gantry systems

Torsten Scheller, André Bastick, Robert Michel-Triller, JENOPTIK Automatisierungstechnik GmbH (Germany); Christon Manzella, Jenoptik Laser Technology Corp. (United States)

In the automotive industry as well as in other industries ecological aspects regarding energy savings are driving new technologies and materials, e.g. lightweight materials as aluminium or press hardened steels. Processing such parts especially complex 3D shaped parts laser manufacturing has become the key process offering highest efficiency. The most established systems for 3D-cutting applications are based on gantry systems. The disadvantage of those systems is their huge footprint to realize the required stability and work envelope. Alternatively a robot based system might be of advantage if accuracy, speed and

overall performance would be capable processing automotive parts.

With the BIM "beam in motion" system, JENOPTIK Automatisierungstechnik GmbH has developed a modular robot based laser processing machine, which meets all OEM specs processing press hardened steel parts. A benchmark of the BIM vs. a gantry system was done regarding all required parameters to fulfil OEM specifications for press hardened steel parts. As a result a highly productive, accurate and efficient system can be described based on one or multiple robot modules working simultaneously together.

The paper presents the improvements on the robot machine concept BIM addressed in 2012 leading to an industrial proven system approach for the automotive industry. It further compares the performance and the parameters for 3D cutting applications of the BIM system vs. a gantry system by samples of applied parts. Finally an overview of suitable applications for processing complex 3D parts with high productivity at small footprint is given.

8963-31, Session 8

High power single-mode fiber laser and its application to metal and non-metal materials

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The power level of Yb doped fiber lasers which operate in continuous wave mode have been increasing in recent years and various kinds of applications using high power single-mode fiber lasers that oscillate in 1microns wavelength range were reported.

Single-mode fiber laser that has excellent beam quality of less than 1.1 M2 value with kW class average power can be focused to tens of microns diameters and its optical power density at the focus point is more than 1x10^8 W/cm2.

In this power density range, the interaction between 1microns laser light and matter, not only metal materials but non-metal materials, is completely different from lower level.

The power density initiates laser processing of copper that relatively high reflectivity at this wavelength range among metals and alumina base plate with over 90% reflectivity. Other interesting material which can be processed by this energy level is carbon fiber reinforced plastics (CFRP).

On the other hand, for industrial application and further processing investigation, modulation speed is one of the most important factors because that relates to processing speed and precise control of laser energy input to a material.

In this paper, we report on the power dependence of some material processing of copper wafer welding, alumina base plate scribing, and CFRP cutting using single-mode fiber laser which is capable of over 1kW peak power operation and has rapid switching time below 50 micro seconds.

8963-32, Session 8

Experimental investigation on fiber laser cutting of aluminium thin sheets

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The most extensively used lasers for these applications are CO2 and Nd:YAG operating in continuous wave and pulsed mode. High power solid state fiber and disk lasers operating in continuous wave mode offer a great potential in improving the cut quality and productivity of highly reflective materials cutting process due to the better absorptivity of 1 ?m laser radiation. The very high processing speeds of CW mode and a good cut quality could be achieved at the same time. In this work, cutting experiments were performed on Al1050 1mm thick sheets using a fiber laser and Nitrogen as assist gas. A DOE approach that consist of fitting the regression models by means of response surface method (RSM) was adopted in order to identify the interactions and the best combination of input parameters that maximize the cut quality. The effects of cutting speed, focal position and assist gas pressure on dross height and roughness parameters were investigated. Results showed that fiber lasers allow obtaining very high processing speeds and a good cut quality and therefore are considered a reliable alternatives to CO2 and Nd:YAG lasers for aluminium cutting.

8963-33, Session 8

Aberration beam shaping in laser cutting with large aspect ratios

Vladimir Yurevich, Sergey G. Gorny, Igor V. Polyakov, Andrey Afonyushkin, Laser Center (Russian Federation)

Laser beam intensity distribution (LBID) on the processed surface is one of the key factors that determines the performance of the laser cutting process. Commonly used refractive optics being irradiated with high averaged power beam can be considered to be an effective aberration beam shaper because the laser induced thermal lens is strongly aberrated though it has small optical power.

Experimental setup consisted of an array of the similar optical systems with the same focal length, F-number and an axial glass thickness. The only difference was the value of uncorrected wave aberration. The last was varied from 0 to 1 wave rms by means of different orientation and spacing of the same lenses within focusing doublets so caustics and LBID profiles produced by the systems were essentially different. All the lenses have been made of the same Heraeus Suprasil 3002 rod with the ultralow bulk absorption (< 0.25 ppm/cm) that allows reducing the thermal effects. The systems have been placed into the same cutting head that has been used with different output beam quality factor. Typical aspect ratio was about 10. The cut quality had been estimated in accordance with minimum striation and dross. Detailed simulations, measurement results and discussion concerning laser induced aberration beam shaping are presented.

Two best cut ranges of beam position had been found for each optical system. In spite of essential differences in LBID as well as local beam intensities the extremums of the best cut ranges were placed symmetrically about the waist position. Furthermore extremum positions have appeared to be the same for all tested systems up to the measuring accuracy. At the same moment the lengths of the ranges were inversely proportional to the value of uncorrected aberration. Additionally for each system the length of the best cut range was minimum where an aberration had been localized and maximum at opposite direction.

8963-34, Session 8

Experimental comparison of the oxygen-assisted laser cutting of low-carbon steel with fiber and ??2-lasers under the condition of minimal roughness

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At the moment, along with CO2-lasers, solid state fiber ones are widely used for metal cutting. Comparison of cut characteristics of two lasers types presents both practical and scientific interest. The latter is related with the fact that the effectiveness of fiber laser application reduces significantly as the metal sheet thickness rises, and physical reasons and mechanisms of it are not clearly determined. Some researchers have already presented the results of experimental comparison of the cutting with the fiber and ??2 lasers. The peculiarity of our approach is that the comparison is done at the best cut quality level. A well-defined quantitative parameter, the cut surface roughness, is chosen as the quality criterion. Generalized dimensionless parameters, at which the roughness is minimal, have been found for the two laser types.

Low-carbon steel sheets of 3… 10 mm were cut with the fiber laser, and 5… 16 mm sheets were cut with the ??2-laser; oxygen was used as an assisted gas. The coefficient of the laser beam absorption was measured in the cut channel during the cutting process. It is demonstrated that the cutting conditions with the minimal roughness can be formulated for the two laser types with the same generalized parameters, i.e. dimensionless absorbed laser power and Peclet number (dimensionless speed). Numerical values of these parameters were found experimentally. The optimum Peclet number is 0.45…0.55 for the ??2-laser cutting, and 0.35…0.4 when the fiber laser is utilized.

8963-35, Session 9

Development of laser cladding system with process monitoring by x-ray imaging

Takaya Terada, Tomonori Yamada, Akihiko Nishimura, Japan Atomic Energy Agency (Japan)

We have been developing a laser cladding system to repair the inner wall erosion in 1-inch heat exchanger tubes. Observing laser cladding process by X-ray imaging with Spring-8 synchrotron radiation, we found that the molten pool depth was formed to be under a hundred micrometers for 10 milliseconds. A Quasi-CW fiber laser with 1 kW was employed for a heat source to generate the shallow molten pool. The X-ray shadowgraph clarified that a molten droplet was formed at the edge of a wire up to a millimeter size. It grew up if the wire didn't contact with the tube wall in initial state. Here we succeeded to measure the thermo-electromotive force voltage between a wire and a tube metal to confirm whether both came in contact.

We should irradiate the inner wall erosion with the best accuracy of laser beam and filler wire. A composite-type optical fiberscope was useful. This fiberscope was composed of a center fiber for beam delivery surrounded by 20000 fibers for visible image delivery. Thus it always keeps target on center of gun-sight. Both laser processing head and filler wire feeding device were designed to fill up the inner wall wastage of 1-inch tubes. The laser cladding system succeeded to make a line clad layer on a tube inner wall which was about 0.6 mm in width and 0.3 mm in height. We propose to apply the laser cladding technology to the maintenance of aging industrial plants and nuclear facilities.

8963-36, Session 9

Analysis of the molten/solidified zone in selective laser melted parts

Sabina Luisa Campanelli, Giuseppe Casalino, Nicola Contuzzi, Andrea Angelastro, Antonio D. Ludovico, Politecnico di Bari (Italy)

The process of Selective Laser Melting (SLM) is an innovative technology for rapid prototyping

that can be included in SFF (Solid Freeform Fabrication) techniques, characterized by "free-form

" manufacturing of solid parts. SLM is an additive technology, that operates on data encoded in a three-dimensional computer aided design (CAD) file and transfers the sliced data to a computer-controlled laser device that fuses successive layers of metal powder to create a three-dimensional product.

The SLM is a technological process which involves both optical, thermal and solidification phenomena; thus the analysis of the process is rather complex. The aim of this work was to study the shape and the size of the molten/solidified zone (MSZ) in SLM parts identifying the functional relationships between quality attributes of built parts and the parameters used to control the process.

The study of the MSZ was conducted by an experimental campaign and subsequent metallographic analysis of the analyzed cross sections.

A statistical analysis was performed in order to determine the significance of the main process parameters involved in the process, such as laser power, scanning speed, hatch spacing between two adjacent vectors, on the width and the depth of the MSZ. The machine used for experiments was equipped with a Nd:YAG laser with a maximum power of 100W and the material investigated was the 18 Ni Marage 300 steel.

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8964-1, Session 1

CW emission at 193 nm using an all solid-state laser source *(Invited Paper)*

Matthias Scholz, Dmitrijs Opalevs, Jürgen Stuhler, Patrick Leisching, Wilhelm G. Kaenders, TOPTICA Photonics AG (Germany); Guiling Wang, Xiaoyang Wang, Rukang Li, Chuangtian Chen, Beijing Ctr. for Crystal Research and Development (China)

We report on the realization of a highly coherent and tunable light source at 193 nm. Narrow-band laser sources at wavelengths below 200 nm promise advantages for a wide range of applications in metrology and lithography. Compared to earlier realizations [1], we increased key parameters of our laser source like output power and lifetime by more than an order of magnitude. In our system, the deep-ultraviolet emission is realized frequency-quadrupling an amplified diode laser, and over 15 mW of laser emission could be generated using the nonlinear crystal KBBF. The power dependence of the output on the fundamental power has been measured and follows theoretical predictions. We demonstrate mode-hop free tuning of the emission over a range of 100 GHz and coarse tuning by 5 nm. The high stability of the setup was proven in an 80 h-measurement using an active power stabilization system, and the impact of the crystal transmission on the output power was thoroughly studied. In order to determine the short-term noise properties, the integrated relative intensity noise of the emission between 10 Hz and 10 MHz has been measured, and a level of 0.22% could be achieved which substantially surpasses the specifications of state-of-the-art bench-top excimer lasers. We see our laser source as an ideal tool for photoemission spectroscopy which reaches the power level to replace excimer lasers in metrological applications.

[1] Scholz et al., Optics Express 20, 18659 (2012)

8964-2, Session 1

High power green, yellow, and UV fiber lasers *(Invited Paper)*

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The excellent beam quality, narrow linewidth, and multi-kilowatt output power levels of Yb-doped fiber lasers make them ideal sources for frequency conversion. In order to realize high conversion efficiencies, careful management of linewidth , polarization and nonlinear effects in the fiber laser are required. We demonstrate sub-100pm PM fiber laser with >30KW peak power that serves as a source for frequency conversion by use of LBO crystals to green, UV, and yellow light. By optimizing the laser and spot sizes in the nonlinear crystals, we reach record efficiencies in single pass conversion to 532nm (>70%) and 355nm (>20%). To realize longer wavelengths in the 560-590nm range we have constructed a novel monolithic long wavelength Yr and Raman fiber engine built using commercially available components and well established LMA fiber technology. A pulsed source in the wavelength range of 1060-1100nm is combined with a narrowband CW seed in the 1100-1180nm range, before amplification to high powers. The LMA Yb- fiber Raman amplifier, not only amplifies the pulses to high peak power, but also efficiently shifts the wavelength by SRS to that of the CW seed. While pulse width is determined by the pulsed source, the wavelength is set by the narrow band CW seed. The high peak powers allow single pass frequency doubling with over 25% efficiency of 915nm pump light to yellow.

The ease of scalability of fiber based sources, enables tens of watts (>40W) in the green and yellow and several watts in the UV.

8964-3, Session 1

A new approach to sum frequency generation of single-frequency blue light in a coupled ring cavity

Ole B. Jensen, Paul M. Petersen, DTU Fotonik (Denmark) and Technical Univ. of Denmark (Denmark)

Tunable single-frequency visible light sources are required for many applications within biophotonics and spectroscopy. Here, a generic approach for the generation of tunable single-frequency light is presented. The concept is based on sum frequency generation between a tapered diode laser operated in a coupled ring cavity and a tapered diode laser operated in a Littrow configuration. Both lasers are single-frequency and tunable within the gain bandwidths of the two diode lasers, respectively. By proper selection of the diode laser wavelengths and nonlinear material, it is possible to cover a very large spectrum.

In the present implementation, the two tapered diode lasers are operated around 1060 nm and 810 nm, respectively, for generation of light around 460 nm. More than 300 mW of single-frequency tunable light is generated with a near-diffraction limited beam quality with M2 < 1.15 enabled by nonlinear beam clean-up. A single-pass conversion efficiency of more than 25% is ensured by the high circulating power in the coupled cavity. The spectral linewidth of the blue light is below 20 MHz and with the two diode lasers used a wavelength coverage of 17 nm is possible with proper selection of nonlinear material. In normal external cavity approaches, electronic locking is necessary to keep the cavity on resonance with the laser frequency. Here, we use optical feedback in the coupled ring cavity to passively lock the laser frequency to a cavity resonance frequency.

8964-4, Session 1

Efficient generation of orange light by frequency-doubling of a quantum-dot laser radiation in a PPKTP waveguide

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Development of compact efficient visible laser sources in the orange spectral region is currently very attractive area of research with applications ranging from photomedicine and biophotonics to confocal fluorescence microscopy and laser projection displays. In this respect, semiconductor lasers with their small size, high efficiency, reliability and low cost are very promising for realization of such laser sources by frequency-doubling of the infrared light in a nonlinear crystal containing a waveguide. Furthermore, the wide tunability offered by quantum-dot external-cavity diode lasers, due to the temperature insensibility and the broad gain bandwidth, is very promising for the development of tunable visible laser sources.

In this work, we show a compact all-room-temperature laser source generating orange light at 606 nm, 608 nm and 611 nm with output

power of 12.04 mW, 10.45 mW and 6.24 mW, respectively, and maximum conversion efficiency as high as 10.29%. This laser source is based on second harmonic generation in periodically-poled KTP waveguides with different cross-sectional areas (4x4μm2, 3x5μm2 and 2x6μm2) using a InAs/GaAs quantum-dot external-cavity diode laser. The wider waveguide with the cross-sectional area of 4x4μm2 demonstrated better results in comparison with the narrower waveguides which corresponded to lower coupling efficiency. Additional tuning of second harmonic light (between 606 and 614nm) with similar conversion efficiency was possible by changing the crystal temperature. The demonstrated laser source represents an important step towards a compact efficient orange light source.

8964-5, Session 1

Generation of 3.5 W of diffraction-limited green light from SHG of a single tapered diode laser in a cascade of nonlinear crystals

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Many applications, e.g., within biomedicine stand to benefit greatly from the development of diode laser-based multi-Watt efficient compact green laser sources. The low power of existing diode lasers in the green area (about 100 mW) means that the most promising approach remains nonlinear frequency conversion of infrared tapered diode lasers.

We present the generation of 3.5 W of diffraction-limited green light from SHG of a single tapered diode laser, itself yielding 10 W at 1063 nm. This SHG is performed in single pass through a cascade of two PPMgO:LN crystals with re-focusing and dispersion compensating optics between the two nonlinear crystals. In the low-power limit, such a cascade of two crystals has the theoretical potential for generation of four times as much power as a single crystal without adding significantly to the complexity of the system. The experimentally achieved power of 3.5 W corresponds to a power enhancement greater than 2 compared to SHG in each of the crystals individually and is the highest visible output power generated by frequency conversion of a single diode laser.

Such laser sources provide the necessary pump power for biophotonics applications, such as optical coherence tomography or multimodal imaging devices, e.g., FTCARS-OCT, based on a strongly pumped ultrafast Ti:Sapphire laser. Examples of such applications are presented.

8964-70, Session 1

SM green fiber laser operating in CW and QCW regimes and producing over 550W of average output power

Valentin P. Gapontsev, Alexey Avdokhin, Pankaj Kadwani, Igor Samartsev, Nikolai Platonov, Roman Yagodkin, IPG Photonics Corp. (United States)

We report a fiber-laser-based single-mode green source capable of operating in a wide range of regimes from CW to high-repetition-rate QCW and generating up to 550W of average power. To the best of our knowledge, this is the highest output power ever reported for a single-mode green laser. The 1064nm fiber laser which we used in our experiment was providing up to 1.06kW of linearly polarized narrow-linewidth emission while still maintaining linewidth of less than 0.1nm and M2<1.15 at full power. It consisted of a linearly polarized single-frequency seed laser diode, linewidth-broadening system which included phase modulator, and a source of amplified RF noise, and a single-mode polarization-maintaining multi-stage fiber amplifier. The QCW regime was realized through direct modulation of the seed laser diode with 20-50% duty cycle. The output of the Yb laser was focused into a high-quality LBO crystal for single-pass SHG. With 1.06kW average power at 1064nm and a duty cycle of 50%, 550W at 532nm was achieved with SHG efficiency over 50% and WPE over 15%. By adjusting the duty cycle, we were able to maintain ~50% SHG efficiency over a wide range of pump powers at 1064nm, i.e., at ~20% duty cycle we obtained 195W at 532nm from 400W at 1064nm. In CW regime we obtained over 350W at 532nm from ~1kW pump with ~35% SHG efficiency. Further optimizing seed laser driver and employing 2kW narrow-linewidth SM Yb fiber amplifier, developed by IPG, we plan to improve SHG efficiency to 60-70%, and increase the green power to 1kW and above. We also plan to extend our approach to create high-power sources operating at other wavelengths of UV and visible spectrum.

8964-6, Session 2

Continuous-wave optical parametric source for terahertz waves tunable from 1 to 4.5 THz frequency *(Invited Paper)*

Jens Kiessling, Karsten Buse, Fraunhofer-Institut für Physikalische Messtechnik (Germany); Konstantin L. Vodopyanov, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); Ingo Breunig, Albert-Ludwigs-Univ. Freiburg (Germany)

Continuous-wave (cw) optical parametric oscillators (OPOs) are known to be working horses for spectroscopy in the near and mid infrared. Their operation in the visible was demonstrated as well. However, strong absorption in nonlinear-optical crystals complicates the generation of far-infrared light. However, it was demonstrated that cascaded optical parametric oscillations, pump-enhanced optical parametric oscillations as well as intracavity difference frequency mixing can be employed to generate terahertz waves. So far, these approaches are based on lithium niobate as the nonlinear-optical medium. But its large absorption for frequencies above 3 THz strongly reduces the performance in this regime. Thus, it is desirable to use a less absorbing nonlinear-optical crystal, e.g. gallium arsenide. We demonstrate the cw operation of a cascade that has been successfully applied for picosecond systems: A doubly-resonant OPO based on lithium niobate generates signal and idler waves close to degeneracy. Subsequently, these two light fields are converted to a terahertz wave via difference frequency mixing in an orientation-patterned gallium arsenide crystal placed inside the OPO cavity. Using this scheme, we generate single-frequency terahertz light tunable from 1 to 4.5 THz frequency with less than 10 MHz linewidth, and a Gaussian beam profile. In our first proof-of-principle experiments, the output power is of the order of tens of μW. Our results indicate that the power of the terahertz light is scalable into the milliwatt regime. This combination of tunability, narrow-linewidth operation, excellent beam quality, and high output power makes such a light source valuable for various applications.

8964-7, Session 2

Ultra-broadband IR and THz generation and detection with ultrashort pulses *(Invited Paper)*

Masaaki Ashida, Eiichi Matsubara, Osaka Univ. (Japan); Ikufumi Katayama, Yokohama National Univ. (Japan)

Generation of phase-locked pulses is one of the most important techniques in modern optical science and engineering. We successfully generated ultra-broadband phase-locked pulses in terahertz and infrared

region up to 200 THz with a combination of organic DAST crystals and 5-fs pulses having ultra-broad spectral widths and directly detected their electric field with a photoconductive antenna. On the other hand, with a combination of air and intense 10-fs pulses, we achieved the generation and detection of the ultra-broadband phase-locked pulses continuously from terahertz to near-infrared region. The comparison between these methods will be discussed in detail.

8964-8, Session 2

Synthesis of few-cycle multi-THz transients for sub-cycle nonlinear optics *(Invited Paper)*

Denis V. Seletskiy, Bernhard Mayer, Christian Schmidt, Johannes Bühler, Jonathan Fischer, Daniele Brida, Alexej Pashkin, Alfred Leitenstorfer, Univ. Konstanz (Germany)

Motivated by exploration of the regime of non-perturbative sub-cycle-resolved light-matter interaction, in this work we discuss our approaches to synthesis of phase-stable high-field multi-THz pulses of nearly single-cycle in duration. In the first approach, we shape the THz pulses directly in the time domain by gating reflectivity of a semiconductor on the femtosecond time scale [1]. In more detail, the electron-hole plasma in intrinsic germanium, generated via interband absorption of sub-15 fs NIR NOPA pulses, acts as a temporal reflectivity/transmission gate on the co-incident and delayed multi-THz pulse. Controlled inter-pulse delay results in synthesis of the multi-THz waveform via the plasma-mediated ultrafast reflectivity change with sub-cycle precision. In the second approach, we implement novel high-field multi-THz waveforms with strong polar asymmetry via coherent ?-2? synthesis [2]. To this end, we generate broadband second harmonic of the few-cycle fundamental pulse centered at 29 THz, thus leading to an octave-spanning combined phase-locked THz spectrum. By addressing the phase difference between the first and second harmonics, we demonstrate controlled polar asymmetry of the pulses directly in the time domain via an ultrabroadband electro-optic sampling. Access to such tailored high-field multi-THz pulses opens a new regime for exploration of nonlinear light-driven phenomena in condensed matter directly with sub-cycle resolution.

[1] A. J. Alcock, P. B. Corkum, and D. J. James, Appl. Phys. Lett. 27, 680 (1975)

[2] A. N. Chudinov et al., Opt. Quant. Electron. 23, 1055 (1991)

8964-9, Session 2

Room temperature terahertz wave imaging at 60 fps by frequency up-conversion in DAST crystal

Shuzhen Fan, Feng Qi, Takashi Notake, Koji Nawata, Takeshi Matsukawa, Yuma Takida, Hiroaki Minamide, RIKEN (Japan)

Terahertz imaging has attracted a lot of interests for more than 10 years. But real time, high sensitive, low cost THz imaging in room temperature, which is widely needed by fields such as biology, biomedicine and homeland security, has not been fully developed yet. A lot of approaches have been reported on the raster scanning imaging technologies or THz camera with photoconductive antenna or microbolometer integrated. But they still have much limitation. THz detection by nonlinear frequency upconversion offers high sensitivity and fast response up to nanosecond scale, making it possible to get real-time imaging at only interested THz frequency. In this paper, for the first time, we report high sensitive video-rate THz image employing a commercial infrared camera, using frequency up-conversion technology, covering a very wide frequency range from about 2 THz to 29 THz. In this system, a flash-lamp pumped nanosecond pulse green laser is used to pump two KTP optical parametric oscillator (OPO) systems. One system with dual KTP crystals is used to generate infrared laser as the pumping of THz difference frequency generation (DFG) in a 4-Dimethylamino-N-Methyl-4-Stilbazolium Tosylate (DAST) crystal. The other one is for generation of pumping laser for THz frequency up-conversion in a second DAST crystal. The frequency up-converted image in infrared region is recorded by a commercial infrared camera working in video rate. High sensitivity has been achieved due to the very high nonlinear coefficient of DAST crystals. And the imaging information of one subject in certain terahertz frequency can be recorded in one shot.

8964-10, Session 3

Intracavity optical parametric oscillators based upon OP-GaAs *(Invited Paper)*

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The nonlinear optical material OP-GaAs has established itself as an excellent material for the generation of deep-infrared radiation through parametric down-conversion. Its many meritorious qualities include a good figure of merit, an optical transmission that penetrates deep into the infrared, and its availability in long interaction length samples. In many ways, it is poised to become the “PPLN” of deep infrared Optical Parametric Oscillators (OPOs). To date, this material has only been utilised in the pulsed regime and is typically pumped by Q-switched lasers in the classic extracavity singly-resonant OPO geometry. Recent developments in fabrication have led to significant improvements in its linear transmission properties at the pumping wavelength around 2?m, and this in turn enables it to be placed within the cavity of the parent pump laser where it can access the high circulating field found there – substantially reducing the external [diode] pumping power required to reach threshold. In this talk I will present recent work towards such an intracavity OPO based upon both established and emergent parent pump laser technology.

8964-11, Session 3

Efficient femtosecond 50 MHz repetition rate mid-IR source up to 17 µm by difference-frequency generation in AgGaSe2

Marcus Beutler, Ingo Rimke, Edlef Büttner, APE GmbH (Germany); Valery V. Badikov, Dmitri V. Badikov, Kuban State Technological Univ. (Russian Federation); Valentin P. Petrov, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany)

We present an efficient coherent source widely tunable in the mid-infrared spectral range consisting of a novel femtosecond Yb-fiber laser operating at 50 MHz repetition rate, a synchronously-pumped OPO (SPOPO) and difference-frequency generation (DFG) in AgGaSe2. With an average input pump power of 5 W at 1030 nm, the SPOPO outputs are tunable from 1700 to 1950 nm (Signal) and from 2200 to 2700 nm (Idler) with pulse durations between 220 and 250 fs over the entire tuning range. After temporally overlapping Signal and Idler through a delay line, the two beams are spatially recombined with a dichroic mirror (reflecting for the Signal in s-polarization and transmitting for the Idler in p-polarization), and focused by a 100 mm CaF2 lens to a beam diameter of ~80 µm. For DFG we employ an uncoated 2-mm thick AgGaSe2 nonlinear crystal cut for type-I interaction at ? =57°. The generated mid-infrared femtosecond pulses are continuously tunable between 5 and 17 µm with average power at 50 MHz up to 60 mW at 6 µm and more than 1 mW at 17 µm. Their spectra and autocorrelation traces are measured up to 14 µm and 8 µm, respectively, and indicate that the input spectral bandwidth and

pulse duration are maintained to a great extent in the nonlinear frequency conversion processes. The pulse duration slightly increases from 250 to ~300fs at 7.2 µm while the spectral bandwidth support sub-200 fs durations across the entire mid-infrared tuning range. For the first time mid-infrared pulses with energy exceeding 1 nJ are generated at such high repetition rates.

8964-12, Session 3

Mid IR light source generated by OPO using PPMgSLT for laser ultrasound testing of carbon-fiber-reinforced plastic (CFRP)

Kenji Kitamura, Hideki Hatano, National Institute for Materials Science (Japan) and SWING Ltd. (Japan); Shunji Takekawa, Hisashi Yamawaki, National Institute for Materials Science (Japan); Junji Hirohashi, Yasunori Furukawa, Oxide Corp. (Japan)

Laser induced ultrasound is a rapidly developing technique for non-destructive testing of composite materials, for example, carbon-fiber- reinforced plastic (CFRP) used in aircraft. Currently, there are products on the market to detect flaws in such composite materials using very powerful short pulse CO2 laser to generate an ultrasonic wave by thermo-elastic expansion of materials. However, high power CO2 gas laser has some problems in size compactness, light guiding, maintenance etc.

On the other hand, there have been some previous reports that a stronger ultrasonic signal can be generated from CFRP surface by using wavelengths in the range 3200-3400nm (mid IR light) compared with signals generated by CO2 laser light (10600 nm wavelength) . The published data indicates that a factor of 3-10 times larger ultrasonic signal can be generated with mid-infrared light compared with long wave infrared. It is now reasonably well established that the enhancement appears to be due to absorption by the carbon-hydrogen bond which is present in all organic polymer matrix material. However, there is no compact, robust, enough powerful, maintenance free, all solid state light source generating such mid IR light on the market.

We have successfully developed very compact, powerful (>30 mJ), short pulsed (~10 ns) mid IR (3200~3500 nm wavelength) light generated by the OPO using large aperture PPMgSLT. Here, we demonstrate the high efficiency of idler light generation, generated ultrasound signals from CFRP surface and less damage of material surface by the laser light irradiation.

8964-13, Session 3

Non-collinear upconversion of incoherent light: designing infrared spectrometers and imaging systems

Jeppe S. Dam, Qi Hu, Christian Pedersen, Peter Tidemand-Lichtenberg, Technical Univ. of Denmark (Denmark)

Upconversion of mid-infrared radiation to near visible wavelengths offers very attractive sensitivity. Incoherent light can easily be coupled into a non-linear crystal at many different angles simultaneously. We consider how each angle will phase match a narrow range of wavelengths. Non-collinear phase matching has been an area of limited attention for many years due to inherent incompatibility with tightly focused laser beams which is necessary for most second order processes in order to achieve acceptable conversion efficiency. However, as will be argued, for upconversion processes this is not the case. Furthermore, the development of periodically poled crystals have allowed for non-critical collinear phasematching of most wavelengths, virtually eliminating the need for non-collinear phasematching. When considering upconversion of thermal light, spectral radiance is limited due to the temperature of the Planck radiation source. On the other hand, it is straightforward to increase the incoherent power by increasing the receiving aperture of the upconversion unit and the diameter of the upconversion laser beam. These facts mean that optimal conversion efficiency for incoherent light is not well suited for tightly focused beams. To the contrary we show it is best to fill the nonlinear crystal with as large a pump beam as possible. Consequently, this allows for upconversion of large angles of incoming incoherent light. We present a fully analytical description of non-collinear mixing and how it affects spectral and spatial resolution in the image, and compare against experiments. We finally discuss how it can be used to actively design and predict systems performance and how upconversion can be used for mid-IR spectroscopy and imaging.

8964-14, Session 3

Broadly tunable Watt-level femtosecond soliton-seeded optical parametric amplifier in the near- and mid-infrared

Tobias R. J. Steinle, Joachim Krauth, Andy Steinmann, Harald W. Giessen, Univ. Stuttgart (Germany)

Tunable mid-infrared laser sources provide access to a versatile field of spectroscopic applications such as near-field and FTIR spectroscopy. In contrast to quantum cascade lasers, parametric light sources based on difference frequency generation, such as optical parametric amplifiers (OPA) and optical parametric oscillators (OPO), are able to provide broadly tunable spectra in the near- and mid-IR.

We demonstrate a femtosecond OPA that generates radiation with more than a Watt continuously tunable in the near-IR (1350-2000 nm) and more than half a Watt in the mid-IR (2.0-4.7 µm) at pulse durations of less than 300 fs. The OPA is directly pumped by a diode-pumped solid-state 7.4 W Yb:KGW oscillator at 41.7 MHz repetition rate, without the need for any amplifier or cavity dumping.

The infrared radiation is generated in magnesium oxide-doped periodically poled lithium niobate (MgO:PPLN) down conversion crystals. In a pre-amplification stage several hundreds of milliwatts are generated and used to operate the main-amplification stage in saturation. An optical soliton, generated in a tapered fiber with pre-compressed pulses, serves as seed for the pre-amplifier. In contrast to OPAs seeded by fiber-based supercontinua, the solitonic seed leads to low intensity noise, stable pulse-to-pulse characteristics, and high conversion efficiencies (up to 60% photon conversion efficiency), while only a very small fraction of the available pump power is sufficient for seed generation.

Due to their simplicity, stability, as well as their fast and continuous tunability, high repetition rate OPAs are most suitable to replace synchronously pumped OPOs in the future. Additionally, the high output power and broad bandwidth of the mid-IR idler is highly attractive as FTIR spectroscopy source.

8964-15, Session 4

Visualization of light filamentation in air and liquids *(Invited Paper)*

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There are numerous interpretations of the filamentation phenomenon, ranging from moving focus, Bessel beams, to self-induced waveguide. Despite continuous wide ranging efforts since the first reports, filaments have remained difficult to reliably create, control, and study. This is due on one hand to the complexity of the phenomenon, making realistic simulations challenging, and on the other hand to the difficulty of observing the filament, as they form and evolve rapidly, and damage detectors and optics. A technique to visualize the propagation of filaments and associated plasma is presented.

The camera system observes light emitted transversally by the filaments, radiation composed of Rayleigh scattering at the filament wavelength, but also fluorescence light at various wavelengths from the ions and molecules excited in the wake of the filament. The slit of the streak camera selects the real image of a line approximately parallel to the filament axis. Two large metal mirrors, one of which can be rotated, relay the light. . An individual streak camera image covers a single row of pixels. Images are continuously captured while the field of view is scanned across the filament by rotating a relay mirror, at a slow enough rate to ensure continuity in the transverse dimension. The individual images are then computationally organized by two dimensional (x, y) pictures organized in successive time steps to provide a video. Jitter in time and space is suppressed computationally by selecting a reference point in the field of view.

8964-16, Session 4

Four wave mixing and coupled solitons

Amin Rasoulof, The Univ. of New Mexico (United States); Danhua Wang, Southern Methodist Univ. (United States); Ladan Arissian, The Univ. of New Mexico (United States); Alejandro B. Aceves, Southern Methodist Univ. (United States); Jean-Claude M. Diels, The Univ. of New Mexico (United States)

The third order susceptibility is responsible for the phenomenon of self-focusing leading to filamentation or self-trapping of high power laser beams. Femtosecond IR and nanosecond UV filaments have been produced in air, the former limited in length by their high nonlinear losses, the latter of considerably higher energy and narrow band, can be an ideal energy reservoir to extend the range of IR filaments, and a pump for Raman scattering of molecules excited by the IR filament. We investigate the mutual coupling of co-propagating UV and IR filaments by third order nonlinearity, leading to the use of the UV pulse as an energy reservoir to amplify the IR

Theory

First we establish the mathematical existence of coupled stationary solitons, solution of eigenvalue equations of which the spatial profiles of UV and IR fields are the eigenfunctions. Next we investigate the four-wave-mixing amplification of the IR by the UV, leading to these solutions, in the near-degenerate case (3 IR photons generated per UV photon).

Experiment

We investigate the coupling between a 40 fs IR pulse at 800 nm and its third harmonic in a liquid (hexafluoroisopropanol). In this degenerate case, the relative phase of the IR and UV is controlled, and its influence on the amplification process investigated. Various ways to control the phase matching are presented.

8964-17, Session 4

Power scaling of diamond Raman lasers beyond 100 W using quasi-cw pumping

Robert J. Williams, Ondrej Kitzler, Aaron M. McKay, Richard P Mildren, Macquarie Univ. (Australia)

Diamond shows strong potential for power scaling of crystalline Raman lasers due to its excellent thermal properties and high damage threshold. Record output powers have been demonstrated in diamond in both cw (10.1 W [1]) and pulsed (24.5 W [2]) operating regimes, and as yet no detrimental thermal effects or thermal lensing have been reported in cw diamond Raman lasers.

Probing the limits of diamond in the cw operating regime places stringent demands on the pump laser, requiring narrow linewidth (comparable to the Raman gain bandwidth, approximately 0.17 nm at 1064 nm) and high brightness for efficient Stokes generation. Our approach is to investigate the thermal dynamics of diamond at high powers in a quasi-cw operating regime, using pulses of several hundred microseconds duration at low duty cycle. As these parameters correspond to standard quasi-cw pump laser technology, the demands on pump laser cost and complexity are significantly relaxed. Furthermore, since the pulse durations are much longer than the thermal time constant expected in diamond, this approach allows us to probe the thermal dynamics of diamond Raman lasers as temperature gradients in the crystal approach steady state.

Using this approach, we report 104 Watts on-time Stokes output power from a long-pulse, quasi-cw diamond Raman laser with overall conversion efficiency of 27% and excellent beam quality. This power level is an order of magnitude improvement on previously-reported cw or quasi-cw diamond Raman laser output, and highlights the potential for power scaling true-cw diamond Raman lasers beyond the 100 W level.

1. O. Kitzler, A. McKay, and R. P. Mildren, Opt. Lett. 37, 2790 (2012).

2. J.-P. M. Feve, K. E. Shortoff, M. J. Bohn, and J. K. Brasseur, Opt. Express 19, 913 (2011).

8964-18, Session 4

Applications of stimulated Brillouin scattering in silicon photonics *(Invited Paper)*

Peter T. Rakich, Yale Univ. (United States)

We describe the development of Brillouin-active silicon photonics, and explore the application stimulated Brillouin scattering to new forms of chip-based signal processing in silicon. By engineering hybrid photonic-phononic waveguides with slow group-velocity phonon modes, we show that tremendous forward stimulated Brillouin nonlinearities can be achieved with strong photon-phonon for frequencies ranging from 1-20 GHz. We show that efficient parametric coupling through such guided-wave interactions can be used to enable a number of radio frequency and photonic signal processing applications.

8964-44, Session PTue

Multicolor frequency upconversion luminescence in europium/terbium co-doped ytterbium-sensitized fluorogermanate glass excited at 980 nm

James R. Silva, Artur S. Gouveia-Neto, Luciano A. Bueno, Univ. Federal Rural de Pernambuco (Brazil)

Rare-earth doped frequency up-converters have drawn much scientific and technological interest lately owing to their potential application in color displays technology, optical sensing devices, visible solid-state lasers, biological markers, amongst many. The frequency upconversion mechanism takes advantage of the multi-ion interaction in rare-earth doped host materials. The multi-ion interaction provides conditions for the so-called sensitization process in which the species excited by a pump photon transfers its excitation to the other species present in the matrix. The exploitation of this ion-pair interaction referred to as energy-transfer has been extensively investigated in Er3+-, Pr3+-, Tb3+-, and Tm3+-doped samples sensitized with trivalent ytterbium. Novel glass materials suitable for the development of solid-state visible and/or white-light emission sources based upon near infrared excited up-converters have drawn much attention during the last few years. Considering

solid-state hosts, fluorogermanate glasses have recently emerged as viable alternative for photonics and bio-photonics applications. These PbGeO3-PbF2-CdF2 glasses are advantageous because they present better mechanical strength, chemical durability, and thermal stability than fluoride-based glasses and are suitable for developing low-loss, high strength, and low-cost optical fibers. In addition, the glass host matrices possess the durability and mechanical properties of an oxide glass and the maximum vibrational energy is intermediate (?800 cm-1) between those of silicate (?1100 cm-1) and fluoride (?500 cm-1) based glasses. Glassy 80GeO3:10PbF2:10CdF2 phosphors triply-doped with europium, terbium, and ytterbium were synthesized and the energy up-conversion luminescence properties investigated as a function of NIR excitation power, rare-earth content combination, and glass phosphor composition. Multicolor visible luminescence with main emissions peaked around 490, 545, 590, 610, 650, and 700 nm was observed when samples were excited by a LED laser at 980 nm. The up-conversion excitation mechanism for both Eu3+, and Tb3+ excited-states emitting levels was achieved via phonon-assisted cooperative energy-transfer from pairs of excited Yb3+ ions. Low color correlated temperature white-light emission was obtained using a proper combination of rare-earth active ions

8964-45, Session PTue

Optical frequency comb generated by means of enhanced multiple four-wave mixing

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This work presents an efficient scheme for generating broadband all-optical frequency combs with high Optical Signal-to-Noise Ratio (OSNR) through multiple Four-Wave Mixing (FWM). Comb Generators have an important role in many applications, including coherent optical communications, generation of Orthogonal Frequency Division Multiplexing (OFDM) super-channel, multi-wavelength DWDM source, optical metrology, high repetition rate pulse source, spectrometer calibration, optical atomic clocks and more precise GPS technology. Our technique consists of creating a series of discrete and equally spaced coherent lines, enhanced by using optical feedback and a proper combination of highly nonlinear, single-mode and erbium-doped fibers. The optical feedback intends to apply the system output, with an already generated frequency comb, as a seed for the erbium-doped fiber. The latter one will gradually increase the FWM products power avoiding pump-back reflection due to Brillouin scattering. Posterior, a single-mode fiber with negative second-order dispersion is used to compress the pulse in the time domain and then to launch it into a new piece of highly nonlinear fiber with a higher peak power, improving the efficiency of multiple FWM products. The result is an optical comb covering a broadband spectrum generated by low power and continuous waves, eliminating the use of pulsed laser sources. The process reliability and efficiency is demonstrated by numerical and experimental results. Experiments demonstrated an expansion from a few lines to over than a hundred of FWM products with high OSNR. Future works regard the transmission of an OFDM super-channel based on the proposed scheme through a metropolitan network.

8964-46, Session PTue

New simple method for measuring nonlinear polarization ellipse rotation with high precision using a dual-phase lock-in

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We report the development of a simple method for measuring nonlinear polarization ellipse rotation (NPER) angle with very high precision for studding refractive nonlinearities. It is well known that due to the tensor nature of these nonlinearities, the magnitude of the nonlinear signals measured by a particular experimental technique does depend of the polarization of the light beam and origin of the nonlinear processes. For example, the NPER can be easily observed when intense elliptically polarized laser pulse is applied in a nonlinear sample and the magnitude of the rotation angle is due to a special nonlinear susceptibility coefficient which can be different from one accessed by other nonlinear effects. In order to take advantage of this characteristic, we developed a new method for measuring the NPER angle with very high precision by means of a dual-phase lock-in and a rotating linear polarizer. In order to change the irradiance and observe the NPER, we move a nonlinear sample along a focused elliptically polarized beam (z-direction). In this way, the angle of the elliptical polarization changes in the way the sample moves at z-direction and reaches its maximum value at the focal point. The elliptically polarized beam was obtained using a suitable quarter-waveplate. We did measurements on several samples with different pulse duration (picosecond and femtosecond) to test our method on nonlinearities with different origins such as: thermal, molecular orientation and nonresonant electronic response, for example, could be easily discriminated. The traditional Z-scan measurements were used to support the results.

8964-47, Session PTue

Reflectance difference spectroscopy and second harmonic generation from strained silicon

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Strain silicon has different optical response than non-strained one. In particular it has been shown that silicon nonlinear optical properties can be enhanced by the strain. This, combined with the maturity of silicon processing technology has made it attractive for some possible applications in integrated devices. The strain is typically induced by growing thin layers of different materials on top of silicon wafers.

It is well known that the second order nonlinear susceptibility from bulk silicon in the dipole approximation must be identically zero, due to symmetry arguments. However, the introduction of inhomogeneous strain by the method described above leads to the breaking of the centrosymmetry and thus to enhanced nonlinearities.

It is necessary not only to quantify the induced strain but also to better understand how the optical properties are affected by it. We present reflectance difference spectroscopy (RDS) and second harmonic generation (SHG) measurements of two different strained flat and vicinal silicon substrates. One of the samples has a compressive strain in its vicinal silicon substrate induced by the growth of a Si1-xCx overlayer. The second sample consists of a thin GaP layer grown on top of Si(001).

Our experiments show that the RDS is able not only to detect, but also to quantify, the strain induced in the silicon by the overlayer. We also find that the SHG signal is also sensitive to the produced strain and it could give information about the Si microstructure of the first few monolayers.

8964-48, Session PTue

Mutual coherence measurement of THz beat notes generated by dual injection in a Fabry-Perot laser by using linear optical sampling

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Dual injection locking of multimode laser is a useful technique to generate THz optical tones. Interesting results has been proposed in different structures. Nevertheless, due to large frequency beating well above available photodiode bandwidth, the coherence is not addressed in most of the presented results. We propose in this paper a new method to measure the coherence of tones, with frequency beating in the THz range, based on linear optical sampling.

Linear optical sampling is a powerful tool to detect high bandwidth envelop optical field (>100 GHz), either in its under sampling or over sampling configuration. The signal under test (SUT) is linearly detected with a coherent detection arrangement using a pulsed local oscillator and sampled with a low sampling rate ADC (<1GS/s). The sampling rate, corresponding to the repetition rate of the pulsed local oscillator, is chosen to avoid aliasing from frequency higher to the phase noise bandwidth of the individual tones, typically 100 MS/s and above. For an asynchronous optical sampling of the SUT, the discrete spectrum of the linearly detected signal consists in two separated tones. The frequency difference can be adjusted by slightly tuning the repetition rate of the local oscillator. A digital time resolved analysis is then achieved to extract the frequency correlation of the SUT.

The proposed method is first used to detect the correlation of a 40 GHz Fabry-Perot mode-locked laser, by using a 500 MHz bandwidth coherent detection. Then, the method is applied to a dual injected Fabry-Perot laser in order to measure the coherence between two generated tones with THz frequency difference. To this end, it will be shown that the proposed experimental method is of first importance to extract information on novel material systems such as those including quantum dot or surface plasmon based diode lasers.

8964-50, Session PTue

Nonlinear index of refraction of borate glass doped with transition metals

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The large interest in nonlinear optical materials has been motivated by their potential use in the fabrication of all-optical photonic devices. Among several interesting candidates for such application, glasses have received special attention because of the facility to tailor their properties by compositional changes. It is well known that nonlinear optical properties are enhancement when the excitation energy approaches an electronic transition. In this study, we have doped a transparent glass (Eg = 3.92 eV) with transition metals, in order to introduce electronic transitions in visible spectrum and to evaluate their influence on the nonlinear index of refraction (n2). A new glassy matrix, containing mainly boron, zinc and lead oxides, was doped with 0.1% mol of CdCl, Fe2O3, MnO and CoO, which resulted in broad absorption bands in different regions of the spectrum. A Ti:sapphire chirped pulse amplified system (150-fs, 775 nm and 1 kHz) and the z-scan technique were employed to measure n2 from 550 up to 1500 nm. For the undoped sample, we found an average value of n2 = 4.5 x10-20 m2/W at visible and infrared regions, being about twice larger than the value for fused silica. Similar values were obtained for the doped samples, which are practically constant in the range of 550-1550 nm, indicating that the dominant transitions contributing to the nonlinear process are located in the UV region of the spectrum and, therefore, associated to the glass matrix.

8964-51, Session PTue

Sum frequency generation process for a new astronomical instrument

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We propose an exotic use of sum frequency generation process (SFG) to develop a new kind of high resolution interferometer for astronomical imaging. SFG is well known as a noiseless non linear process of upconversion which permits a wavelength shift. Thereby we propose to shift astronomical MIR and FIR radiation to shorter wavelength where optical fibers and optical components are available and efficient.

In order to demonstrate the validity of this method for high resolution imaging we plan to set up a two-arm upconversion interferometer on the CHARA telescope array (California). Each arm would include an upconversion stage at the focus of telescope.

The success of such a project is obviously conditioned by the quality of nonlinear components (waveguided PPLN), in term of efficiency and noise. Moreover, coherence study requires the use of identical non linear components which implies manufacturing constraints.

To ensure the feasibility of this project, several studies have been conducted. By implementing an upconversion interferometer in laboratory we have recently demonstrated our ability to analyze the coherence properties of a 1550nm signal at visible wavelength. We also have successfully converted astronomical light using one arm of this interferometer at Hawaï observatory. It showed the scalability of our instrument to astronomical observing conditions in photon counting regime.

A preliminary mission at CHARA observatory allowed us to check the compatibility of our instrument with the environment onsite and available photometric levels. From these data we estimate that we are able to study the coherence of astronomical target at 1550nm.

8964-52, Session PTue

Upconversion enhanced degenerate four-wave mixing in the mid-infrared for sensitive detection of acetylene in gas flows

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We present a new type of mid-IR detector based on parametric upconversion applied for measuring low concentrations of acetylene diluted in a N2 gas flow. Acetylene is known as an important diagnostics gas in combustion physics. The mid-IR wavelength range is an ideal wavelength range for acetylene detection due to the presence of strong ro-vibrational transitions.

The upconversion detector replaces a cryogenic InSb point detector in an existing mid-IR degenerate four wave mixing (DFWM) setup configured in a forward phase-matching geometry. The mid-IR laser system is composed of an injection seeded Nd:YAG laser, a dye laser, and a frequency mixing unit. The upconversion detector converts the mid-IR signal in a sum frequency generation PPLN crystal placed as an intracavity component and a CCD camera detects the upconverted light.

The DFWM method is in principle a background free method, but with the image information from the upconversion detector a speckle pattern from scattered light was identified. We present a spatial analysis technique to discriminate the signal from the scattering and thus lower the influence of the background light at low signal levels. This enabled us to exploit the low detector noise in the CCD further.

We show a comparison between the detection limits for the cryogenic InSb and the upconversion detector and demonstrate at least a 10 fold increase in sensitivity with the upconversion detector. The detection limit is measured to 11 ppm based on the R9e line and limited still by stray light, not by dark current of the upconversion detector.

8964-53, Session PTue

Compact, room temperature 9.3 THz source

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The system consists of a pulsed, dual-wavelength laser source, whose output is used for generating terahertz radiation by difference-frequency generation (DFG) in a nonlinear organic crystal.

The source's pulsed beams from Nd:YAG (1.06 µm) and Yb:YAG (1.03 µm) crystals are combined and time-locked by a beam splitter, a common resonator output coupler and a Q-switch. Coarse energy equalization and synchronization of the two pulses is achieved by maintaining the ratio of the laser beam cross sections of ~14 in Nd:YAG and Yb:YAG crystals (the inverse of the ratio of the respective emission cross sections). Precise synchronization is achieved by fine-tuning the optical pumping of the laser crystals.

Organic crystal OH1 is employed as the optical difference-frequency mixer. This crystal has the highest figure of merit for DFG into the THz region. Due to low coherence length (~50 µm) for the 1-µm pump wavelength, a stack of several thin OH1 organic crystals is employed using quasi-phase matching.

With the currently assembled source emitting 10-ns pulses with energies of 0.6 mJ per wavelength at a 1.5 kHz repetition, we expect to achieve ~500 µW of average terahertz power (30 W peak power) by an optimized structure of OH1 crystals.

8964-54, Session PTue

Mid-IR peak power scaling in a ZGP OPO, pumped by a Tm:fiber MOPA system

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We report on scaling peak power in singly and doubly resonant ZGP optical parametric oscillator (OPO) cavity configurations using a novel Thulium-doped fiber laser system. The laser consists of a Q-switched oscillator based on a step-index fiber with 10/130 µm core/cladding diameters and two amplifier stages based on ultra-large-mode-area photonic crystal fibers (PCFs) with 50/250 µm core/cladding diameters. With pulse durations of ~8 ns at 4 kHz repetition rate, the pump laser provides up to 120 kW of polarized peak power. The excellent beam quality of the pump laser is transferred to the mid-IR at all output power levels. In the doubly resonant oscillator configuration (DRO), we have achieved total mid-IR output peak powers of ~28 kW with wavelength tuning from 3-5 µm (signal and idler). These results are, to the best of our knowledge, the highest mid-IR peak powers demonstrated with a Tm:fiber laser pumped ZGP OPO. The mid-IR conversion efficiency is >29% from this flat-flat OPO cavity. In order to provide idler tunability to wavelengths >5 µm, we utilize a flat-curved singly resonant oscillator (SRO) cavity. We are currently optimizing the SRO cavity in order to overcome the higher threshold of ~12 MW/cm2 and provide nanosecond pulses from ~2.5-8 µm at kHz repetition rate with sufficient pulse energy for ablation experiments. We intend to use this system as part of materials processing experiments to investigate on/off resonance ablation in the mid-IR.

8964-55, Session PTue

Mid infrared upconversion spectroscopy using diffuse reflectance

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We present a novel approach for mid infrared (mid-IR) spectral analysis using upconversion technology applied in a diffuse reflectance setup. We demonstrate experimentally that mid-IR spectral features in the 2.6-4 µm range using different test samples (e.g. zeolites) can be obtained. The results are in good agreement with published data. We believe that the benefit of low noise upconversion methods combined with spectral analysis will provide an alternative approach to e.g. mid-IR Fourier Transform microscopy. We discuss in detail the experimental aspects of the proposed method.

The upconversion unit consists of a PPLN crystal situated as an intracavity component in a Nd:YVO4 laser. When mixing incoming spectrally and spatially incoherent light from the test sample with the high power intracavity beam of the Nd:YVO4 laser enhanced conversion efficiency results. The upconverted light is spectrally located in the near infrared (NIR) wavelength region easily accessible for low noise Silicon CCD camera technology. Thus the room temperature upconversion unit and the Silicon CCD camera replaces noisy mid infrared detectors used in existing Fourier Transform Infrared spectroscopy.

We demonstrate specifically that upconversion methods can be deployed using a diffuse reflectance setup where the test sample is irradiated by a thermal light source, i.e. a globar. The diffuse reflectance geometry is particularly well suited when a transmission setup cannot be used. This situation may happen for highly scattering or absorbing samples.

8964-56, Session PTue

Near diffraction limited mid-IR spectromicroscopy using frequency upconversion

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Mid infrared microscopy and spectroscopy is interesting due to its medical, biological and chemical applications. Spectromicroscopy can be used for histopathology, sample analysis and diagnosis. The ability to do spectromicroscopy in the 2.5 to 4.5 µm wavelength range where many organic molecules have their fundamental vibrations, with the addition of sufficient spectroscopic resolution to resolve these bands, can potentially allow for diagnostics without the need for staining of the sample. On a longer timeframe mid-IR spectromicroscopy has the potential for in-vivo diagnostics, combining morphological and spectral imaging.

Recent developments in nonlinear frequency upconversion, have demonstrated the potential to perform both imaging and spectroscopy in the mid-IR range at unparalleled low levels of illumination, the low upconversion detector noise being orders of magnitude below competing technologies.

With these applications in mind, we have incorporated microscopy optics into an image upconverson system, achieving near diffraction limited spatial resolution in the 3 μm range. Spectroscopic information is further acquired by appropriate control of the phase match condition of the upconversion process.

Multispectral images for a region of interest can be obtained by XY-scanning this region of interest within the field of view of the mid-IR upconversion system. Thus, the whole region of interest can be imaged with all available converter wavelengths, and the spectral representation becomes equal for all points in the image. In addition, the range of converted/imaged wavelengths can be tuned continuously by changing the temperature of the crystal, or discretely by using a different poling channel in the PPLN crystal.

8964-57, Session PTue

Saturable absorption properties of multi-core nonlinear fiber arrays

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Present saturable absorber (SA) technologies have deficiencies that limit their usefulness in boosting up the pulse energy and peak power to higher values in mode-locked fiber lasers. An alternative saturable absorption method is to use nonlinear mode coupling in multi-core fibers; in these fibers neighboring cores exchange optical power at low intensities, while at high optical powers nonlinear effects alter the refractive index of each waveguide and reduce the effective couplings to neighboring cores. Thus for an optical pulse propagating through the fiber array,

its low intensity sides will be coupled to the neighboring cores while its high intensity peak remains in the launch core leading to a power-dependent transmission which is required for a saturable absorber.

In this work the saturable absorption performance of several one dimensional and two dimensional multi-core fiber array couplers are investigated as a function of the number of the fiber cores. The results indicate that the performance of all these saturable absorbers are comparable and two-core fibers produce sufficiently reasonable results. Thus increasing the core numbers of a two-core fiber nonlinear coupler will just make the device more complex, while its saturable absorption performance will not be improved significantly.

The reason is that the power transmission curves for all of the studied multi-core fiber couplers

are quite similar. Our observation is further supported by the comparable pulse characteristics obtained from the simulation of a generic mode-locked fiber laser cavity with each of these couplers used as SAs.

8964-58, Session PTue

500μJ femtosecond UV laser and top-hat pulse shaping

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Several applications require high energy femtosecond pulses in the UV, such as micromachining, chemical analysis (LIBS, ICPMS), or production of electrons using photocathodes. Solutions are usually based on solid-state ultrafast sources in the infrared, subsequently converted into the UV by SFG.

We report here a fully diode-pumped solution, based on an Yb ultrafast commercial source delivering 2mJ pulses with 500fs pulse duration at 1030nm central wavelength, efficiently converted by FHG to 258nm wavelength, ending to a UV pulse energy of 530μJ.

The infrared laser exhibits a 0,3% rms pulse-pulse stability, providing a UV stability of 0,6% rms, with a very good beam quality. Owing to the CW pumping operation of the femtosecond laser, the repetition rate is adjustable from single pulse to 1kHz with a constant pulse energy.

For applications requiring specifically top-hat temporal shape, we built a compact pulse shaping system. This system is based on passive components, and transforms the UV 500fs long Gaussian pulse shape into a nearly top-hat shape with adjustable pulse duration from 2 to 10ps. The temporal shape is measured using a cross-correlation system, giving a rise-time below 1ps, and amplitude modulations around 15%. The overall transmission efficiency of the pulse shaper is better than 70%.

8964-59, Session PTue

High energy Yb:CaF2 femtosecond laser for efficient terahertz generation in lithium niobate

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We present a study on intense Terahertz generation in lithium niobate cooled to different temperatures (down to 20 K) and pumped by a powerful Yb:CaF2 laser. The unique laser system delivers transform-limited pulses of variable duration (0.5-1 ps) with a pulse energy of up to 12 mJ at a center wavelength of 1030 nm. From theoretical investigations it is expected that those laser parameters are excellently suited for efficient THz generation. Here we present experimental results on both the conversion efficiency and the THz spectral shape for a series of transform-limited pump pulse durations and for different crystal temperatures and discuss the optimum pump parameters for most efficient THz generation.

8964-60, Session PTue

Continuously-tunable, broadband 40 ps pulse train generation source, from MHz to GHz applications

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Semiconductor optical amplifiers exhibit a nonlinear phase shift on their amplified signals, which is of interest in many signal processing applications as optical switching, wavelength conversion, clock recovery, etc. Our interest is focused on the short pulse train generation, which is the key element for further pulse compression in the highly tunable sub-ps pulse generation process. These versatile pulse sources have an important application in optical sampling processes.

We propose a method to generate pulse train with a huge tunability of repetition rate, from MHz to GHz range based on nonlinear amplification in a semiconductor optical amplifier (SOA). SOA induces a strictly negative nonlinear phase shift during the amplification of a dynamic signal. Hence, by filtering out negative frequencies beside the carrier of an amplified rectangular signal, we isolate the transitory signal of the induced-distortion signal train.

In this work, we demonstrate the generation of 40 ps pulses with repetition frequency from 1 MHz to 5 GHz with continuous tunability.

Other analysis to support the best knowledge of the non-linear dynamics about this process was realized by methods such as duty cycle alteration and numerically signal spectrum reconstruction.

8964-61, Session PTue

Enhanced second harmonic generation in lithium niobate hexagonal micro-resonator via total internal reflection quasi-phase-matching

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Quasi-Phase-Matching (QPM) is used to enhance the efficiency of nonlinear interactions, such as second harmonic generation (SHG), in cases where full phase-matching cannot be applied. In certain cases, QPM can be achieved by utilising the relative Fresnel phase shift between the fundamental FW and second harmonic generated wave SH -induced upon total internal reflection (TIR) of the two waves at the reflecting interface- in order to compensate for the dispersion phase mismatch. Here, we propose and demonstrate TIR-QPM based SHG in an hexagonal nonlinear optical microcavity where the FW is resonantly enhanced, which sub-sequently increases the efficiency of the non-linear process while maintaining the small device size. Hexagonal optical microcavities are suggesting a favourable shape as they exhibit advantageous long input/output-coupling and this requirement is facilitated here by the avail-ability of realisable hexagonal optical cavities of superior optical quality fabricated by dif-ferential etching of inverted ferroelectric domains in lithium niobate crystals with associated large d33 coefficient for efficient SHG. The combined TIR-QPM effect in the hexagonal nonlinear resonator was studied by a simplified six-bounce trajectory model. The phase matching operational condition between FW and SH waves sets the constraints for obtaining the ideal cavity size for a given operational wavelength, by semianalytical solutions. FDTD model was used to validate successfully the simplified model and calculate the time evolu-tion of the SHG process. The performance is shown to be limited mostly by the reflection losses by cavity's facets which essentially limits the number of round trips and compromises the power build-up.

8964-62, Session PTue

Polarization evolution of laser filaments in air and the contribution of pre-filamentation propagation

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A major application of filamentation in air is remote nonlinear interactions and spectroscopy via direct or Raman scattering. Thus, it is essential to understand how the optical field is propagated at distances. We present an analysis of the polarization evolution with propagation in air, for 800 nm optical pulses (45 to 300 fs, and 9 to 30 mJ), initially prepared by a quarter-wave plate with various degrees of ellipticity.

For an initial polarization close to circular, dramatic change of light polarization (ellipticity and orientation) is observed, strongly dependent on the initial preparation (in vacuum or air), the pulse parameters and propagation length. We observe a change of polarization even for the shortest pulse width of 45fs, when alignment is mostly neglected. We also measure the contribution of pre-filamentation propagation by focusing the laser in vacuum before lunching it in air, through an aerodynamic window, as compared to focusing in air.

The filaments are prepared by focusing the beam with a 3 m focal length. The filament is attenuated by a thin quartz plate at grazing angle, which is followed by a rotating polarizer cube for polarization analysis.

We confirm that nonlinear effects in air modify laser light parameters before filamentation occurs, as was already established for the generation of new spectral component. Our results were in good agreement with Close1996 that circular polarization is modified by molecular orientation; cross-phase modulation results in stronger self-focusing of the weaker polarization component, resulting in an elliptical polarization along that weaker axis.

8964-63, Session PTue

Multi-watt frequency divide-by-three optical parametric oscillator

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All-optical frequency dividers were proposed in 1990 for high-precision optical to microwave metrology . Important demonstrations in this direction have been done with KTP-based divide-by-2 and PPLN-based divide-by-3 doubly resonant parametric oscillators (DRO) systems. Furthermore, although DRO's oscillation threshold is lower than a singly-resonant parametric oscillator (SRO), SROs provide better amplitude and spectral stability and control. So SRO might be a viable alternative to build an all-optical frequency divide-by-3 divider.In summary, we have succeeded in constructing a multi-watt divide-by-three CW SRO, and the beat frequency between signal wave and externally frequency-doubling idler wave can reach 9 MHz.

8964-64, Session PTue

Supercontinuum pulse train fluorescence technique: triplet state dynamics determination

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It is well-known that the optical properties of molecules are determined mainly by their electronic structure and dynamics, and consequently, it is of great interest to investigate their electronic states from both fundamental and practical point of views. The importance of obtain precisely information of about the intersystem crossing rate and the triplet state quantum yield have been subject of many works. In this way, the present work introduces an interesting method in which the fluorescence induced by a set of white-light supercontinuum pulses produced by a special Ti:sapphire amplified laser system (1 kHz, 40 fs, 800 nm) is used to determine the excited-state dynamics. Such laser system produces a train pulses equally spaced by about 10 ns. Each pulse has an energy following an envelope similar of one of Q-switched modelocked laser. This supercontinuum pulse train fluorescence technique allows exciting the material at different wavelengths ranged between 450 until 750 nm, just by using a simple tunable filter, for instance, which replace a more complicated tunable-laser system such as an OPA. Because of the pulse train shape, this technique allows measuring signal at function of pulse intensity and probe delay in a single measurement without any beam overlap problem. In order to evaluate this technique, we carried on measurements in four distinct porphyrins, which have been characterized previously by other well-known nonlinear techniques. Additionally, this technique has resolution time of about few microseconds which could be used to determine the phosphorescence relaxation time as well.

8964-65, Session PTue

Difference frequency generation of Mid-IR radiation in PPLN crystals using a dual-wavelength all-fiber amplifier

Karol Krzempek, Grzegorz J. Sobon, Jaroslaw Z. Sotor, Grzegorz

Dudzik, Krzysztof M. Abramski, Wroclaw Univ. of Technology (Poland)

We present a method of generating mid-IR radiation by means of nonlinear difference frequency generation (DFG) effects occurring in periodically polled lithium niobate (PPLN) crystals using an all-fiber dual-wavelength amplifier. The presented mid-IR laser source incorporates an unique double-clad (DC) Erbium and Ytterbium doped amplifier stage capable of simultaneous amplification of both wavelengths required in the DFG process - 1064 nm and 1550 nm. The amplifier delivered more than 23.7 dB and 14.4 dB of amplification for 1550 nm and 1064 nm wavelength, low power, off-the-shelf, fiber pigtailed, distributed feedback (DFB) laser diodes, respectively. The dual-wavelength amplifier parameters crucial for the DFG process were investigated, including long-term power and polarization instabilities and optical spectrum characteristics of both amplified wavelengths. The DFG setup used a single collimator radiation delivery scheme and an 40 mm long MgO doped PPLN crystal. In effect the DFG source was capable of generating 1.14 mW of radiation centered around 3.4 µm. The overall performance of the mid-IR source was elaborated by performing sensitive Tunable Diode Laser Absorption Spectroscopy (TDLAS) detection of methane (CH4) in ambient air on an free-space optical path-length of 8 m. The measured detection limit of the sensor was 26 ppbv with a 1? SNR of 69.

8964-66, Session PTue

Nonlinear refraction in rutile TiO2

Sarah Griesse-Nascimento, Harvard School of Engineering and Applied Sciences (United States); Christopher C. Evans, SeungYeon Kang, Orad Reshef, Michael G. Moebius, Eric Mazur, Harvard Univ. (United States)

Titanium dioxide (TiO2) has attractive optical properties for nonlinear optical applications ranging from telecommunication to interconnect wavelengths (800–1600 nm). TiO2 has large linear and nonlinear indices of refractions as well as wide transparency from infrared to wavelengths as short as 400 nm. In addition, the low two-photon absorption for wavelengths longer than 800 nm makes TiO2 a promising material for telecommunication and interconnect wavelength bands. To understand the potential applications across a wide spectrum, we study nonlinear refraction and multiphoton absorption in bulk rutile TiO2 using the Z-scan technique. An optical parametric amplifier allows us to probe TiO2 over wavelengths ranging from 800–1600 nm. Using closed-aperture Z-scan, we investigate nonlinear refraction for these wavelengths. We extract values for the nonlinear index of refraction by fitting our data to a standard Z-scan model. We report on the birefringence in nonlinear index of bulk rutile. In addition, we investigate multiphoton absorption using the open-aperture Z-scan technique. Using these results, we compare the dispersion of the nonlinear index of refraction to theoretical predictions. We calculate nonlinear figures of merit and then discuss the feasibility of ultra-fast optical devices in TiO2 with extended wavelength compatibility.

8964-67, Session PTue

Theoretical analysis of effect of pump and signal wavelengths on modal instabilities in Yb-doped fiber amplifiers

Shadi A. Naderi, Iyad Dajani, Timothy Madden, Air Force Research Lab. (United States); Thien-Nam Dinh, Univ. of Delaware (United States)

We present, using numerical simulations, investigations of the modal instabilities thresholds in high-power Yb-doped fiber amplifiers as functions of signal and pump wavelengths. These amplifiers are typically pumped at 976 nm. The amplified signal is typically generated around 1064 nm. It is generally agreed upon that the onset of these instabilities is a result of interplay between thermal effects and modal interference. Quantum defect which is dependent on the pump and signal wavelengths is the source of the generated heat. We use a time-dependent temperature solver coupled to the optical fields and population inversion equations to determine the temporal dynamics of the modal content of the signal as well as the modal instabilities threshold. Our numerical code is parallelized to achieve fast computations; thus allowing us to perform detailed numerical studies of fiber amplifiers ranging in lengths from 1-20 meters using various pump and seeding wavelengths. Notably, we examine the modal instability threshold of a gain fiber pumped using fiber lasers operating at 1018 nm; similar to the multi-kilowatt single-mode fiber laser demonstrated by IPG. Furthermore, we investigate the modal instability threshold of a fiber seeded with combination of seed wavelengths and allowing for laser gain competition to provide the output in the desired wavelength. This technique, which has been shown to suppress SBS, generates a temperature profile that significantly deviates from the temperature profile of a co-propagating fiber amplifier seeded with a single wavelength. Consequently, the modal instability threshold of the amplifier can be altered using this technique.

8964-68, Session PTue

Pump suppressed four-wave mixing in optical fibers for correlated photon generation using feedback technique

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Four-wave mixing (FWM) in highly-nonlinear fibers (HNLFs) is used to generate correlated photon pairs. Typically, a strong pump, launched into an HNLF generates signal and idler photons by spontaneous FWM. However, in these experiments, only a fraction of pump power (~5%) is gainfully converted into signal and idler photons. The residual pump power at the output of HNLF must be suppressed by more than 80-90dB to obtain high-fidelity correlated photons. Fiber-Bragg gratings are used to suppress pump power in FWM experiments. In order to achieve high values of suppression, FBG reflectivity at pump wavelength must be better than 99%. Such high-reflectivity imposes stringent requirements on the FBGs.

We describe a technique to increase pump suppression by feeding the residual pump back to the input of the HNLF. An optical amplifier in the feedback path amplifies the pump; the forward and feedback pump are combined using a 3dB coupler and launched into the HNLF.

In our setup, two pumps at wavelengths 1549.70 and 1549.85nm are combined using a 50:50 coupler and fed to a HNLF (length 1km, nonlinear coefficient of 12.4/W-km, and zero dispersion wavelength (ZDW) of 1513nm). Without feedback, we obtained ratios of -21 dB and -20.6 dB for signal and idler components respectively. After pump suppression by FBGs (center wavelengths: 1549.70nm and 1549.85nm and reflectivity: 95% and 96% respectively), the ratio increases to -14.08dB and -12.18dB respectively. With the residual pumps fed back to the HNLF, the ratio improved to -7.54 and -8.6dB for signal and idler to pump.

8964-19, Session 5

All-optical signal regeneration of advanced modulation formats *(Invited Paper)*

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With growing demand on transmission capacity, spectral-efficient multilevel modulation formats like quadrature amplitude modulation (QAM) become of great interest. One of their major drawbacks is the high sensitivity to noise accumulation, especially in long-haul transmission systems.

Our studies have shown, for the first time to our knowledge, the possibility of all-optical regeneration of multiple amplitude and phase states.

The periodicity of the interference conditions in modified nonlinear fiber Sagnac interferometers provides a staircase-like power transfer characteristic which can be used for phase-preserving amplitude regeneration of multiple amplitude states. Processing of QAM with up to three none-zero amplitude states, e.g. 16QAM, has been demonstrated in numerical simulations. Furthermore, simultaneous amplitude regeneration of a star-8QAM format with two amplitude states was performed experimentally.

Recently, it has been shown that phase-sensitive amplification for multiple phase states can be realized in fiber optical parametric amplifiers using four-wave mixing (FWM) with high-order idler. Our numerical simulations and experimental results for star-8QAM revealed that this approach can be used for reduction of phase noise in multilevel phase-shift keying also for signals with multiple amplitude states.

The transmission improvement using a cascade of these two regenerators has been demonstrated in numerical simulations and experiments. In both cases noise was reduced. Numerical investigations also confirm the possibility to combine both in one device by using the highly nonlinear fiber in the Sagnac interferometer loop simultaneously for phase-sensitive amplification in one propagation direction.

8964-20, Session 5

Generation of low-noise frequency replicas in parametric frequency combs via phase-sensitive process *(Invited Paper)*

Zhi Tong, Lan Liu, Stojan Radic, Univ. of California, San Diego (United States)

The ability to replicate (or multicast) an incoming optical signal in frequency domain without loss of fidelity is a holy grail for both fundamental physics and practical applications spanning from telecommunications to quantum processing. Dual-pump driven four-wave mixing in dispersion-engineered waveguides (e.g. optical fiber) is able to generate a large number of signal copies via optical frequency comb generation at precisely defined frequencies, in an ultrafast and coherent manner, however, this phase-insensitive (PI) parametric process also induces excess noise, which scales with the copy count under the ideal phase-matching condition. The reason for noise scaling in PI multicasting relies on the fact that with ideal phase matching (i.e. zero dispersion in the parametric device (or mixer), all generated copies couple the same amount of quantum noise to each replica frequency, provided these copies are power equalized. We have found that this conclusion does not apply to mixers with small normal dispersion: conversely, the replica noise-figure (NF, defined as the ratio between the output and input signal-to-noise ratio) eventually approaches 6 dB, rather than scaling upward with increased copy creation. This discovery indeed points out possible direction towards low-noise or even noiseless spectral replication: parametric multicasting using multi-mode phase-sensitive (PS) process in highly-efficient mixer with finite normal dispersion. In this talk, we review the basic principle and realization of low-noise, four-mode PS multicasting. Recent experimental results of such multicaster in comparison to conventional EDFA preamplifiers are also demonstrated. Moreover, potential applications and technical challenges are discussed.

8964-21, Session 5

Mode-selective frequency up-conversion in a chi(2) waveguide

Young B. Kwon, Michael Vasilyev, The Univ. of Texas at Arlington (United States)

Parametric amplification and frequency conversion of spatially-multimode light have been recently gaining attention in both classical and quantum signal-processing contexts, owing mostly to the emergence of the space-division multiplexing and mode-division multiplexing communication systems. Multimode parametric amplifiers could be an attractive solution for inline amplification in these systems, whereas “1550-nm-to-visible” frequency converters can be used to improve the single-photon detection efficiency and to discriminate among various spatial modes.

This paper focuses on such a frequency converter implemented in a waveguide in order to achieve good power efficiency. We study sum-frequency generation (SFG) in a 20x4 sq. micron multimode periodically-poled KTP waveguide. We show that under proper quasi-phase-matching, it can support one of the two spatial-mode-selective up-conversion scenarios. In the first scenario, a single pump mode can up-convert several different signal modes to different SFG modes, which is similar to an image up-conversion. In the second scenario, one pair of signal and pump modes is converted to an SFG mode and, at the same time, a different pair of signal and pump modes is up-converted to the same SFG mode. In that case, by adjusting the relative phases and magnitudes of the two pump modes, one can select for up-conversion any superposition of the two corresponding signal modes, without affecting the orthogonal superposition or any other modes. The latter scenario can be used for dynamically reconfigurable spatial-mode demultiplexing in both classical and quantum communications.

8964-22, Session 6

Effect of pump coherence on third-order nonlinear processes

Stephane Virally, Nicolas Godbout, Ecole Polytechnique de Montréal (Canada)

Third-order nonlinear processes are routinely observed when high power pumps propagate in optical fibers. At any given time, there exists a variety of such processes competing for pump power. We show that some nonlinear processes can be more efficiently produced when an incoherent pump is used, as other competing processes are suppressed.

In order to model the nonlinear propagation of an incoherent pulse, we extend the quantum mechanical concept of the density matrix to the classical realm. We derive the propagation equations for the density matrix from the well-known propagation equations of the amplitudes in the coherent case. This constitutes a theoretical basis for incoherent nonlinear optics. Contrary to previous treatments of incoherent pulse propagation in the nonlinear case, this model is not statistical in nature. In particular, numerical analysis can be performed without random seeding.

Using the new model, we show that some nonlinear processes actually benefit from the lack of coherence of the pump. This counterintuitive effect is produced thanks to the suppression of competing processes that require a higher degree of coherence. We show in particular, both numerically and experimentally, that scalar modulation instabilities can be suppressed by self-phase modulation when the pump is coherent. In contrast, when an incoherent pump is used, self-phase modulation is greatly inhibited and scalar modulation instabilities can fully develop.

8964-23, Session 6

Influence of fiber laser pump conditions at 1550 nm on broadband infrared supercontinuum generation in all-solid all-normal dispersion photonic crystal fibers

Mariusz Klimczak, Bartlomiej Siwicki, Institute of Electronic Materials Technology (Poland); Grzegorz J. Sobon, Jaroslaw Z. Sotor, Wroclaw Univ. of Technology (Poland); Dariusz Pysz, Ryszard Stepien, Institute of Electronic Materials Technology (Poland); Tadeusz Martynkien, Krzysztof M. Abramski, Wroclaw Univ. of Technology (Poland); Ryszard R. Buczynski, Univ. of Warsaw (Poland) and Institute of Electronic Materials Technology (Poland)

Supercontinuum generation (SG) in photonic crystal fibers (PCFs) usually takes advantage of soliton dynamics, when pump wavelength is located in the anomalous dispersion region near the zero-dispersion wavelength of the fiber [1]. This results in broader bandwidth than pumping in the normal dispersion region (NDR). SG in NDR is of interest, because of its potential for high degree of coherence and low intensity fluctuations. It was experimentally demonstrated in silica fibers and PCFs pumped around 1000 nm, covering the visible and near-infrared [2,3].

We developed an all-solid PCF with hexagonal lattice made from N-F2 capillaries, with lattice constant ?=2.275µm, filling factor d/?=0.9, and a solid N-F2 core with 2,5µm diameter. The capillaries were filled with thermally matched borosilicate glass rods with lower refractive index. The PCF has all-normal dispersion, flattened within 1400-1270 nm (-35 to -29 ps/nm/km) and a local maximum of -29 ps/nm/km at 1550 nm. Measured attenuation in 1500-1600 nm is around 3.2 dB/m. Nonlinear coefficient calculated at 1550 nm is 17/W/m. We numerically investigate the evolution of supercontinuum formation with a maximum bandwidth of 900-2400 nm. Considered pump pulse lengths were between 1 ps and 50 fs, with corresponding peak powers from 20kW to 200kW. Measured coupling efficiency using 20x microscope objective was 50%. One-photon-per-mode noise was used to simulate pump noise and multi-shot SG spectra were calculated. Preliminary experimental results are in good agreement with developed model.

[1] J.M.Dudley et.al., Rev.Mod.Phys. 78, 1135.

[2] A.M.Heidt et.al., Opt.Express 19,3775

[3] R.Song et.al., Laser Phys.Lett. 10, 015401

8964-24, Session 6

Fiber laser driven dual photonic crystal fiber femtosecond mid-infrared source tunable in the range of 4.2 to 9 ?m

Yuhong Yao, Wayne H. Knox, Univ. of Rochester (United States)

We report a novel approach to tunable femtosecond mid-IR source based on difference frequency mixing of the outputs from dual photonic crystal fibers (PCF) pumped by an ytterbium fiber chirped pulse amplifier. The source amplifier delivers 1.3 W, 1035 nm, 300 fs pulses at 40 MHz. It is split into two and used to pump two different types of PCFs for generating spectrally separated pulses. The shorter wavelength pulses are generated in one PCF with single zero dispersion wavelength (ZDW) at 1040 nm. Low dispersion around the pumping wavelength enables spectral broadening dominated by self-phase modulation (SPM), which extends from 980 to 1090 nm with 315mW of average power. Longer wavelength pulses are generated in a second PCF which has two closely spaced ZDWs at 1010 and 1075 nm. Facilitated by its special dispersion profile, the pump wavelength is converted to the normal dispersion region at 1260 nm via four wave mixing (FWM), resulting in the narrow-band intense Stokes pulses with up to 60 mW of average power. By difference frequency mixing the outputs from both PCFs in a type-II, 2 mm thick AgGaS2 crystal, mid-IR pulses tunable from 4.8 to 8.2 µm are generated with average power ranging from 200 – 560 µW, corresponding to 5 – 14 pJ of pulse energy, which is comparable to reported fiber based approaches. This novel method employing SPM and FWM in fiber is scalable, which we believe to be a promising solution for developing compact broadband femtosecond mid-IR sources.

8964-25, Session 6

Investigations of SBS and laser gain competition in high-power phase modulated fiber amplifiers

Angel Flores, Iyad Dajani, Air Force Research Lab. (United States); Dane W. Hult, Trex Enterprises Corp. (United States)

We present experimental results of SBS suppression in high power, monolithic, Yb-doped fiber amplifiers via dual wavelength seeding. The superior SBS mitigation is based on two-tone laser gain competition between a combination of broad and narrow linewidth laser signals. Notably, the two-tone concept has been theoretically and experimentally shown to provide a 2x-3x enhancement in SBS over single-tone fiber amplifiers. In addition, the two-tone concept can be used in combination with additional SBS mitigation schemes such as external phase modulation to achieve enhanced nonlinear suppression. In this work, we extend the two-tone concept to higher-powers using a narrow line (phase modulated) 1064 nm seed in conjunction with a broadband 1036 nm seed source. Here a pseudo-random binary sequence (PRBS) phase modulation scheme is used to spectrally broaden the laser signal for additional SBS mitigation. Consequently, through integration of both two-tone and PRBS concepts, SBS enhancement factors of greater than 12 dB were achieved in an 8.5 meter long Nufern 25/400 fiber at a linewidth of 500MHz. A pump-limited output power of 500W was attained without reaching the SBS threshold. Ideal seeding ratios between the 1036nm and 1064nm seed sources leading to optimal SBS suppression will be discussed. Significantly, the results represent a near order of magnitude reduction in both SBS and laser linewidth over current state of the art high power, monolithic, fiber amplifiers. Moreover, the pump- limited results were attained without the onset of SBS and ongoing experimental work at higher pump powers will be discussed.

8964-26, Session 6

Second-order coherence measurement of supercontinuum

Mikko Närhi, Tampere Univ. of Technology (Finland); Minna M. Korhonen, Jari Turunen, Ari T. Friberg, Univ. of Eastern Finland (Finland); Goëry Genty, Tampere Univ. of Technology (Finland)

Supercontinuum generation has been the subject of intense research in the past decade. This has arisen not only because of the complex nonlinear dynamics involved in the generation of these broadband spectra but also because of the wide range of potential applications ranging from spectroscopy, metrology and communications to remote sensing and advanced imaging. A central property of supercontinuum sources is their coherence that ultimately limits the field of application. For example, in metrology perfect coherence between the comb teeth is paramount whilst for imaging it is the spectral bandwidth that determines the resolution and incoherent sources are perfectly adapted.

Recently, it was shown theoretically that the second-order coherence properties of supercontinuum reveal additional intrinsic characteristics associated with the shot-to-shot intensity and phase fluctuations that are not captured by the usual first-order degree approach. Specifically, the second-order approach allows to separate the coherence properties into two distinct contributions whose relative magnitude depends on the input pulse parameters used to generate the supercontinuum: a quasi-coherent

contribution where fluctuations are negligible and a quasi-stationary part where the extreme fluctuations destroys the coherence.

Here, we report the first experimental measurement of the second-order coherence properties of supercontinuum in optical fibers. Using a combination of interferometry and cross-correlation frequency optical gating we capture both the coherent and quasi-stationary contribution to the second-order coherence functions, both in the frequency and time domain. Our results open up the way for sources of on-demand temporal and spectral correlations with optimized performance in broadband imaging and sensing applications.

8964-27, Session 7

SWIR and MIR super-continuum lasers and field trial results *(Invited Paper)*

Mohammed N. Islam, Univ. of Michigan (United States)

Super-continuum (SC) lasers combine the broadband attributes of lamps with the spatial coherence and high brightness of lasers. Short-Wave Infrared (SWIR) and mid-infrared SC lasers will be described that are all-fiber integrated SC lasers with no moving parts and that can be built using commercial-off-the-shelf components. The SC laser architecture is simplified by exploiting a modulational-instability initiated mechanism to generate SC using the nature physics of the fiber (Fig. 1).

A mid-infrared SC laser (MISCL) has been developed that can span the wavelength range between about 0.8 and 4.5 microns. One version of this MISCL is based on an erbium/ytterbium doped power amplifier (Fig. 2), while a second version is based on a thulium-doped power amplifier (Fig. 3). Prototypes of the two lasers have been made for use in government laboratories. One application of the MISCL is as the jammer laser in an infrared counter-measures system.

As another example, a power scalable Thulium doped fiber amplifier based SC laser covering the SWIR from 2-2.5 ?m is demonstrated. The SC laser has an average power up to 25.7 W and a spectral density of >12dBm/nm. Power scalability of the laser is proven by showing that the SC laser maintains a nearly constant spectral output, beam quality (M2 measurements) and output spectral stability as the SC average power is scaled from 5W to 25.7W average output power. The SC laser beam is shown to have a nearly diffraction limited with an M2<1.2 for all power levels. Output spectral stability measurements with power scaling show a radiometric variability of <0.8% across the entire SC spectrum.

Finally, results of a field trial of a 5W SWIR-SC (Fig. 4) covering the wavelength range from ~1.55 to 2.35 ?m will be presented. The SC laser is kept on a twelve story tower at the Wright Patterson Air Force Base (WPAFB) and propagated through the atmosphere to a target 1.6 km away (Fig. 5). Beam quality of the SC laser after propagating through 1.6 km is studied using a SWIR camera and shows a near diffraction limited beam, with an M2 value of < 1.3. The SC laser is used as the illumination source to perform spectral reflectance measurements of various samples at 1.6 km, and the results are seen to be in good agreement with in-lab measurements using a conventional lamp source. Spectral stability measurements are performed after atmospheric propagation through 1.6km and show a relative variability of ~4-8% across the spectrum depending on the atmospheric turbulence effects. Spectral stability measurements are also performed in-lab and show a relative variability of < 0.6% across the spectrum.

8964-28, Session 7

Mid-IR supercontinuum generation using nanospike chalcogenide-silica fibers *(Invited Paper)*

Markus A. Schmidt, Institut für Photonische Technologien e.V. (Germany); Nicolai Granzow, Philip St. John Russell, Max-Planck-Institut für die Physik des Lichts (Germany)

Chalcogenide nanowires inside silica fibers represent a new approach to implement highly nonlinear fibers. We fabricated arsenic trisulfide hybrid fibers with aspect ratios > 2000. At the input the chalcogenide core is inversely tapered down to diameters below 100nm, forming a 300?m long nanospike. Adiabatic mode conversion along this spike increases the in?coupling efficiency of the 2?m pump light (65fs) by a factor of 60. The core diameter in the 2?mm?long untapered section is kept constant at 1?m. Strong supercontinuum generation, spanning more than one octave and extending out to 4?m, was observed at pulse energy of only 18pJ.

8964-29, Session 7

Broadband IR supercontinuum generation in hexagonal lattice tellurite photonic crystal fiber with dispersion optimized for pumping over 1500 nm

Mariusz Klimczak, Grzegorz Stepniewski, Institute of Electronic Materials Technology (Poland); Henry T. Bookey, Heriot-Watt Univ. (United Kingdom); Dariusz Pysz, Institute of Electronic Materials Technology (Poland); Andrew J. Waddie, Heriot-Watt Univ. (United Kingdom); Ryszard Stepien, Institute of Electronic Materials Technology (Poland); Ajoy K. Kar, Mohammed R. Taghizadeh, Heriot-Watt Univ. (United Kingdom); Ryszard R. Buczynski, Univ. of Warsaw (Poland) and Institute of Electronic Materials Technology (Poland)

Tellurite glass photonic crystal fibers (PCF) offer a large potential for broadband supercontinuum generation with bandwidths of 4000 nm demonstrated in suspended-core tellurite PCFs under pumping at 1500-1600 nm [1].

We fabricated a hexagonal-lattice, tellurite PCF with lattice constant ? = 2 µm, linear filling factor d/?=0.75 µm, and a solid core with 2.7 µm diameter. Dispersion, calculated from SEM image of drawn fiber, has ZDW at 1500 nm and 4350 nm with a maximum of 193 ps/nm/km at 2900 nm. Under pumping with 150 fs / 36 nJ / 1580 nm pulses, supercontinuum in a bandwidth from 800 nm to over 2500 nm was measured in a 2 cm long PCF sample. Measured coupling efficiency was 8%. Dispersive and nonlinear length scales are 52 cm and 0.2 mm respectively, yielding nonlinearity-dominant propagation regime in the fiber. Numerical analysis of measured supercontinuum spectrum using NLSE, enabled identification of soliton fission and their subsequent red-shifting, dispersive wave generation across first ZDW, as well as FWM among the red-shifted spectral components. FWM phase-matching condition in the fiber is satisfied in a broad range from 1500 nm to 4000 nm with roughly 900 nm bandwidth around the signal wavelength. Developed model is in good agreement with experimental results. Model is used to estimate supercontinuum bandwidth for other experimental conditions with pump pulse lengths up to 1 ps and PCF lengths up to 10 cm.

[1] P. Domachuk et.al., Opt.Express 16, 7161

8964-30, Session 7

500-MHz-rep-rate mid-IR frequency comb produced in a fractional sync-pumped optical parametric oscillator

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High repetition rate frequency combs in the mid-infrared (mid-IR), or 'molecular fingerprint' region, allow the extension of well-established near-IR applications, such as optical metrology, time-resolved spectroscopy and astronomical spectrograph calibration [1]. As shown previously, when pumped with a near-IR frequency comb, degenerate OPOs preserve the salient characteristics of the near-IR pump [2]. In this paper, we use a commercial 1.56-?m frequency comb source with a 100-MHz repetition rate to pump a fractional (1:5) length synchronously pumped subharmonic OPO, based on periodically poled lithium niobate (PPLN), to generate a spectrally broad mid-IR frequency comb centered around 3.1?m while simultaneously increasing the repetition rate by a factor of 5. For a synchronously pumped OPO, the cavity round-trip time is typically equal to the period of the pump pulses. By reducing the cavity length by a rational fraction of this period, the repetition rate can be increased. In this experiment, the cavity length of the ring-type OPO was 60 cm resulting in an output repetition rate of 500 MHz. We used a chirped mirror specifically designed to compensate the dispersion of 1-mm-long piece of PPLN. Output coupling was achieved using a pellicle beamsplitter. The maximum achieved output of the OPO was 6.5 mW with a temporal pulse width of 109 fs and a spectral bandwidth of 144 nm. Assuming each output pulse was identical in time and frequency, we estimated the chirp of the pulses and calculated a time-bandwidth product of 0.65, suggesting the Gaussian pulses were slightly chirped.

8964-31, Session 7

Mid-infrared supercontinuum generation using lead-bismuth-gallium-oxide glass-based photonic crystal fibers pumped at 1560 nm

Grzegorz J. Sobon, Wroclaw Univ. of Technology (Poland); Mariusz Klimczak, Institute of Electronic Materials Technology (Poland); Jaroslaw Z. Sotor, Karol Krzempek, Wroclaw Univ. of Technology (Poland); Dariusz Pysz, Ryszard Stepien, Institute of Electronic Materials Technology (Poland); Tadeusz Martynkien, Grzegorz Dudzik, Krzysztof M. Abramski, Wroclaw Univ. of Technology (Poland); Ryszard R. Buczynski, Institute of Electronic Materials Technology (Poland) and Univ. of Warsaw (Poland)

Broadband supercontinuum sources spanning from the near to mid-infrared spectral regions find many applications in the field of spectroscopy and sensing. Up till now usually silica-based photonic crystal fibers (PCF) were used as nonlinear media for visible and near-infrared supercontinuum generation. However, the transmission of silica glass is strongly limited to around 2.4 µm. Soft-glass PCFs seem to be an interesting alternative for silica fibers thanks to their fabrication flexibility for the creation of mid-infrared supercontinuum sources. In this paper we present results on supercontinuum generation in a PCF fabricated from lead-bismuth-gallium-oxide glass (PBG-08) pumped at 1560 nm wavelength. The PBG-08 glass, synthetized in our labs and selected for PCF development has the following composition [mol%]: 40% SiO2, 30% PbO, 10% Bi2O3, 13% Ga2O3, 7% CdO. It has a transmission window between 400 nm and 6000 nm, a high refractive index (about 2.0) and a high nonlinear refractive index n2 = 4.3 ? 10?19 m2/W measured using the z-scan method at 1240 nm wavelength. The nonlinear refractive index value for PBG-08 is very high for oxide soft glasses and is much higher than that reported for any other oxide glass used in mid-infrared supercontinuum generation. PBG-08 is also suited for crystallisation-free fiber drawing. In our experiment, a short-length piece of PCF (4-5 cm) is pumped by a chirped pulse amplification (CPA) setup, which is seeded by a graphene-based mode-locked Er-doped fiber laser. Broad supercontinuum spanning from 900 to 2400 nm can be obtained at pulse energies lower than 20 nJ.

8964-69, Session 7

Mid-infrared frequency comb generation using a continuous-wave pumped optical parametric oscillator

Markku M. Vainio, Univ. of Helsinki (Finland) and Ctr. for Metrology and Accreditation (Finland); Ville Ulvila, Univ. of Helsinki (Finland); Christopher R. Phillips, ETH Zurich (Switzerland); Lauri Halonen, Univ. of Helsinki (Finland)

We report a mid-infrared frequency comb generator, which produces up to 3 W of output power. The comb mode spacing is 208 MHz, the spectral bandwidth is ~300 GHz, and the center wavelength is tunable between 3 and 3.4 µm. The comb generation is based on intracavity difference frequency mixing between near-infrared pump and signal beams of a continuous-wave-pumped optical parametric oscillator. The signal beam, which is resonant in the cavity, acquires a comb structure through cascading quadratic nonlinearities in a periodically poled lithium niobate crystal. This comb structure is transferred to the spectrum of the mid-infrared idler beam via the difference frequency mixing process.

8964-32, Session 8

Directly laser written chalcogenide photonics devices *(Invited Paper)*

Ajoy K. Kar, Heriot-Watt Univ. (United Kingdom)

A focussed ultrashort laser pulse can modify the local refractive index of certain materials, significant research has been expended into using ultrafast lasers to fabricate integrated optical devices. Integrated optical waveguides – the optical analogue of wires – can be simply fabricated by translating the sample in the path of such short optical pulse trains, which effectively amounts to fabricating the desired optical circuit in a controlled way in the liner and nonlinear optical materials. This direct-write approach offers several key benefits over conventional fabrication techniques. It neither requires use of expensive clean room facilities, nor involves complex film deposition and subsequent etching processes. This technology can also yield 3D structures, unachievable through any other technologies.

In my talk I will present how the ultrafast laser inscription technology can be used to develop components like lasers and supercontinuum sources in chalcogenide glasses. I will also describe how all-optical devices could be monolithically integrated into a substrate in the form of optical integrated circuits sensing applications.

8964-33, Session 8

Sensitive absorption measurements in bulk material and coatings using a photothermal and a photoacoustic spectrometer

Stephan Fieberg, Niklas Waasem, Frank Kühnemann, Fraunhofer-Institut für Physikalische Messtechnik (Germany); Karsten Buse, Fraunhofer-Institut für Physikalische Messtechnik (Germany) and Univ. of Freiburg (Germany)

The availability of high-power pump lasers has made nonlinear frequency conversion processes more and more effective. With increasing pump powers, however, even weak absorption in optically nonlinear components due to residual impurities or crystal imperfections may lead to thermal or mechanical malfunction of the devices. Proper characterization of the materials is of scientific interest and practical relevance.

Absorption spectra in lithium niobate (LiNbO3) and lithium triborate (LBO) crystals are measured using two complementary sensitive measurement techniques. A photoacoustic spectrometer (PAS) detects the pressure wave created by light-induced local heating of the sample. The second system, a photothermal common-path interferometer (PCI) is based on a pump-probe technique and measures the absorption via the light-induced thermal lens. Due to a crossed-beam setup it also differentiates between surface and bulk absorption.

Both spectrometers detect residual absorption down to 10(-5) cm(-1) and, using optical parametric oscillators (OPOs), cover the wavelength range from 212 – 2500 nm (pulsed, PAS) and 700 – 3900 nm (continuous-wave, PCI). The use of two independently calibrated systems, both tunable in the near-infrared wavelength regime, improves the precision of the measurements and the calibration.

The measurements reveal differences in the transparency for crystals obtained from different vendors, and in the case of LBO an induced absorption in the UV wavelength range becomes evident, which leads to a degradation of the material. The absorption spectra of LiNbO3 allow the identification of residual impurities like iron, hydrogen, and chromium.

8964-34, Session 8

Dielectric breakdown in periodically poled LiTaO3 crystal during second harmonic generation

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Periodically poled ferroelectric crystals such as LiNbO3 (LN) and LiTaO3 (LT) are widely used for a variety of laser frequency conversion processes. The theory of nonlinear optical con-version allows reliable efficiency prediction under low intensities. Under high intensities addi-tional effects are involved inhibiting non-linear conversion: two-photon absorption and multi-photon absorption resulting in electron generation into conduction band, heating, harmonics wave vectors mismatch, lensing, and inter-band defects generation many of which can be taken into account by performing rigorous computer simulations. It is generally accepted that in laser-matter interaction the electrons absorbing energy from the radiation dissipate this energy to the lattice and the equilibrium is established for laser pulses extending longer than the electron-to-lattice energy transfer time. We show that additionally to this process an opposite lattice-to-electron energy transfer takes place in nonlinear crystals.

We conclude that in the experiments for SHG of 532 nm radiation using a periodically poled SLT crystal the discharge and damage are due to the following mechanism: (i) the photo-absorption increase during SHG at the back side of the crystal induces (ii) an initial temperature increase of ≈1 K at the back of non-symmetric crystal lattice leading to (iii) a high gradient of the spontaneous polarization across the irradiated zone and (iv) to the onset of high electric field, enabling (v) acceleration of free electrons to the energy above the critical value, ≈1.5Eg ≈6.9 eV, followed by (vi) the impact ionization and structural damage of operating crystal.

8964-35, Session 8

Simultaneous three band CW laser by utilizing PPMgSLT devices

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Simultaneous three band (IR, visible, and UV) CW laser was demonstrated by combining fiber laser and 2 PPMgSLTs. In machining application, lasers have been dramatically utilized because of their rapid increase of powers. Especially, 1064nm (IR) and its harmonics such as 532nm (visible) and 355nm (UV) are the most popular. As a result, it becomes important to inspect related passive optics such as lenses and mirrors as a function of bulk, surface and coating properties. To precisely characterize them, it requires preparing corresponding wavelength lasers. The CW laser we demonstrate here realizes those laser sources (IR, visible, and UV) in one laser configuration. It mainly consists of 1064nm polarization maintain CW fiber laser and two PPMgSLTs. The 1064nm light from the fiber was collimated and focused into the 1st PPMgSLT (30mm long) for 532nm generation and after that focused into the 2nd PPMgSLT (10mm long) for 355nm generation with cascade single-pass configuration. Several dichroic mirrors were put properly and pure 1064nm, 532nm and 355nm CW lights were simultaneously obtained from each output port of laser head. Its head size was 100?45?160mm3. From 7W of input 1064nm light, we obtained 5W, 1W and 30mW of 1064nm, 532nm, and 355nm, respectively. Since the conversion efficiencies were less than 20%, the output beams of each wavelength were almost Gaussian. This type of multi-band CW laser could not be realized by conventional intra-cavity configuration and only be available by using PPMgSLTs, which have high power durability, high conversion efficiency and high transparency at UV.

8964-36, Session 8

An analysis of thermal effects in high power (8 W) KGW Raman lasers

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Double metal tungstate crystals such as potassium gadolinium tungstate (KGW) form an integral part of many modern laser systems, either doped as a gain element or as a Raman frequency shifter, and at times both. Recently, much effort has been directed towards mitigating thermal effects in high power doped (inversion) lasers [1]. To date, however, Raman laser powers of up to a few watts have been investigated [2], and the design considerations under high heat loads are not yet understood.

Here we report the laser performance for an extra-cavity Raman laser pumped at input powers up to 46 W and in a regime where thermal effects are extensive. We used a 1064 nm Q-switched laser generating 30 ns pulses at 38.6 kHz and a Raman laser configured for 1316 nm output. When operating at low duty cycle, more than 18 W was generated with slope efficiencies higher than 50%. Under continuous operation, a maximum output power of 8 W was obtained at much reduced efficiency and with highly asymmetric near and far-field beam properties.

We present a detailed characterization of the device and analysis of the thermal lens contributions. We find that the end-face bulging and thermo-optic contributions are symmetric about the b-axis propagation direction and tend to cancel each other. We show that the highly anisotropic thermal expansion coefficients in the transverse plane, and the resultant strain-induced photoelastic effects, are largely responsible for the strong asymmetry in Raman output. We discuss strategies for mitigating these thermal effects and compare results to recent advances in diamond which has starkly contrasting thermal properties.

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8964-38, Session 9

All-epitaxial growth of orientation-patterned GaAs and GaP waveguides

Peter G. Schunemann, Peter A. Ketteridge, Paul R. Moffitt, BAE Systems (United States)

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 will be presented.

8964-39, Session 9

HVPE growth of bulk orientation-patterned gallium phosphide (OP-GaP) on MBE templates

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Orientation patterned gallium phosphide (OPGaP) is an exciting new engineered nonlinear optical crystal for efficiently shifting widely available 1-micron laser sources deep into the mid-infrared. OPGaP templates were grown by molecular beam epitaxy (MBE) in a dedicated Varian Gen II MOD system. After growing a 200-nm-thick buffer layer on 3-inch GaP vicinal (100) substrate (4° off cut toward 111B), a 5-nm lattice-matched non-polar Si inversion layer was grown modified in a small auxiliary chamber equipped with a hi-temperature thermal silicon cell. A 5.4-nm-thick AlGaP smoothing layer was grown on the Si followed by growth of a 100-nm-thick GaP layer with an orientation inverted relative to that of the starting substrate (as verified by in situ RHEED measurements). The GaP inverted layer was then photolithographically patterned with grating periods ranging from 14.5 to 95.9 microns, then etched by reactive ion etching in BCl3 prior to simultaneous MBE regrowth of domains with alternating polarity. The resulting OPGaP templates were loaded into a commercial low-pressure hydride vapor phase epitaxy (LP-HVPE) reactor and thick quasi-phasematched layers (>300 microns) were grown at temperatures between 720°C and 820°C, 20 mbar reactor pressure, and V/III ratios between 2 and 3. Device crystals were cut, polished, and AR-coated for in-plane pumping by 1-micron and 2-micron solid state lasers. Preliminary results will be reported.

8964-40, Session 9

GaP refractive index measurements between 0.7 and 5.2 µm

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The refractive indices of GaP from 0.7 to 5.2 ?m were measured using the minimum-deviation method. A prism was fabricated from a 12-mm-thick slice from a 3-inch-diameter boule grown by LEC. A prisms was cut with 20x22 mm2 faces and an apex angle of 30 degrees bisected by the (001) axis with the (100) axis perpendicular to the triangular faces. At minimum deviation the input light was propagating perpendicular to the (001) axis. The output from either a mercury xenon lamp or an Oriel 7340 light source with an IR6363 glow bar heater was coupled into a CVI Model 240 1/4-m monochromator to provide the discrete wavelengths used in the experiment. Refracted beams in the 2–5-?m range were imaged with a BAE Cincinnati Electronics IRRIS 160 infrared camera that employs a liquid-nitrogen-cooled InSb array as its detector. A Moller–Wedel divided-circle spectrometer was used to obtain measurements of the prism apex angle and the angles of minimum deviation. The refracted beam was located on each side of the prism, and the minimum-deviation angle was calculated as half the difference between the two readings. The refractive index was then calculated for each measured minimum deviation angle with the standard formula. The temperature for all measurements was 22–25 °C. The resulting data points were fit to the following sellmeier equation with an error less than 2 x 10-4 at any individual wavelength: n2 = 3.04072 + 6.06463??????????????????????????

8964-41, Session 9

Laser damage studies of CdSiP2 and ZnGeP2 nonlinear crystals with nanosecond pulses at 1064 and 2090 nm

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CdSiP2 (CSP) is a very promising nonlinear crystal for the mid-IR spectral range with a nonlinear coefficient slightly larger than that of ZnGeP2 (ZGP). In contrast to ZGP, CSP is phase-matchable and can be employed in 1.064-µm pumped OPOs without two-photon absorption. Although low damage resistivity has been reported in such initial OPO tests of CSP, no reliable data on the damage-threshold of uncoated CSP exists. We compare in this work the damage resistivity of uncoated CSP with ZGP at two wavelengths, 2.09 µm (1 kHz, 21 ns) and 1.064 mm (100 Hz, 8 ns). The Q-switched Nd- and Ho-lasers used exhibited M2 parameter ~1.4. The spot sizes were comparable, 3-3.1?10-4 cm2 at 2.09 µm and 5.2-6?10-4 cm2 at 1.064 µm, respectively. The ~2-mm thick samples were illuminated for 30 s (30000 shots) at 2.09 µm and for 1 min (6000 shots) at 1.064 nm following the R-on-1 ISO procedure. 11 (12) sites were tested in CSP (ZGP) at 2.09 µm and 24 (14) sites in CSP (ZGP) at 1.064 µm. Damage occurred only on front surface in ZGP but also on rear surface in CSP. The 0% damage probability at 2.09 µm corresponded to 0.9 J/cm2 in ZGP and 0.44 J/cm2 in CSP but 100% probability was at 4 J/cm2 in ZGP while only at 1.4 J/cm2 in CSP. The 0% damage probability at 1.064 µm corresponded to 0.27 J/cm2 in both crystals but 100% probability was at 1.4 J/cm2 in ZGP while only at 0.4 J/cm2 in CSP.

8964-42, Session 9

Estimation of random duty-cycle error in periodically-poled lithium niobate by simple diffraction experiment

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Fabrication of quasi-phase-matching (QPM) devices from ferroelectric crystals generates inevitable randomness in the domain-wall locations in the QPM grating. For a reasonably good QPM device, its standard deviation, called the random duty-cycle error (RDE), gives quantitative estimation of the device quality. RDE not only affects the frequency

conversion efficiency, but also generates non-phase-matched background noise which can be detrimental to few-photon upconversion processes, as reported by J. S. Pelc, et. al., Optics Lett. 36, 864-866 (2011). They estimated the RDE by measuring the pedestal in the second-harmonic generation (SHG) spectrum.

In this work, instead of SHG we took a far-field diffraction pattern which is mathematically equivalent to the SHG spectrum. The advantages of the diffraction measurement are that the same RDE information can be obtained with a simple experiment with any low-power laser, and that one can measure the pure background noise far from the orders, which is difficult in SHG due to the limited tunable range of the lasers.

In order to demonstrate our method, we periodically poled a z-cut lithium niobate wafer, and slightly etched out the surfaces of the domains with negative polarity to form a surface-relief grating. A collimated He-Ne laser beam was used to uniformly illuminate the whole sample, and the diffraction pattern was taken at the Fourier plane. The average diffraction-noise (In) was measured at the mid-point between the 1st (I1) and the 2nd orders. From the ratio In/I1, we could estimate a RDE of 9.5% of the period, which agrees well with the statistics obtained from microscopic observation.

8964-43, Session 9

Direct measurement of thermal lensing in GaAs induced by 100 W Tm:fiber laser

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Several recent efforts to develop high average power mid-IR and THz sources via nonlinear conversion in GaAs and orientation-patterned GaAs (OP-GaAs) have utilized high average power pumping at 2 μm wavelength. The induced thermal lens is critical consideration particularly in optical parametric and/or enhancement cavities. For example, in-situ measurements within an OPO enhancement cavity show a phase shift of more than 5 π for 100 W incident power. In this work, we utilize a 100 W narrow linewidth, linearly polarized CW Tm:fiber laser focused to ~150 μm diameter to induce a thermal lens in bulk GaAs and OP-GaAs samples. For 500-μm thick bulk GaAs samples, probing the induced thermal distortion with a 1080 nm laser and characterizing the wavefront distortion with a Shack-Hartmann wavefront sensor (SHWS) reveals a thermal phase delay of ~0.003 π/W. Due to the geometry of OP-GaAs samples, we have to significantly modify the probe illumination in order to use the SHWS. We evaluate the accuracy and sensitivity of this method relative to a Z-scan method. This work is closely associated with efforts to produce CW THz via difference frequency generation in GaAs and OP-GaAs by mixing two spectrally beam combined CW Tm:fiber lasers at frequency separations of ~1 – 1.5 THz.

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8965-1, Session 1

Reliability study on high power 638 nm broad stripe LD with a window-mirror structure

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Laser based displays, as laser pico to cinema projectors and laser diode (LD) backlight liquid crystal display (LCD) TVs, have gathered much attention because of large gamut, low power consumption, and so on. Laser light sources for the displays are operated mainly in CW, and requested to be highly reliable, meaning the lasers should be highly reliable. In this paper, we will present the latest reliability study on high power 638 nm broad stripe LD with a window-mirror structure, which is formed by using Zn diffusion into a quantum well active layer. Although the LD shows no catastrophic optical degradation exceeding the output of 1.6 W at initial, the LDs at high power as 1.0 to 1.5 W show sudden degradation during 1,000 to 4,000 hours. The duration to the failure shortens as the power increases. Electro-luminescence imaging from an n-side cladding layer revealed that the route cause of the sudden degradation is catastrophic optical degradation (COD) at a front facet even though the LD has a measure to COD. The LDs at 0.42 W output show no COD up to 6500 hours with extremely stable operation. And it was clarified that mean time to failure due to COD is proportional to optical density to the -3.2, indicating that the small power density design is necessitated to realize long-term stable operation at higher output power. LDs, which have around 60% small power density compared to the former, show stable one up to 4,000 hours without COD at 1.25 W.

8965-2, Session 1

Internal degradation of 980nm emitting single-spatial-mode lasers during ultrahigh power operation

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The degradation behavior of 980 nm emitting ridge waveguide devices is monitored at high emission powers in continuous wave and pulsed operation (2 µJ, 20 W). In pulsed operation, a step test scheme is employed, where single pulses of increasing current amplitude are applied until the device degrades. Nearfield kinetics is resolved with pico-second resolution by streak-camera measurements. In parallel, temperature analysis is provided by thermal imaging. Subsequently devices are opened and defects are inspected by cathodoluminescence (CL) mapping and spectroscopy. This combined approach enables in situ monitoring of degradation events and sequences as well as the detailed analysis of defect propagation kinetics. This allows for the reconstruction of degradation scenarios as follows: Initially the device leaves single-spatial-mode operation as is evident from streak-camera measurements. Switching to multi-spatial-mode operation reduces the facet load and hinders degradation at the facets. Then devices typically thermally roll-over. At ultrahigh powers, however, a catastrophic internal optical damage event may occur creating a defective spot within the cavity. From this starting point, subsequently defects propagate along both directions of the cavity. CL analysis shows the final defect extension to match exactly the signatures observed in situ by the thermal imaging. These findings complete earlier results obtained for broad-area lasers and allow for the establishment of generalized models covering both classes of edge-emitting devices.

8965-3, Session 1

Catastrophic degradation in high power multi-mode InGaAs-AlGaAs strained quantum well lasers with intrinsic and irradiation-induced defects

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A number of groups have studied reliability and degradation processes in GaAs-based lasers, but none of these studies have yielded a reliability model based on the physics of failure. Most of laser diode manufacturers perform accelerated multi-cell lifetests to estimate lifetimes of lasers using an empirical model, but this approach is a concern for satellite communication systems where high reliability is required of lasers. Since it is a challenge to control defects introduced during the growth of laser structures, we studied degradation processes in broad-area InGaAs-AlGaAs strained QW lasers with intrinsic defects as well as those with defects introduced via proton irradiation.

We investigated the root causes of catastrophic degradation processes in MOCVD-grown broad-area InGaAs-AlGaAs strained QW lasers using various failure mode analysis techniques. A number of lasers were proton irradiated with different energies and fluences. We also studied GaAs double heterostructure test samples with different amounts of intrinsic defects introduced during MOCVD growth. These samples were proton irradiated as well to introduce additional defects. Deep level transient spectroscopy (DLTS) and time-resolved photoluminescence (TR-PL) techniques were employed to study traps due to point defects and non-radiative recombination centers in pre- and post-stressed lasers, respectively. These characteristics were compared with those in pre- and post-proton irradiated lasers and DHs to study the role that defects and NRCs play in catastrophic degradation processes. Lastly, we employed focused ion beam, electron beam induced current, and high-resolution TEM techniques to study dark line defects and crystal defects in both post-aged and post-proton irradiated lasers.

8965-4, Session 1

Nanoscale coatings for erosion and corrosion protection of copper microchannel coolers for high powered laser diodes

Matt Flannery, Angie Fan, Tapan Desai, Advanced Cooling Technologies, Inc. (United States)

High powered laser diodes are used in a wide variety of applications ranging from telecommunications to industrial applications. Copper microchannel coolers (MCCs) utilizing high velocity, de-ionized water coolant are used to maintain diode temperatures in the recommended range to produce stable optical power output and control wavelength characteristics. However, aggressive erosion and corrosion attack from the coolant limits the lifetime of the cooler to only 6 months of operation. Currently, gold plating is the industry standard for corrosion and erosion protection in MCCs. However, this technique cannot perform a pin-hole free coating and furthermore cannot uniformly cover the complex geometries of current MCCs involving small diameter primary and

secondary channels. Therefore, a thin coating is needed to provide a pin-hole free coating of fine microchannels that provides erosion-corrosion protection without increasing thermal resistance.

Advanced Cooling Technologies, Inc., will present a corrosion and erosion resistant coating applied by atomic layer deposition (ALD) for enhanced protection of MCCs. MCC samples were coated with a nanometer thin ALD coating, and were exposed to accelerated erosion and corrosion testing in high velocity, high purity water that simulates laser diode operating conditions. The ceramic coating was characterized throughout the corrosion and erosion testing by electrochemical impedance spectroscopy (EIS) and scanning electron microscopy (SEM). EIS and SEM analysis demonstrated significant increases in corrosion and erosion protection, respectively. Ultimately, performance testing demonstrated a five-fold increase in lifetime on laser diode cooler stacks without affecting flow or thermal performance of the MCCs, thus extending costly replacement intervals.

8965-5, Session 1

Feedback-induced catastrophic optical mirror damage (COMD) on 976nm broad area single emitters with different AR reflectivity

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To maximize the optical output power of broad area lasers, long cavities have become more common in the last few years. AR coatings with decreased reflectivity of ~1% are usually used for cavity lengths of ≥4 mm to obtain high conversion efficiencies. This bears the risk of catastrophic optical mirror damage (COMD) by back reflected light, e.g. from optical components like micro-lenses or fiber ends.

We have carried out a comprehensive study on 976nm single emitters with different AR coatings (1%, 3%, 4%, and 5%), which have been exposed to different strengths of optical feedback to investigate damages caused by back-reflected light and how to prevent them. By observing the near-field pattern while varying the probe current, we got information about the influence on filamentation and on peak-power densities with and without optical feedback.

For constant feedback strength, the filamentation became more pronounced and more dynamic with increasing current. We observed bistable and chaotic “jumping” of high-intensity filaments. While investigating space-resolved emission, we found slight differences in the spectral distribution of single filaments.

A similar behavior was observed for a certain current by varying the feedback strength between 4% and 16%. For usual operation currents and optical feedback strengths of ≥4%, the single emitters show COMDs; their positions correlate with excessive peaking in the near field pattern. Finally we found that an increasing AR reflectivity depletes the influence of feedback light on the near-field pattern as well as on the emission spectra and lowers the risk of COMD.

8965-6, Session 2

Advancements in laser diode chip and packaging technologies for application in kW-class fiber laser pumping

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The laser diode pump is an important component that drives the performance, reliability and cost of a fiber laser system. Here we report advancements in both laser chip and packaging that will lead to improvements for kW-class fiber lasers. A new 100-micron aperture, 920nm wavelength laser diode chip was developed to improve lateral divergence angle and reliability. After 5,000h of accelerated life testing on (240) chips, at currents as high as 19A, less than 4% failures have been observed. These chips have been assembled into single-emitter and multi-emitter fiber-coupled packages. The single-emitter package is rated for 12W output from 105-micron diameter fiber. Over 9 million accelerated device-hours on over (1,300) units have been accumulated in active and passive testing without a single package failure. Ongoing life tests at currents as high as 16A show less than 2% failure rate after 4,000h. The multi-emitter package is rated for 140W output from 106-micron diameter fiber. Over 95% of the power is confined to less than 0.15NA. A typical operating current of 12A is required for 140W output power at nearly 50% power conversion efficiency. Ongoing accelerated life tests on (54) units, at powers ranging from 140W to 180W at 35C, show approximately 3% chip failures after 5,000h. No package-related failures have been observed at these extreme operating conditions.

8965-8, Session 2

Watt-level continuous-wave diode lasers at 1180 nm with InGaAs quantum wells

Katrin Paschke, Frank Bugge, Gunnar Blume, Christian Fiebig, Steffen Knigge, Hans Wenzel, Götz Erbert, Ferdinand-Braun-Institut (Germany)

Diode lasers in the wavelength range at and beyond 1180 nm are interesting for non-linear frequency conversion (SHG) to the yellow and orange spectral range. Laser sources at and around 589 nm are key components for many applications, e.g. laser cooling of sodium atome, high resolution glucose content measurements as well as spectroscopy on rare earth elements. The advantages of single-pass SHG laser modules at 589 nm based on diode lasers are unprecedented degrees of miniaturization and efficiency, while allowing direct modulation.

At the conference we will show results on the development of high-power diode lasers at 1190 nm as a prerequisite for future high-brilliance laser diodes with a good beam quality and small spectral line width. Therefore, highly strained InGaAs quantum well laser structures were grown by metalorganic vapor-phase epitaxy, wich allow future integration of a Bragg grating. The laser structure achieved a transparency current density of 66 A cm 2, internal losses below 1.6 cm 1 and a characteristic temperature of 133 K. A continuous-wave output power of 100 µm broad area lasers of more than 2 W at a heat-sink temperature of 15 °C with a conversion efficiency of more than 40% was obtained. In preliminary reliability tests at 1 W a lifetime of more than 1,200 h could be demonstrated.

Due to their compactness these monolithic diode lasers are paving the way for high-brilliance laser sources for efficient single-pass SHG and allow the miniaturization of existing laser systems for bio-analytics and spectroscopy, respectively.

8965-44, Session 2

Inverse thermal lens for far-field angle reduction of high-power lasers

Joachim Piprek, NUSOD Institute LLC (United States)

High-power broad-area laser diodes often suffer from a widening of the slow axis far-field with increasing current. This so-called far-field blooming is mainly attributed to self-heating of the laser and it is detrimental to applications that require the coupling of the laser beam into an optical fiber. The non-uniform temperature profile inside the

waveguide leads to a lateral refractive index gradient (thermal lens) that enhances the built-in index guiding of laser modes. In good agreement with published measurements, we reproduce the far-field blooming quantitatively using self-consistent electro-thermal-optical simulation and thereby link the widening of the far field to an increasing order of lateral lasing modes. Our simulations also reveal that a substantial part of the far field blooming is not caused by self-heating but by increasing carrier and gain non-uniformity in the quantum wells. Based on these results, we investigate possible countermeasures that can lead to a far-field angle reduction with rising current. In particular, we study previously proposed thermal path engineering concepts and demonstrate that the formation of an inverse thermal lens destabilizes higher-order lateral modes and consequently leads to a narrowing of the lateral far-field with rising current. References: [1] J. Piprek and S. Li, Appl. Phys. Lett. 102, 221110 (2013); [2] J. Piprek, IEEE Phot. Techn. Lett. 25, 958 (2013)

8965-46, Session 2

High reliability of high power and high brightness diode lasers

Manoj Kanskar, Ling Bao, John Bai, Keith Kennedy, Mike Grimshaw, Mark DeVito, Jeff Tibbals, David M. Hemenway, Weimin Dong, Xing Guang, Shiguo Zhang, Kirk Price, Rob Martinsen, Jim Haden, nLIGHT Corp. (United States)

This paper presents our continued progress in the development of high power and high brightness single emitter laser diodes from 790 nm to 980 nm for reliable use in industrial and pumping applications. We report on latest updates on reliability of long cavity chip, at both chip level and module level. We report 915 to 980 nm long cavity chip reliability to be comparable to mid-length cavity chip that had undergone an extensive 2-year long multi cell life test, at the same power density, current density and junction temperature, within 90% confidence level. The chip reliability can be further improved by screening out early lifetest failures through improved burn-in screening methods. Initial probes have shown encouraging results and long-term lifetests are underway. We will also report on progress of long chip development at 808 nm and 885nm. In addition, a new enhanced long chip design has been specifically developed for our elementTM with a 105µm fiber coupling and a 0.15 NA, for further improved power, brightness and reliability. Initial results of this new chip design at 980 nm demonstrated a ~20% brightness improvement compared to the current chip design and allows ~14W output power per chip for use in elementTM. This chip design optimization can be also easily applied to other wavelengths to achieve similar level of scaling of power and reliability for high brightness application. The reliability assessment of the new chip design is underway.

8965-10, Session 3

A 25kW fiber-coupled diode laser for pumping applications

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In this paper we report about the development of a new fiber-coupled diode laser for pumping applications capable of generating 25kW with four wavelengths. The delivery fiber has 2mm diameter and 0.22 NA resulting in a Beam Parameter Product (BPP) of 220mm mrad.

Previously, beam transformation techniques have been described that improve the efficiency of coupling a diode stack into a fiber. To achieve the above specifications a special beam transformation technique has been developed combining two high power laser stacks in one module. After fast axis collimation and beam reformatting a beam with a BPP of 200 and 40mm mrad in the slow and fast-axis respectively is generated. Based on this architecture a customer-specific pump laser with 25kW optical output power has been developed, where two modules are polarization multiplexed for each wavelength at 980nm, 1020nm, 1040m and 1060nm. After slow-axis collimation these wavelengths are multiplexed using dense wavelength coupling before focusing onto the fiber tip.

This new laser has been based on a turn-key industrial platform, allowing straight-forward integration into any pump application. The complete system has a footprint of less than 1.4m? and a height of less than 1.8m. The diodes are actively cooled, have a wall-plug efficiency of up to 60%, and have proven lifetimes of typically >30,000 hours.

The new beam transformation techniques opens up prospects for the development of pump sources with only three wavelengths delivering more than 20kW as well as for a new generation of HPDLs with more than 25kW at four wavelengths.

8965-11, Session 3

High-power dense wavelength division multiplexing (HP-DWDM) of frequency stabilized 9xx diode laser bars with a channel spacing of 1.5 nm

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We present a compact High-Power Dense Wavelength Division Multiplexer (HP-DWDM) based on Volume Bragg Gratings (VBGs) for spectrally stabilized diode lasers with a low average beam quality M? ≤ 50. The center wavelengths of the five input channels with a spectral spacing of 1.5 nm are 973 nm, 974.5 nm, 976 nm, 977.5 nm and 979 nm. Multiplexing efficiencies of 97 % ± 2 % have been demonstrated with single mode, frequency stabilized laser radiation. Since the diffraction efficiency strongly depends on the beam quality, the multiplexing efficiency decreases to ≈ 94 % (M? = 25) and 85 % ± 3 % (M? = 45) if multimode radiation is overlaid. Besides, the calculated multiplexing efficiency of the radiation with M? = 45 amounts to 87.5 %. Thus, calculations and measurements are in good agreement. In addition, we developed a dynamic temperature control for the multiplexing VBGs which adapts the Bragg wavelengths to the diode laser center wavelengths.

In short, the prototype with a radiance of ≈ 70 GW/(m?sr) consists of five spectrally stabilized and passively cooled diode laser bars with 40 W output after beam transformation. To achieve a good stabilization performance ELOD (Extreme LOw Divergence) diode laser bars have been chosen in combination with an external resonator based on VBGs. As a result, the spectral width defined by 95 % power inclusion is < 120 pm for each beam source across the entire operating range from 30 A to 120 A. Due to the spectral stabilization, the output power of each bar decreases in the range of < 5 %.

8965-12, Session 3

high-power fiber-coupled diode lasers with superior brightness, efficiency, and reliability

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Advances in high performance fiber coupled diode lasers continue to

enable new applications as well as strengthen existing uses through progressive improvements in power and brightness. These improvements are most notable in multi-kW direct diode systems and fiber laser platforms that effectively transform better beam quality into superior system performance. We report on our recent single-emitter based 60W and 120W, 105um, 0.14 NA fiber-coupled products at 8xx/9xx nm. The product is a culmination of numerous packaging improvements, improving wall plug efficiencies (>48% electrical-to-optical) while improving volume manufacturability enabling lower costs; and chip improvements that increase useable brightness, > 20% over previous generation chips, and upgrade the reliable output power to 14W per chip. We additionally report on current developments to extend the power of the product platform to as high as 300W. This will be realized primarily through new chip architectures projected to further increase the useable chip brightness by approximately 30 % and correspondingly scaling reliable output powers. Second order improvements are proposed in packaging enhancements that capitalize on the increased chip power and brightness as well as expand the package's thermal capabilities. Finally, an extended performance roadmap will translate expected power advances and increasing volumes into a projection of relative $/W decreases for the next several years.

8965-13, Session 3

Near diffraction limit coherent addition of array of 10 broad-area laser diodes

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We studied coherent beam combination of high-power array of 10 broad area laser diodes in the external V-shape Talbot cavity. We explored the paths of increasing the optical feedback coupling among the laser diodes. The V-shape external Talbot cavity was optimized with low external cavity loss and well-controlled narrow spectral line-width. High quality (lower) anti-reflection coating is needed to suppress the intrinsic board-area laser diode modes oscillation. The output power of each individual broad-area laser diode is increased with single transverse mode emission. As a result, the electrical to optical power conversion efficiency was improved with well-maintained coherence beam. A near diffraction limited beam with high visibility (~95-99% dependent on the operational power) was experimentally demonstrated.

8965-14, Session 3

Integrated coherent beam combining of a laser diode mini-bar

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Coherent beam combining is a promising method to obtain high power, high spectral brightness laser source. The existing methods to coherently combine broad-area laser diodes require precise phase control and/or external optical components, which makes the final laser system bulky, expensive and unreliable. Here we propose and demonstrate a monolithically coherently combined mini laser bar of six angled-grating broad-area lasers (alpha-DFBs) with near diffraction-limited beam quality. The angled-grating broad-area laser is used as the building block for the combined laser bar since it can support the snake-like zigzag mode and eliminate direct Fabry-Perot feedback between two end facets to obtain the single mode lasing of a broad area diode laser. In our design, adjacent angled-grating broad-area lasers have opposite tilting angles and overlap at one facet. The overlapped areas define several integrated 2D photonic crystal coupling regions. The coherent beam combining is obtained through the Bragg diffraction in these coupling regions.

We measure the light-current (LI) curve, near field, far field and optical spectra of the combined mini laser bar. Near diffraction-limited interference patterns with high contrast ratio are clearly observed in the far field, indicating excellent spatial coherence among all the emitting apertures. The theoretical far field is also calculated based on the measured near field. The measured far field matches well with the calculated results. The optical spectra of each output aperture exhibit the same lasing wavelengths. These measurement results show that all the six emitters in the mini bar are coherently combined without any external optical components.

8965-15, Session 4

High brightness, direct diode laser with kW output power

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We will present our modular product design that combines tens of single emitters in a compact package and launches them into a 200?m fiber with 0.08 NA. Dense spectral combining enables power scaling from 100W to kilowatts. Volume Bragg Gratings and dichroic filters yield high optical efficiencies of more than 80% and low cost.

Each module emits 500W with a beam quality of 5.5 mm*mrad and 17nm linewidth. High speed switching power supplies are integrated into the module and rise times as short as 6 µs have been demonstrated. Fast control algorithms based on FPGA and embedded microcontroller ensure high wall plug efficiency with a unique control loop time of only 30 µs.

Individual modules are spectrally combined to result in direct diode laser systems with kilowatts of output power at identical beam quality. For low loss fiber coupling a 200 µm fiber is used and the NA is limited to 0.08 corresponding to a beam quality of 7.5 mm*mrad. The controller architecture is full scalable without sacrificing loop time.

We leverage automated manufacturing for cost effective, high yield production. A precision robotic system handles and aligns the individual fast axis lenses and tracks all quality relevant data. Similar technologies are also deployed for dense spectral combining aligning the VBG and dichroic filters.

These systems are mainly used in cutting and welding, but the technology can also be applied over multiple wavelengths. Around 1.5 µm the diodes are successfully used for resonant pumping of Erbium lasers.

8965-16, Session 4

High density volume Bragg grating spectral beam combiner for pumping application using commercial fiber coupled laser diode modules

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The brightness of LD sources is one of their most critical parameters when used for pumping or direct high power laser applications. The brightness of commercial spatially combined fiber couple LD sources are enough close to theoretical limits. SBC of LD modules is alternative approach that can increase the brightness in ~10 times. One of the most advanced and well developed techniques for SBC is based upon reflecting VBG. This approach has demonstrated the combination of single mode laser beams to multi kilowatt level without degradation of the combined beam quality. Serious obstacle though for using this method for combining multimode beams that have wide divergence is the angle selectivity of the VBG. By using new decisions in VBG technology, gratings which could be used for combining of LD sources were developed. We demonstrate here the possibility to combine commercial

available LD modules by such VBGs. Three 30W fiber coupled modules were spectrally narrowed down to 90-130 pm through output fiber and their emission centered at desirable wavelengths separated by ~1nm. After that they were combined in a single output channel with efficiency of more than 91%. The beam divergence after the VBG combiner was equal to the divergence of the input channels. Main sources of losses were scattering (2%) and cross-talk (~6%) between the nearest channels. An analysis of the required VBG parameters, constructions of compact combiner and sources of possible losses will be presented.

8965-17, Session 4

Narrow-stripe broad-area lasers with distributed-feedback surface gratings as brilliant sources for high power spectral beam combining systems

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Laser systems based on spectral beam combining (SBC) of broad-area (BA) diode lasers are promising tools for material processing applications. However, the system brightness is limited by the in-plane beam parameter product, BPP, of the BA lasers, which operate with a BPP of > 3mm mrad. The EU project BRIDLE (www.bridle.eu) is developing novel diode laser sources for such systems, and several technological advances are sought. For increased system brightness and optimal fibre-coupling the diode lasers should operate with reduced BPP and vertical far field angle (with 95% power content), VFF95. The resulting diode lasers are fabricated as mini-bars for reduced assembly costs. Gratings are integrated into the mini-bar, with each laser stripe emitting at a different wavelength. In this way, each emitter can be directed into a single fibre via low-cost dielectric filters.

Distributed-feedback narrow-stripe broad-area (DFB-NBA) lasers are promising candidates for these SBC systems. We review here the design process and performance achieved, showing that DFB-NBA lasers with stripe width, W = 30µm, successfully cut off higher-order lateral modes, improving BPP. Uniform, surface-etched, 80th-order Bragg gratings are used, with weak gratings essential for high efficiency. To date, such DFB-NBA sources operate with > 50% efficiency at output power, P > 6W, with BPP < 1.8mm mrad and VFF95 < 36°. The emission wavelength is about 970nm and the spectral width is < 0.7nm (95% power). The BPP is half that of a DFB-BA lasers with W = 90µm. We conclude with a review of options for further performance improvements.

8965-18, Session 4

Scalable and modular diode laser architecture for fiber coupling that combines high-power, high-brightness, and low weight

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The demand for high-power and high-brightness fiber coupled diode laser devices is mainly driven by applications for solid-state laser pumping and materials processing. The ongoing power scaling of fiber lasers requires scalable fiber-coupled diode laser devices with increased power and brightness. In particular, applications and technologies that demand a high degree of mobility, such as airborne or field transportable systems, also require a robust and extremely lightweight design.

We have developed a scalable and modular diode laser architecture that combines high-power, high-brightness, and low weight that fulfills these requirements for a multitude of applications.

At the heart of the concept is a specially tailored diode laser bar with an epitaxial and lateral structure designed such that only standard fast- and slow-axis collimator lenses are required to couple the beam into a 200?m fiber with a numerical aperture (NA) of 0.22. To fulfill the requirements of scalability and modularity, a reduced size heat sink populated with multiple tailored bars is used. This enables a compact and lightweight design with minimum beam path length. The design concept is capable of providing single wavelength, high-power laser diode modules, with optional volume holographic gratings for wavelength stabilization. Output power levels of more than one kW at a power-to-weight ratio of less than 1 kg/kW have been achieved.

In this paper, two laser modules based on this concept are presented. The optical output power is above 500W at a module weight less than 500g and 300W at 300g. Both modules are coupled into a 200µm, 0.22NA fiber.

8965-19, Session 4

Numerical analysis of external feedback concepts for spectral stabilization of high-power diode lasers

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External feedback concepts (biaxial divergent, uniaxial divergent, inverse self imaging and self imaging) including VBGs with reflectivities from 7.5% to 90% for spectral stabilization of high-power diode lasers are numerically modeled to be compared to each other with respect to stabilization efficiency and sensitivity to the smile-error. The paper gives a brief summary about the applied models for the optical elements and proceeds with the results for the different concepts.

The transverse electrical field is propagated throughout the system based on Fourier-optics. Furthermore, diffraction at the VBG is calculated according to the angular and spectral profile based on the coupled wave theory. Refraction at lens surfaces is either determined by Fourier-optical methods, or by calculating the diffraction integral for curved surfaces (for the acylindrical FAC). The input field to the external system is delivered by a diode laser simulator (presented in earlier works), which calculates the astigmatic and filamented output beam based on the semiconductors carrier and temperature distributions. In an iterative procedure the fraction of the light reflected by the external system is fed back to the diode laser simulator.

The effective external reflectivity (4% for self image up to 12% for biaxial divergent), losses in the optical system and losses due to the back-coupling into the waveguide (nearly 100% for self image to 18% for biaxial divergent) are extracted from the simulations. Furthermore, the influence of the feedback on the vertical field profile is taken into account by determining the average optical confinement factor inside the semiconductor. To quantify the stabilization efficiency a dimensionless parameter including the parameters listed above is introduced and evaluated for each concept.

8965-20, Session 5

Dense array slab-coupled optical waveguide laser capable of 500W/bar

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Data will be presented demonstrating >200W/4% fill factor (FF), 10mm bar dense array slab-coupled optical waveguide lasers (DA-SCOWLs).

The salient characteristics of the DASCOWL bar are 100 single-mode emitters, spaced 100μm apart, resulting in a 4% FF in a 10mm wide bar. We have extracted > 2W/emitter in array format. Data will also be presented showing the near diffraction limited output of the SCOWLs is preserved with a spacing down to 40μm, corresponding to 250 emitters in a10mm bar. The goal of 2W/emitter, 500W/bar represents a 5X increase above the conventional 10% FF broad area laser diode that operates at 10W/emitter. Such a high power is possible when DASCOWLs are attached to SRL's EPIC low thermal resistance heat sinks. The two important advantages of DA-SCOWLs are a near-diffraction-limited output from each emitter and the 3X larger mode size that reduces the optical power density at the output facet, and thereby increases the COD level. The large mode size, especially in the fast-axis (FA) dimension has another attractive feature, namely, a smaller FA divergence of the emanating laser beam. The nearly ideal beam quality and smaller FA divergence of DA-SCOWLs make them an attractive candidate for next-generation, light-weight fiber-coupled pump lasers as well as for high-quality beam-combining architectures.

8965-21, Session 5

High-brightness 800nm fiber-coupled laser diodes

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Fiber-coupled laser diodes have become essential sources for fiber laser pumping and direct energy applications. Single emitters offer reliable multiwatt output power from a 100um lateral emission aperture. By their combination and fiber coupling, pump powers up to 100W can be achieved from a low-NA fiber pigtail. Whilst in the 9xx nm spectral range the single emitter technology is very mature with >10W output per chip, at 800nm the reliable output power from a single emitter is limited to 4W - 5W. Consequently, commercially available fiber coupled modules only deliver 5W – 15W at around 800nm, almost an order of magnitude down from the 9xx range pumps.

To bridge this gap, we report our advancement in the brightness and reliability of 800nm single emitters. By optimizing the wafer structure, laser cavity and facet passivation process, we have demonstrated QCW device operation up to 19W limited by catastrophic optical damage to the 100um aperture. In CW operation, the devices reach 14W output followed by a reversible thermal rollover and a complete device shutdown at high currents, with the performance fully rebounded after cooling. The lifetest data for these emitters indicate a reliable operating power of 9W in CW operation.

We also report the beam properties of our 800nm single emitters and provide a comparative analysis with the 9xx nm single emitter family. Pump modules integrating several of these emitters with a 105um / 0.15NA delivery fiber reach 35W in CW at 808nm. We discuss the key opto-mechanical parameters that will enable further brightness scaling of multi-emitter pumpmodules and their robust behavior under thermal cycling and vibration tests.

8965-22, Session 5

High-volume manufacturing of 8XXnm-10XXnm single emitter pumps by MBE growth technique

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We report on GaAlInAs/GaAs lasers manufactured by the industry's biggest MBE tool. The GEN2000 MBE reactor allows for growth on 23 three-inch wafers at a time, at a cost that compares favorably with the MOCVD method. Data on epitaxial material uniformity across the entire GEN2000-growth area and on chip-on-submount performance are presented and compared to the quality of material produced by smaller MBE tools. We also present data on the performance characteristics of spatially combined fiber coupled passively cooled single emitter-based pumps produced by GEN2000. The data include performance characteristics of 40W 80Xnm-CW pumps and 120W 9XX-nm QCW-pumps; both pumps use a 100?m core diameter fiber to launch power confined within NA<0.15.

8965-23, Session 5

Study of waveguide designs for high-power 9xx nm diode lasers operating at 200K

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Currently, a new generation of ultra-high-energy laser systems (ELI, HILASE) is in development that requires huge amounts of pump power. Their diode laser pump sources should be low cost ($/W) and operate with the highest power conversion efficiency. One way to increase both output power and efficiency is to lower the operating temperature.

We present latest results of detailed design investigations into 9xx nm, AlGaAs based broad-area devices, specifically targeting low temperature (200K) operation. We show experimentally that decreasing temperature reduces threshold current and increases internal efficiency. However, the series resistance RS increases, limiting the net benefit especially at high powers. To address this limitation, the impact of aluminum content in the diode laser AlGaAs waveguide has been studied using 100 µm wide devices mounted p-up on CuW. Near room temperature, structures with low Al-content in the waveguide have poor optical performance, due to high carrier leakage. However at temperatures around 200K, carrier leakage is shown to be strongly suppressed, eliminating the low-aluminum performance penalty of a higher threshold and lower slope efficiency. Simultaneously RS is halved for low Al-content structures. Overall, we show that optimized designs should enable single 100 µm broad-area lasers to operate at 200K with an efficiency of 72% at 20 W output power, corresponding to about 1.5 kW from a bar with 75% fill-factor. The latest results of ongoing device analysis and fully processed devices will be presented, as will their impact on laser bar performance.

8965-24, Session 5

Two photon absorption in high power broad area laser diodes

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Recent advances in thermal management and improvements in fabrication and facet passivation enabled extracting unprecedented optical powers from laser diodes (LDs). However, even in the absence of thermal roll-over or catastrophic optical damage (COD), the maximum achievable power is limited by optical non-linear effects. Due to its non-linear nature, two-photon absorption (TPA) becomes one of the dominant factors that limit efficient extraction of laser power from LDs. In this paper, theoretical and experimental analysis of TPA in high-power broad area laser diodes (BALD) is presented. A phenomenological optical extraction model that incorporates TPA explains the reduction in optical extraction efficiency at high intensities in BALD bars with 100µm-wide emitters and cavity lengths ranging from 4mm to 7mm. The model includes two contributions associated with TPA: the straightforward

absorption of laser photons and the subsequent single photon absorption by the holes and electrons generated by the TPA process. TPA is a fundamental limitation since it is inherent to the LD semiconductor material. Therefore scaling the LDs to high power requires designs that reduce the optical intensity by increasing the mode size.

8965-25, Session 5

High differential efficiency tilted wave laser

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Laser diodes with a thick or ultrathick vertical waveguide have significant advantage for constructing coherent high-power high-brightness laser diode arrays operating in external cavity as a broad output aperture of a chip facilitates coupling of light reflected from an external mirror back to the chip. Tilted Wave Laser (TWL) is a device of such kind based on a thin active waveguide optically coupled with a thick passive waveguide, the latter ranging from an epilayer with a thickness of ~10 micrometer and more to an ultimately thick waveguide realized by a transparent substrate ~100-150 micrometer thick. It was shown that the substrate-based 1060 nm GaAs/GaAlAs TWL reveals all lasing concentrated in two ultimately narrow diffraction-limited beams each having 0.65 degrees full width at half maximum (FWHM), the far field being independent of the current, and differential efficiency being ~50%. The epilayer-based device with an 11 micrometer-thick passive waveguide demonstrates lasing, where about 65% of the emission is concentrated in two narrow beams, each 4.4 degrees FWHM, the rest angularly broad part of the emission decreases upon current, and the differential efficiency is the highest observed for all TWLs and equals 75%.

8965-26, Session 6

High power pump laser diodes for 2 µm fibre laser

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Fibre lasers emitting in the 2 ?m wavelength range offer several advantages over the established 1 ?m systems: enhanced processing of plastics like transparent plastic cutting, the potential for higher output power due to larger mode size or the reduced sensitivity of the human eye. Additionally, such wavelength would be enabling additional opportunities in free-space communications or medical procedures just to name some aspects. In the European FP7 project “Integrated disruptive componentS for 2 ?m fibre LAsers” (ISLA) a consortium aims to optimize components especially for use in 2 ?m fibre lasers.

In this communication we report on Oclaro’s latest results on laser diode sources in the 790 nm range for pumping the fibre laser of the ISLA approach which is based on a novel two-stage pumping scheme that employs thulium (Tm) doped and holmium (Ho) doped double-clad fibres. With an optimized design we have increased the output power of 90 ?m wide broad-area single-emitters to more than 11 W in CW operation mode and 17 W in qCW mode (500 ?s, 8% duty cycle). The power conversion efficiency has also been improved reaching 60% between 4 and 5 W at room temperature (25° C). Accelerated life tests are ongoing for 5000 hours by now.

Updated results will be shown including fiber coupled results implementing the devices in a 105 ?m 0.15 NA multi-emitter platform and progress for on-chip wavelength stabilization.

8965-27, Session 6

Wavelength stabilization of high power and high brightness laser systems using volume holographic gratings

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We present our latest experimental results in wavelength stabilization of high power and high brightness laser diode systems by using Volume Holographic (Bragg) Gratings. Wavelength stabilized high power laser system are used as optical pumps to increase the efficiency and brightness of Thin Disk Lasers. Wavelength stabilization of High Brightness Systems allows effective spectral multiplexing for direct diode applications.

To achieve a wide locking range from threshold until well past the operation current (for example from 30A to 250A), careful control of laser system alignment is necessary to ensure effective feedback and locking, but without using strong grating which could reduce laser efficiency. For this purpose, we use wavefront correction optics to compensate for laser bar smile and Fast Axis Collimation pointing errors. We reduce the pointing errors from up to 1 mrad to an average under 0.1 mrad across the bar and across the entire stack. Time resolved spectra are used to investigate the dynamic locking behavior, with the goal of achieving locking speed comparable to the rise time of the current (100 microsecond). Experimental results for multi-kW laser system are presented, both in CW and soft pulsed operation modes.

8965-28, Session 6

New highly-efficient laser bars and single emitters for 8xx-10xx nm pumping applications

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High-power laser bars and single emitters have proven as attractive light sources for many industrial applications such as direct material processing or as pump sources for solid state and fiber lasers. There is also a great interest in quasi-CW laser bars for laser ignition and fusion applications. These applications require a continuous improvement of laser diodes for reliable optical output powers and simultaneously high electrical-to-optical efficiencies. JENOPTIK presents an overview of recent progress in the development of highly efficient CW and quasi-CW laser devices emitting in a wide wavelength range between 880 nm and 1020 nm.

9xx 12 W single emitters and 976 nm 55 W laser arrays have efficiencies above 65%. Life time tests for single devices currently exceed 6000 h of reliable operation. Our technology of new generation 940 nm high fill-factor bars has been currently extended to emission wavelengths of 976 nm and 1020 nm with excellent results: 200 W output power with 63% efficiency using passive cooling. Additionally, performances of high brightness low fill-factor laser bars with resonator lengths of 4 mm are shown.

The innovative design of the laser structure enables, moreover, the

realization of 500 W 880 nm quasi-CW laser bars with wall-plug efficiencies of 55% and a narrow fast-axis divergence angle of 40% (95% power content). Recent work at JENOPTIK focuses on the development of high efficient 808nm laser bars for CW and quasi-CW applications. Here, first results will be reported.

8965-29, Session 6

Methods for slow axis beam quality improvement of high power broad area diode lasers

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TRUMPF's semiconductor broad area diode lasers have been utilized on fiber coupled multi-kilowatt direct diode laser systems, "TruDiode", for material processing. To further advancing our products in terms of increased brightness but decreased overall cost, we must minimize the slow axis beam quality degradation at very high operation power level due to the far field blooming, which is caused predominantly by the build in index step and thermal lens effect. According to device analysis and related simulations, with the operation current increase, the self-heating nature of the waveguide causes an increase in the thermal gradient between the waveguide and surrounding materials. Consequently, higher order modes can reach their thresholds, yielding larger lateral far fields. Most of the publications about beam quality improvements of semiconductor broad area diode lasers need sacrifice the device efficiency and reliable output power.

In order to improve the beam quality as well as increase efficiencies and reliable output power, we investigated methods of reducing local heat generation, thermal gradient across the slow axis direction and discriminating high order modes. Based on our findings from these experiments, we have combined these different methods in our new device design. Subsequently, the BPP of the CB with 10% fill factor bar has improved by approximately 30% at the 8W/emitter operation power level without efficiency penalty. In this paper, we will elaborate on the methods we used as well as the test results our new product yielded.

8965-30, Session 7

Automated alignment of fast-axis collimator lenses for high-power diode laser bars

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The active alignment of fast axis collimator lenses (FAC) is the most challenging part in the manufacturing process of optical systems based on high power diode laser bars. This is due to the high positioning accuracy in up to 5 degrees of freedom and the complex relations between FAC misalignment and properties of the resulting power density distribution.

In this paper an experimental approach for FAC alignment automation is presented. The alignment algorithm is derived from a beam propagation model based on wave optics. The model delivers explicit relations between FAC misalignment and properties of the distorted power density distribution in the near and far field. The model allows to calculate the FAC misalignments and to correct them in one or several steps.

The alignment algorithm is tested with an experimental demonstrator system. The demonstrator contains an optical system which allows a real time analysis of the near field and far field power distribution of individual emitters. For the tests two different types of FAC lenses and high power diode laser bars are used. The FAC lenses are pre-aligned within a range of +/-50 µm and 0.5° around the suitable position. During the automated alignment process the translational and rotational remaining misalignment and the properties of the far field power density distribution are recorded.

The experimental results are evaluated regarding reliability and flexibility of the presented FAC alignment algorithm.

8965-31, Session 7

Aplanatic beam shaping for diffraction limited beam circularization of tapered laser diodes

Arne Heinrich, Pantec Biosolutions AG (Liechtenstein); Clemens Hagen, Maximilian Harlander, Bernhard Nussbaumer, Pantec Engineering AG (Liechtenstein)

Many applications require a circular, astigmatism free, diffraction limited beam. A tapered laser diode can generate up to 6 W output power in a diffraction limited beam, although elliptical and highly astigmatic. Typically the astigmatism of high power tapered laser diodes is about 1.4 mm making the design of beam shaping challenging.

We present a diffraction limited beam shaping for circularization and collimation especially for highly astigmatic beams consisting of a simple plano-convex cylindrical lens in the aplanatic condition and an air-spaced doublet. The first lens matches the divergence of the fast axis to the slow axis at the point where the beam is circular. The aplanatic condition is fulfilled by choosing a glass with a specific refractive index depending on the ratio of fast to slow axis divergence. This cylindrical lens does introduce neither spherical error nor primary coma, which makes it insensitive against misalignment. Afterwards the beam is collimated with a doublet lens. The setup has been tested with a high power laser diode at 980 nm with a 6 mm long taper (angle 6°) and a facet length of 425 µm. The optics has an overall efficiency of about 85% and the resulting beam has an M2<3. Finally fiber-coupling into a 15 µm fiber (NA 0.1) corresponding to a brightness B=32.2 MW/(cm2 sr) with 30% efficiency, respectively, 1.8 W is shown, which can be further scaled by beam combination techniques.

8965-32, Session 7

Micro optics for laser diode beam shaping

Manfred Jarczynski, Jana Fründt, Ingo Steiner, Melanie Brodner, Udo Fornahl, Thomas Mitra, Jens Meinschien, LIMO Lissotschenko Mikrooptik GmbH (Germany)

Micro optics is well-known for beam shaping inside of diode lasers. Collimation or etendue matching are one operation area, homogenizing and field or line generation another one. We present laser diode optimized approaches of fast axis collimation considering advantages of high refractive index glasses and addressing beam steering approaches for best etendue treatment. Several applications do not only need high brightness, but also specially shaped beams like homogeneous lines or fields. Two principle zoom setups for adjustable laser lines are figured out: A classical telescope setup with moveable lenses and a patent pending approach based on moved arrays of micro lenses. Moderate line length from 4 to 60mm, contrasts below 7% and efficiencies over 80% are achieved in simulation and application.

8965-33, Session 7

Robust precision adhesive bonding of diode laser optics

Tobias Mueller, Sebastian Haag, Fraunhofer-Institut für Produktionstechnologie (Germany); Thomas Gisler, Hansruedi Moser, FISBA OPTIK AG (Switzerland); Petteri Uusimaa, Modulight, Inc. (Finland); Christoph Axt, Rohwedder Micro Assembly GmbH (Germany); Christian Brecher, Fraunhofer-Institut für Produktionstechnologie (Germany)

Laser technology has become an integral part of many industries. Still economic challenges remain. Assembly costs are driven by the demanding requirements regarding alignment and adhesive bonding. Especially challenging in diode laser assembly are the interdependencies between alignment and bonding. Multiple components need to be aligned within smallest spatial and angular tolerances in submicron order of magnitude. A major challenge in adhesive bonding is the fact that the bonding process is irreversible. Accordingly, the first bonding attempt needs to be successful. Today's UV-curing adhesives inherit shrinkage effects during curing which are crucial for the submicron tolerances of e.g. FACs or beam combiners based on wavelength multiplexing what makes the bonding of these components very delicate assembly tasks. However, the shrinkage of UV-curing adhesives is not only varying between different loads due to fluctuations in raw materials, it is also changing along the storage period. Accordingly, the characterization before application of the adhesive is necessary for precision optics assembly in order to reach highest output yields, minimal tolerances and ideal beam-shaping results. The work presented in this paper aims for a significantly reduced impact of shrinkage effects during curing of highly durable UV-curing epoxy adhesives resulting in increased precision. Key approach is the highly precise volumetric dispensing of the adhesive as well as the characterization of the shrinkage level. These two key factors allow most reproducible adhesive bonding in automated assembly cells. These proceedings are essential for standardized automated assembly solutions which will prospectively play a major role in laser technology.

8965-34, Session 7

Highly efficient and compact free beam kW-diode laser modules

Jens Meinschien, Stephan Schneider, Dennis Bonsendorf, Melanie Brodner, Udo Fornahl, Dirk Hauschild, Ulrich Jentsch, Sebastian Liebl, Thomas Mitra, Detlef Stöhr, Michael Voss, LIMO Lissotschenko Mikrooptik GmbH (Germany)

The application of highly specific laser beam shape gain increasing importance, especially for diode lasers. The first choice of beam shape is not anymore always circular instead line or rectangular field geometries are very often of favourable interest. The characteristics of broad area laser diode bars in conjunction with cylindrical shaped optics are powerful for the design of very compact configurations to generate high brightness and highly homogenous fields. The design and performance data of several systems in the kW power range are evaluated.

A distinct unique approach of line configuration is shown which allows scalability in terms of line length and also the switching on and off of line segments. Special emphasis is given on the beam shaping itself. Several more line configurations are presented which also include systems with wavelength in the extended NIR spectral range, e.g. 1470 nm or 1950 nm.

8965-35, Session 8

High power laser diodes at 14xx nm wavelength range for industrial and medical applications

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We report on the development of the latest generation of high power lasers at 14xx nm wavelength range suitable for industrial applications such as plastics welding and medical applications including acne treatment, skin rejuvenation and surgery. The paper will present the newest chip generation developed at Oclaro, increasing the output power and the power conversion efficiency while retaining the reliability of the initial design. With the optimized design applied to 1cm bars emitting at 1430nm, maximum power values as high as 35W for conductively cooled devices, and 55W for bars on active micro channel coolers, have been obtained. The power conversion efficiency has been improved to 40%, reducing the required power budget to operate the bars. Both active and conductive bar assembly configurations show polarization purity greater than 98%. Initial life testing at 95A, 50% duty cycle and 0.5Hz hard pulsed operation is being conducted on bars which were soldered to conductive copper CS mounts using OCLARO hard solder technologies. So far the results after 2300h, or 4.1 million "on-off" cycles, show an average degradation of less than 0.6% per 1000h. Updated results will be shown including the performance map for various configurations (active coolers, passive coolers, stacks) as well as an updated picture on reliability.

8965-36, Session 8

High power and high efficiency 14xx nm wavelength Fabry-Perrot lasers

Tawee Tanbunek, Rajiv Pathak, Zhiji Wang, Heiko Winhold, Serguei Kim, Coherent, Inc. (United States)

High power and high efficiency 14xx nm wavelength Fabry-Perrot lasers

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We have successfully design and fabricated high power and high efficiency 1450-1470 nm wavelength Fabry-Perrot lasers using high throughput low pressure MOCVD technology. We obtained a CW output power more than 30 W from a 1 cm bar 20% FF 100 um wide aperture and 2 mm long cavity at 25C using TEC cooler on a conduction cooled platform using Indium solder. With a QCW pulse, output power approaching 90 W is obtained. A single emitter device with a cavity length of 2 mm bonded on a C-mount fabricated from the same improved epi design shown a conversion efficiency of 42% with output power as high as 6 watts at 20C TEC heat sink temperature. A preliminary long term life test of the 1450 nm wavelength 1 cm bar operating at a power output close to 30 Watts showed no significant degradation after 1800 hrs. of testing.

8965-37, Session 8

High power diode lasers emitting from 639 nm to 690 nm

Ling Bao, Mike Grimshaw, Mark DeVito, Manoj Kanskar, Weimin Dong, Xingguo Guan, Shiguo Zhang, Keith Kennedy, Rob Martinsen, Jim Haden, nLIGHT Corp. (United States)

There is increasing market demand for high power reliable red lasers for display and cinema applications. Due to the fundamental material system limit at this wavelength range, red diode lasers have lower efficiency and are more temperature sensitive, compared to 808 nm diode lasers. In terms of reliability, red lasers are also more sensitive to catastrophic optical mirror damage (COMD) due to the higher photon energy. Thus developing higher power-reliable red lasers is very challenging. This paper will present our recent development work on improving power and reliability of single emitter red diode lasers. These single emitter diode lasers are particularly targeted to be efficiently integrated into our compact, passively-cooled Pearl™ and element™ fiber-coupled module architectures. In order to improve power and reliability, a series of design optimizations have been focused on epi design/growth, chip configuration/processing and optical facet passivation. Initial optimization has demonstrated promising results on 639 nm diode lasers for 1.0-1.5W rated power. Further design optimization and extensive accelerated lifetest are underway. The finalized chip configuration would enable a Pearl™ or element™ fiber-coupled module ~ 25W at 639 nm and ~ 50W at 690 nm. All design optimizations can be easily transferred to 650- 660 nm to achieve similar level of scaling of power and reliability.

8965-38, Session 8

High-power visible spectrum diode lasers for display and medical applications: beam sources with tailored beam quality and spectral characteristics

Andreas Unger, Bernd Köhler, Jens Biesenbach, DILAS Diodenlaser GmbH (Germany)

High power diode laser sources in the visible spectral region, are currently a highly active field of research. The availability of red high power diode bars and GaN-based blue emitters with growing output powers opens up new fields of applications like cinema projectors, lithography or photodynamic therapy. These applications all have special requirements on a laser source, with regard to output power, spectral characteristics, beam quality and stability.

Previously we presented a modular and scalable platform for the realization of fiber coupled beam sources from 5W to 100W into a 400µm NA0.22 fiber. Based on this platform 10W to 100W red laser modules were actually realized. In this paper we report on the further progress on these beam sources with regard to beam quality and spectral characteristics. Improved beam shaping concepts allow coupling into smaller fibers. For medical applications beam sources with narrow wavelength distribution in the blue spectral region were developed. Based on our modular approach modules up to 100W in a 400µm NA0.22 fiber were realized. Progress in manufacturing technologies allows for coupling of more than 25W into a 200µm NA0.22 fiber in the blue wavelength range.

8965-39, Session 8

High power and high efficiency kW 88x-nm multi-junction pulsed diode laser bars and arrays

Zhigang Chen, John Bai, Weimin Dong, Xingguo Guan, Shiguo Zhang, Sandrio Elim, Ling Bao, Mike Grimshaw, Mark DeVito, Manoj Kanskar, nLIGHT Corp. (United States)

There is great interest in the development of high-power, high-efficiency and low cost QCW 88x-nm diode laser bars and arrays for pumping solid state lasers. We report on the development of kW 88x-nm diode laser bars and arrays that are based on a bipolar cascade design, in which multiple lasers are epitaxially grown in electrical series on a single substrate. Multiple laser junctions, each of which is based on nLight's high performance 88x-nm epitaxial design, are separated by low resistance tunnel junctions with resistivity as low as 8E6 Ohm cm^2. Optimization of bar geometry and wafer fabrication processes such as etch and regrowth was explored for electrical and optical performance improvement in double-junction diode laser bars. A record-high maximum QCW power of 630 W was demonstrated in a 3-mm wide mini-bar with 3-mm cavity length. This linear power density is equivalent to 2.1 kW out of a full cm-width-bar. Peak efficiency of 61% was measured with 200 us and 14 Hz pulses, at a heatsink temperature of 10 °C. Ongoing work for further power scaling includes development of double-junction stacked array that emits > 10kW optical power, and development of triple-junction diode laser bars. Our effort to extend the multi-junction designs to other wavelength ranges, such as 808 nm, will also be discussed.

8965-40, Session 8

Simple design for fiber coupled 9xx nm kW-QCW pump module with high duty cycle based on customized chips and lateral heat removal

Wolfgang Pittroff, Bernd Eppich, Götz Erbert, Rene Platz, Ferdinand-Braun-Institut (Germany); Dieter Tyralla, Technische Hochschule Wildau (Germany); Günther Tränkle, Ferdinand-Braun-Institut (Germany)

High power 9xxnm QCW- pump modules are very interesting for high- and ultra-high-energy laser systems. Main relevant issues beside price and power conversion efficiency are long term stability of the mounting scheme and stable fiber coupling. We present a design based on diode laser stacks with lateral heat removal. A single stack element consists of a diode laser, which is soldered on both sides to CuW carriers using AuSn. Life test over 1000 h showed no degradation. DCB coolers are subsequently mounted on both outer sides of the stack. The thermal resistance of one stack element is about 1.7 K/W. For >3 J pulse energy the stack contains 28 elements. >65% power conversion efficiency of the used 940 nm diode laser chips at 120 W output power allows >20% duty cycle without substantial heating (maximum measured output power >200 W). The light is collimated in vertical direction for each stack element. We choose a size for the FAC which allows staggering the beams of two stacks. The diode laser chips have an aperture width of 1.2 mm and a lateral divergence <14° (95 % power) at 120 W. Further beam shaping will be done by cylindrical lenses in both directions. For 6 J pump energy two stacks are used, coupled into 1.9 mm diameter fiber with a high optical coupling efficiency of >90 %. The principle design is very flexible to match other demands in fiber size and output power.

8965-7, Session PTue

Characterization of diode-laser stacks for high-energy-class solid-state lasers

Pawel Sikocinski, Jan Pilar, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Alina Pranowicz, Institute of Physics of the ASCR vvi (Czech Republic); Martin Divoky, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Paul Crump, R. Staske, Ferdinand-Braun-Institut (Germany); Antonio Lucianetti, Tomás Mocek, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

We present a comparative study of high power 940nm QCW diode laser stacks produced by several commercial manufacturers, as used as pump sources for high energy class diode-pumped solid-state laser systems. A cross-check of measurements performed at HiLASE-IoP and Ferdinand-Braun-Institut (FBH) shows very good agreement between the results. Our study reveals the presence of discontinuities in the spectra of two diode stacks. This is probably due to small changes in the dynamics of the cavity modes. We compare the stack performance both to the requirements for the HILASE system and to the latest research into novel ultra-high power bars.

8965-42, Session PTue

Coupled function based stepped-tilted windows algorithm of Dammann grating optimization

Ning Zhang, Yu Zhou, Jianfeng Sun, Liren Liu, Shanghai Institute of Optics and Fine Mechanics (China)

This paper has tried to use the recent computer technology to optimize the Dammann grating, which we expect will reach some good results. For years, we have stumbled around the low combining efficiency of Dammann grating. Though, some researches have been done to reach almost 100 percent combining efficiency using continuous relief grating, it costs too much to make it used widely and easily. The old algorithm is based on orthogonal relief function which can simplify the calculation process, but basically it's still belong to one dimensional optimization due to the orthogonal procedure, which decreases the optimization DOF(Degree of Freedom). If we use the former algorithm to model the experimental condition, the required memory consumption is astonishing. Based on these facts, the former researches though have significant influences on coherent beam combining, for further research, we need to find a new path to consider the problem. To solve the huge calculation process, the author put forward stepped-tilted window algorithm which can reduce the calculation pressure by windowing the computation domain. Thus we can run the optimization program on a PC at the same time reaching the maximum optimized phase transition points. We believe this research can greatly promote the efficiency of designing Dammann grating for coherent beam combination as well as reduce the design and fabrication cost.

8965-43, Session PTue

Laser technology in automotive lighting

Ceren Altingoz, Magneti Marelli Mako Elektrik Sanayi Ticaret A.S (Turkey)

The last few years have seen something of a revolution in automotive lighting facilitated by a range of new photonics advances. The lighting industry as a whole is moving rapidly from the incandescent and gas discharge based technologies that dominated the 20th century to solid state technology in the form of Light Emitting Diodes (LED) which are a point source light, Organic Light Emitting Diodes (OLED) which are an area source light and at the edge the increasing use of lasers with different functional applications.

In this paper I will focus on this edge technology of lasers as they are still trying to find their right place in automotive lighting. To better analyse their potential, the working principle of a laser will be explained, laser types used in automotive lighting, their application methods, advantages and disadvantages of their usage will be declared, application examples from the current trials of some leading automotive industry research groups will be given and finalization will be with an overall view of the possible future laser applications in th field of automotive lighting.

8965-45, Session PTue

High-resolution spectral mapping of a lensed high power laser bar

Caleb D. Gannon, Rose-Hulman Institute of Technology (United States); Tobias P. Koenning, Steven G. Patterson, DILAS Diode Laser, Inc. (United States); Paul O. Leisher, Rose-Hulman Institute of Technology (United States)

Alkali gas lasers based on rubidium vapor have an extremely narrow absorption band (<0.01 nm, standard temperature and pressure) at 780 nm. Diode-pumped alkali lasers (DPALs) require high-power diode arrays having emission spectra which are closely matched to this absorption peak. There are several methods which can be used for narrowing and stabilizing the output spectrum of a diode laser bar including external locking via a volumetric holographic grating (VHG). While this approach offers several advantages over internal stabilization techniques, the effect of pointing error arising from bar smile can be detrimental to the locked performance of the lensed array. In order to investigate the effect of smile on wavelength locking, a system capable of mapping the emission spectrum of the lensed diode laser bar was developed. The approach utilizes an imaging system and spatial filter to couple light from individual emitters of the lensed array into a commercial optical spectrum analyzer. This approach offers a larger dynamic range than traditional spectral mapping techniques, with a resolved signal-to-noise ratio in excess of 60 dB. Results from the characterization of a VHG-locked 780 nm laser bar array will be presented.

8965-47, Session PTue

Coupling of DBR tapered diode laser radiation into a single-mode-fiber at high powers

Daniel Jedrzejczyk, Ferdinand-Braun-Institut (Germany); Patrick Asbahr, Ferdinand-Braun-Institut (Germany) and FCC FiberCableConnect GmbH (Germany); Markus Pulka, FCC FibreCableConnect GmbH (Germany); Bernd Eppich, Katrin Paschke, Ferdinand-Braun-Institut (Germany)

Efficient high-power lasers in continuous-wave (CW) operation emitting spectrally narrow-band near-infrared radiation in spatial fundamental mode are desired for applications such as pumping of solid-state and fiber lasers or frequency conversion. A distributed Bragg reflector (DBR) tapered diode laser is well suited to fulfil these requirements [1]. However, its simple astigmatic beam and, in particular, the variation of astigmatism with output power adjusted by taper current represent a major impediment with regard to beam shaping.

In this work, we investigate coupling of DBR tapered diode laser radiation into a single-mode-fiber (SMF) with a core diameter of approx. 6 µm. The aim is to improve the spatial properties of the spectrally narrow-band, high-power laser radiation, in particular, to provide a stigmatic, nearly Gaussian laser beam independent of the taper current and thus independent of the optical power level.

At the conference, the results of coupling experiments conducted in a bench-top setup will be presented. A DBR tapered diode laser emitting

nearly diffraction-limited, single-frequency CW radiation around 1064 nm is applied as a laser light source [2]. The coupling efficiency and the spatial and spectral laser beam properties behind SMF are investigated in dependence on diode laser beam quality and optical power in front of SMF. A maximum power of more than 3 W ex fiber at a coupling efficiency in excess of 60 % is reached.

1 C. Fiebig et al., "High-brightness distributed-Bragg-reflector tapered diode lasers: pushing your application to the next level", SPIE Proc. 7918, 79180R, 2011

2 B. Sumpf et al., "1060 nm DBR tapered lasers with 12 W output power and a nearly diffraction limited beam quality", SPIE Proc. 7230, 72301E, 2009

8965-48, Session PTue

Design and fabrication of high power single mode double-trench ridge waveguide laser

Shaoyang Tan, Teng Zhai, Wei Wang, Ruikang Zhang, Dan Lu, Chen Ji, Institute of Semiconductors (China)

A high power single-lateral-mode double-trench ridge waveguide semiconductor laser is reported. The laser has a compressively strained double quantum-well (DQW) and an GaAs/AlGaAs separate confinement structure. The ridge waveguide is defined by two trenches of finite width on either side of the ridge, which will result mode radiation towards outside of the trenches. The relationship between the leakage loss and the waveguide geometry of the each lateral mode is studied with effective index method. The relationship under different bias condition is evaluated. The maximum single-lateral-mode operation currents under various trench width, trench depth and ridge width are simulated. Based on the simulation, lasers with various trench width, trench depth and ridge width are fabricated and tested. With optimized geometry parameters, a laser of 1.5-mm cavity length with a maximum single-lateral-mode operation current of 550 mA is obtained. The threshold current and the slope efficiency of the laser is 30 mA and 0.72 W/A, respectively. The maximum single-lateral-mode power is up to 340 mW. Suggestions for further improvements of the maximum single-lateral-mode operation current of lasers are proposed.

8965-49, Session PTue

Improved macro cooler for reduced thermal resistance

David A. Irwin, DILAS Diode Laser, Inc. (United States); Wilhelm Fassbender, DILAS Diodenlaser GmbH (Germany); Steven G. Patterson, DILAS Diode Laser, Inc. (United States); Jens Biesenbach, DILAS Diodenlaser GmbH (Germany)

For high power diode laser applications, temperature control of the chip material is critical. High junction temperature has many unwanted consequences, including decreased diode lifetime, decreased efficiency, increased slow axis divergence, and large temperature induced wavelength shift. These effects are particularly undesirable in high brightness applications (e.g. fiber pumping) because of the fundamental limitations imposed on the beam parameter product (BPP) by excess diode heating.

Traditional diode cooling methods include conductively cooled and micro-channel structures, although both methods suffer from important drawbacks. Conductively cooled mounts are inexpensive and robust, but provide relatively poor cooling performance. Alternate structures, termed micro-channel coolers (MCC's), have long provided the best available cooling performance, but suffer their own penalties. In addition to higher cost, their system requirements can complicate use in industrial and military applications.

To be presented are new lightweight cooling structures that show cooling performance approaching that of micro-channel coolers, but remove nearly all of the constraints imposed by MCC designs. Termed macro-coolers, these new structures demonstrate a 50% reduction in thermal resistance and 17% reduction in cooler weight compared to earlier generations. With direct copper bonding (DCB) techniques, these structures are low cost and high yield, and are easily extensible to other wavelengths, diode form factors, and system architectures. Data from a new diode pump source that utilizes DCB macro-coolers to achieve an output power of 600W at 976nm from a 200µm, 0.22NA fiber at a module weight of 400g will be presented as demonstration of the efficacy of this cooling technology.

Conference 8966: Vertical External Cavity Surface Emitting Lasers (VECSELs) IV

LASE
SPIE Photonics West

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8966-1, Session 1

Microscopic VECSEL Modeling

(Keynote Presentation)

Stephan W. Koch, Philipps-Univ. Marburg (Germany); Jörg Hader, Jerome V Moloney, College of Optical Sciences, University of Arizona (United States)

This tutorial gives an overview of the microscopic approach developed to describe equilibrium and nonequilibrium effects in optically excited semiconductor systems with an emphasis to the application for VECSEL modelling. It is outlined how nonequilibrium quantum theory is used to derive dynamic equations for the relevant physical quantities, i.e. the optically induced polarization and the dynamical carrier occupation probabilities. Due to the Coulombic many-body interactions, polarization and populations couple to expectation values of higher-order quantum correlations. With the help of a systematic correlation expansion and truncation approach, we arrive at a closed set of equations. Formally these can be combined with Maxwell's equations for the classical light field, yielding the Maxwell-semiconductor Bloch equations (MSBE). However, instead of the more traditional approach where losses and dissipative processes are treated phenomenologically and/or through coupling to external reservoirs, we derive fully microscopic equations for the carrier-carrier and carrier-phonon scattering as well as the effective polarization dephasing. Formally, these equations resemble non-Markovian quantum Boltzmann equations which involve nonlinear combinations of carrier populations and polarizations as well as high-dimensional integrals. Due to their general nature, the resulting equations are fully valid under most experimentally relevant conditions. In particular, they are capable of describing semiconductor laser properties under high-power and extremely short-pulse operation conditions.

The theory is applied to model the high-intensity light field in the VECSEL cavity coupled to the dynamics of the optical polarization and the nonequilibrium carrier distributions in the quantum-well gain medium. Applications of the theory and comparison to current experiments are discussed.

8966-2, Session 1

Exploring ultrafast negative Kerr Effect for self-modelocking vertical external-cavity surface-emitting lasers *(Invited Paper)*

Alexander R. Albrecht, The Univ. of New Mexico (United States); Denis V. Seletskiy, Univ. Konstanz (Germany); Yi Wang, The Univ. of New Mexico (United States); Jeffrey G. Cederberg, Sandia National Labs. (United States); Mansoor Sheik-Bahae, The Univ. of New Mexico (United States)

Quasi-stable self-mode-locking of an InGaAs vertical external-cavity surface-emitting laser (VECSEL) emitting around 1020 nm has been observed, resulting in 500 fs pulses at a repetition rate of 1 GHz. The mechanism is attributed to negative ultrafast Kerr lensing in the semiconductor gain structure. Our calculations show that a mode narrowing on the order of 0.5% can be obtained at the concave cavity end-mirror or at the gain medium. This is consistent with experimental observations, as mode-locking can be achieved by placing a (hard) aperture before the concave cavity end mirror inside the VECSEL cavity, or by the soft aperture created by changing the pump spot size in relation to the lasing mode on the gain chip. The pulse train generated by the VECSEL has been analyzed by a fast InGaAs photo diode and oscilloscope, RF spectrum analyzer, and second harmonic intensity autocorrelation. The effect of dispersion on pulse width has been studied, hinting at soliton-like pulse formation.

8966-3, Session 1

Influence of Coulomb screening on lateral lasing in optically-pumped semiconductor disc lasers

Chengao Wang, Kevin Malloy, Mansoor Sheik-Bahae, The Univ. of New Mexico (United States)

Parasitic lateral lasing in certain optically pumped semiconductor disc lasers drains the gain of the vertical mode and thus causes power scaling degradation and premature rollover in surface emitting operation. We have observed this effect in both MQW (InGaAs/GaAs) and double heterostructures (GaAs/GaInP) under pulsed excitation even when the gain chip lateral dimensions are much larger than the diameter of the pump laser. Lateral lasing occurs persistently between cleaved facets at a band-tail wavelength much longer than the peak of the gain. We show that the effect of bandgap renormalization due to Coulomb screening explains this phenomenon. Exploiting the simple analytical plasma theory of bulk semiconductors (Banyai & Koch), we can account for such an effect in double heterostructures.

8966-4, Session 2

Carbon nanotube mode-locked vertical external-cavity surface-emitting laser *(Invited Paper)*

Kai Seger, Niels Meiser, KTH Royal Institute of Technology (Sweden); Sun Y. Choi, Bo H. Jung, Dong-Il Yeom, Fabian Rotermund, Ajou Univ. (Korea, Republic of); Oleg G. Okhotnikov, Tampere Univ. of Technology (Finland); Fredrik Laurell, Valdas Pasiskevicius, KTH Royal Institute of Technology (Sweden)

A passively mode-locked semiconductor disk laser was demonstrated where a transmitting single-walled carbon nanotube saturable absorber mounted at Brewster's angle in the cavity was used as a mode-locker. This first application of a single-walled carbon nanotube saturable absorber for mode-locking of a vertical external-cavity surface-emitting laser represents an important step for a further enhancement of the versatility of both devices and can be seen as an alternative, easy to implement and cost effective design.

The purified single-walled carbon nanotubes were dispersed in a PMMA-dichlorobenzene solution and spin-coated onto a quartz window. The fabricated saturable absorber was characterized by linear and nonlinear transmission measurements: The linear transmission of the saturable absorber was 99% and the modulation depth was measured to be 0.25. In addition, a pump-probe trace was recorded and the fast and slow decay time constant were 150 fs and 1.1 ps respectively.

The semiconductor gain structure was grown by molecular beam epitaxy and the gain region was composed of 3 GaInAs quantum wells. The structure was grown in reverse order on an n-type GaAs substrate, which was etched away after the growth.

The laser setup represents a highly practical and simple solution for a high repetition rate solid-state laser operating in the near-infrared spectral region and delivered stable cw single pulse mode-locking with

a maximum average output power of 136 mW at a repetition rate of 613 MHz. The corresponding pulse energy is 0.22 nJ. Without dispersion compensation, a pulse duration of 1.23 ps was achieved.

8966-5, Session 2

Graphene modelocked VECSELs *(Invited Paper)*

Christian A. Zaugg, ETH Zurich (Switzerland); Valentin J. Wittwer, Zhipei Sun, Daniel Popa, Silvia Milana, Tero Kulmala, Ravi S. Sundaram, Univ. of Cambridge (United Kingdom); Mario Mangold, Matthias Golling, ETH Zurich (Switzerland); Young Lee, Jong-Hyun Ahn, Sungkyunkwan Univ. (Korea, Republic of); Andrea C. Ferrari, Univ. of Cambridge (United Kingdom); Ursula Keller, ETH Zurich (Switzerland)

In the past decade, passively modelocked optically pumped vertical external cavity surface emitting lasers (OP-VECSELs), sometimes referred to as semiconductor disk lasers (OP-SDLs), impressively demonstrated the potential for generating femtosecond pulses at multi-Watt average output powers with gigahertz repetition rates. Passive modelocking with a semiconductor saturable absorber mirror (SESAM) is well established and offers many advantages such as a flexible design of the parameters and low non-saturable losses.

Recently, graphene has emerged as an attractive wavelength-independent alternative saturable absorber for passive modelocking in various lasers such as fiber or solid-state bulk lasers because of its unique optical properties. Here we present and discuss the first modelocked VECSELs using graphene saturable absorbers. The broadband absorption due to the linear dispersion of the Dirac electrons in graphene makes this absorber interesting for wavelength tunable ultrafast VECSELs. Such widely tunable modelocked sources are in particularly interesting for bio-medical imaging applications.

We present a straightforward approach to design the optical properties of single layer graphene saturable absorber mirrors (GSAMs) suitable for passive modelocking of VECSELs. We demonstrate sub-500 fs pulses from a GSAM modelocked VECSEL. The potential for broadband wavelength tuning is confirmed by covering 46 nm in modelocked operation using three different VECSEL chips and up to 21 nm tuning in pulsed operation is achieved with one single gain chip. A linear and nonlinear optical characterization of different GSAMs with different absorption properties is discussed and can be compared to SESAMs.

8966-6, Session 2

Graphene-based saturable absorbers in semiconductor lasers

Saima Husaini, Robert G. Bedford, Air Force Research Lab. (United States)

Due to its unique zero-bandgap structure, linear dispersion of electrons and compatibility with various optoelectronic platforms, graphene has become one of the principal material components in many nonlinear devices. Functionalized graphene-composites exhibit excellent optical limiting properties while single layer graphene specifically has shown great promise as a saturable absorber in mode locking fiber lasers from the visible to infrared regime. However, more recently work has been done to integrate graphene in a vertical external cavity surface emitting lasers (VECSELs). In addition to allowing flexibility in tuning over a wide wavelength range, the 'open' architecture of a VECSEL cavity allows for the incorporation of intracavity elements with ease. Currently VECSELs employ semiconductor-based saturable absorbers which have extremely narrow tuning range and require complex fabrication procedures.
By developing a graphene-based saturable absorber, one can take advantage of its zero bandgap structure, its thermal and mechanical stability as well as its frequency-independent absorption to passively modelock lasers over a wide frequency range - potentially through the terahertz regime. Here we will report on recent developments in VECSELs as applicable to Air Force applications. Further, work done in studying the nonlinear optical properties of graphene as applicable to the development of saturable absorbers as well as optical limiters will also be presented. Finally, preliminary fabrication and characterization work conducted to integrate the graphene-based materials in a VECSEL will be presented.

8966-7, Session 2

Femtosecond MIXSEL *(Invited Paper)*

Mario Mangold, Valentin J. Wittwer, Christian A. Zaugg, Sandro M. Link, Matthias Golling, Bauke W. Tilma, Ursula Keller, ETH Zurich (Switzerland)

Modelocked semiconductor disk lasers are attractive candidates for numerous industrial and scientific applications that benefit from simple, compact and inexpensive ultrashort pulse sources delivering high output power and excellent beam quality. The modelocked integrated external-cavity surface emitting laser (MIXSEL) combines the gain of vertical-external-cavity surface-emitting lasers (VECSELs) with the saturable absorber of a semiconductor saturable absorber mirror (SESAM) in one single semiconductor wafer. This concept enables a higher level of integration to reduce complexity, packaging, and manufacturing cost, and allows for stable and self-starting passive modelocking in a simple straight cavity. With quantum-dot (QD) based saturable absorbers record-high watt-level average output power was demonstrated, however the pulse duration was limited to 17 ps until now.

Here we present the first femtosecond operation of a MIXSEL, generating 620-fs-pulses at a repetition rate of 4.8 GHz and 101 mW of output power. The novel high-power MIXSEL structure relies on a quantum-well (QW) absorber for passive modelocking. The low temperature grown QW is embedded in AlAs spacers and carefully optimized for achieving low saturation fluences and fast recovery dynamics. Combined with a top-coating for low group-delay-dispersion, this leads to the shortest pulse duration achieved from a MIXSEL to date. In addition we present a detailed characterization of the saturable absorber and give guidelines for further optimization. Together with power scaling this will lead to a femtosecond MIXSEL at watt-level average output power levels in the near future.

8966-8, Session 3

Intensity and frequency noise properties of multi-Watt single frequency VECSEL with and without active stabilization *(Invited Paper)*

Alexandre Laurain, Jörg Hader, College of Optical Sciences, The Univ. of Arizona (United States); Stephan W. Koch, Wolfgang Stolz, Philipps-Univ. Marburg (Germany); Jerome V. Moloney, College of Optical Sciences, The Univ. of Arizona (United States)

Single frequency laser sources are of high interest for numerous applications such as high resolution spectroscopy, atomic clock, radar-lidar, metrology or telecommunications. Those demanding applications often require additional features like high power, high beam quality, continuous tunability, wavelength versatility, long term stability, very narrow linewidth, ultralow intensity noise, low cost and compactness. At best, existing laser technologies (fiber, SSL, DFB) combine three or four of these features altogether. Here, we show that the VECSEL technology can offer all of these features in one source. First, we demonstrate the highest free running single frequency power reported to date, with more than 15W in continuous operation and at room temperature. The laser characteristics such as the beam quality, the intensity noise and the linewidth are studied in detail. We investigate the different sources of

intensity and frequency noise and their contributions to the linewidth. We then demonstrate that with an active stabilization of the laser frequency, we can significantly decrease the linewidth, typically below 30kHz over one second, as well as the long term stability. The laser is locked to a mechanically and thermally stable reference cavity, made with high reflective mirrors and a Zerodur spacer. We also show that the frequency stabilization is not made at the expense of a high intensity noise. The laser frequency is controlled and tuned varying the cavity length using a high bandwidth piezoelectric element while intensity fluctuations are reduced by varying the pump intensity. Intrinsic and stabilized linewidth and intensity noise are compared.

8966-9, Session 3

Frequency-stabilized ultraviolet semiconductor disk laser *(Invited Paper)*

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Optically-pumped semiconductor disk lasers (SDLs) are attractive sources covering a wide spectral range with high brightness. Furthermore, due to their internal dynamics and high finesse laser cavities, they are well suited for achieving highly coherent emission.

Narrow linewidth, tunable ultraviolet lasers are sought for applications such as interference lithography, metrology and atmospheric spectroscopy. As compared to solutions based on multi-harmonics of a narrow-linewidth infrared laser, we propose a more direct route based on intracavity frequency-doubling of a stabilised red-emitting SDL. Our gain structures are based on GaInP quantum wells and the conversion to the ultraviolet is achieved using intracavity beta barium borate (BBO). Single frequency emission is obtained with the addition of a birefringent filter and a glass etalon. In this configuration a total power of up to 26 mW was obtained in a single frequency, tunable from 337 to 342 nm. In order to narrow the laser linewidth, active stabilisation based on the side of fringe technique has been implemented; a Fabry-Perot cavity was used as the frequency reference and the frequency fluctuations were corrected via a piezoelectric transducer on which one of the cavity mirrors was glued. With this locking setup, the relative linewidth was measured as 16 kHz for a 10 µs sampling time and as 50 kHz for 10 s. While further improvements are expected from increasing the finesse of the reference cavity together with a larger correction bandwidth, the coherence length achieved is already more than sufficient for interference lithography.

8966-10, Session 3

Record-low noise performance of high-power picosecond MIXSEL

Sandro M. Link, Mario Mangold, Valentin J. Wittwer, Alexander Klenner, Matthias Golling, Bauke W. Tilma, Ursula Keller, ETH Zurich (Switzerland)

We present timing-jitter measurements of a free-running and actively stabilized modelocked integrated external-cavity surface emitting laser (MIXSEL). The MIXSEL combines the gain of a VECSEL and the saturable absorber of a SESAM into a single semiconductor structure. The MIXSEL concept offers excellent noise performance due to the short nonlinear interaction in gain and absorber, and the low-loss and high-Q cavity. We demonstrate a noise performance comparable to ion-doped solid-state lasers, which typically show excellent stability even at GHz repetition rates.

The water-cooled MIXSEL in a stable home-made housing is pumped by a commercial fiber-coupled diode array and has excellent rms intensity noise of 0.11% (1 Hz to 40 MHz). We measured the single-sideband timing phase noise power spectral density with a signal-source-analyzer. In free-running operation the MIXSEL generated 14.3-ps-pulses with 600 mW of average output power at 2 GHz repetition rate. We obtained rms timing-jitters of 127 fs (100 Hz to 10 MHz) and 70 fs (300 Hz to 10 MHz). This is the lowest timing-jitter of a free-running passively modelocked semiconductor laser to date. Subsequently the repetition rate of around 2 GHz was stabilized with a piezo-actuator controlling the cavity length. Generating 16.7-ps-pulses at 700 mW average output power, the laser was phase-locked to a low noise reference oscillator with a feedback loop. In stabilized operation a low rms timing-jitter of less than 70 fs (1 Hz to 100 MHz) was obtained. In the range between 100 Hz and 10 MHz we report the lowest timing-jitter ever measured from a passively modelocked semiconductor laser with a value of 31 fs.

8966-12, Session 4

Terahertz generation by difference frequency conversion of two single-frequency VECSELs in an external resonance cavity *(Invited Paper)*

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Terahertz (THz) sources are the subject of active research due to the variety of potential applications. One promising approach to generate continuous wave THz radiation is based on parametric down conversion of two laser wavelengths into the THz frequency range by difference frequency generation (DFG). However, for an efficient DFG process high optical intensities are required. Vertical external cavity source emitting lasers (VECSELs) are a promising avenue for development of higher power THz sources. Because semiconductor quantum wells have a broad gain bandwidth, a VECSEL chip designed for a specific wavelength may lase over a 10 nm bandwidth. Moreover, VECSELs can generate high optical output power in a narrow-linewidth single frequency operation.

By combining the high output power of two single-frequency VECSELs with an external enhancement cavity approach, we demonstrate a table-top, room temperature 1.9 THz source with more than 100 µW output power. To achieve optical intensities of 200 W within the DFG crystal, we phase lock the two VECSELs with emission wavelengths spaced by 6.7 nm simultaneously to the external buildup cavity. The reflection from the cavity which is separated by a grating into its two wavelength components is used for the feedback control. To increase the frequency stability, we pre-stabilize one of the VECSEL lasers to a zerodur reference cavity which results in a lasing linewidth of 25 kHz. To characterize the THz waves, we employed a cryogenic hot electron bolometer receiver as used in astronomy applications and measured a THz linewidth below 100 kHz.

8966-13, Session 4

Novel architecture of highly-compact diffraction limited single frequency vertical external cavity surface-emitting organic laser (VECSOL) with volume Bragg grating (VBG) output coupler

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Narrow-linewidth visible lasers are mandatory for high-resolution spectroscopy, LIDAR or quantum information processing applications. Such applications require compact, robust to misalignment lasers with good beam quality, high spectral purity and low cost. Organic Solid-state lasers are attractive sources able to fulfill these requirements. Unlike archetypal organic distributed-feedback lasers, Vertical external cavity surface-emitting organic lasers (VECSOLs) enable high conversion efficiencies, excellent beam quality, and power scalability. However, there is a tradeoff between a long cavity (centimeter size) offering a good M? factor but highly multimode spectrum and modest efficiency under pulsed pumping, and a short cavity (down to micrometer size) with degraded M? and larger linewidth. In this paper, we demonstrate the solution of this problem by using a volume Bragg grating (VBG) as an output coupler: their narrow angular selectivity is used as a spatial mode discriminator, while their narrow spectral selectivity ensures single-mode operation. The setup consists of a highly reflective plane mirror coated with an 18-µm-thick film of polymethylmethacrylate doped with Rhodamine 640. An 8-mm-thick VBG with ~98% diffraction efficiency at 632.8 nm closes the 0.5-mm long cavity. The laser is end-pumped at 532 nm with 20-ns pulses from a frequency-doubled Nd:YAG laser. A diffraction-limited beam (M2 = 1.09) is obtained even for unmatched pump and cavity beams or for a plano-plano unstable resonator. The linewidth was deduced to be 160 MHz FWHM from a measured coherence length of 60 cm. The laser cavity is compact (volume ~1 cm3), unlike traditional surface grating-tuned dye lasers of comparable linewidth.

8966-14, Session 4

Wafer-fused VECSELs emitting in the 1310 nm waveband *(Invited Paper)*

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1310 nm waveband lasers capable of producing high output power that can be coupled into single mode fibers are important for new generations of fiber lasers and amplifiers . In addition, these lasers are expected to find broad applications in frequency doubled lasers, bio-medicine, etc . At 1310 nm wavelengths, the maximum output power that can be coupled into a single mode fiber with existing edge-emitting lasers is limited to about 0.5 W. It is very recently that optically pumped VECSELs emitting in the 1310 nm band have demonstrated output power levels in excess of 6 W. This high performance was reached due to the application of gain mirrors based on InAlGaAs/InP active cavities and AlGaAs/GaAs wafer fused distributed Bragg reflectors (DBRs). Previous demonstrations of high power 1310 nm VECSELs were based on gain mirrors with intra-cavity diamond heat-spreaders that are quite efficient in extracting heat generated in the active region. Nevertheless this approach has drawbacks of multiple line lasing spectra, high complexity and cost. In this paper we will present for the first time Watt-level 1310 nm wafer-fused VECSELs based on gain mirrors with heat dissipation in the "flip-chip" configuration - the approach that is widely used in the state-of-the-art and industrial VECSELs emitting around 1 um. It is expected that this advancement will boost the development of new types of fiber lasers and amplifiers based on the recently developed Bi-doped fibers as well as of frequency-doubled red lasers.

8966-28, Session 4

High-efficiency tunable yellow-orange VECSEL with an output power of 20 W

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Frequency-doubled Vertical-External-Cavity Surface-Emitting Lasers (VECSELs) offer a viable solution for generating high-brightness light in the visible wavelength range. They are an excellent alternative to the more complex and expensive dye and solid state lasers for use in many applications. Furthermore, their cost-effectiveness and compactness make them especially suitable for medical applications, such as eye surgery, dermatology and cell imaging. High power VECSELs operating in the yellow-orange range are also promising light sources for laser guide star applications.

We report on the development and realization of a high-efficiency intra-cavity frequency doubled VECSEL emitting around 588 nm. The MBE-grown gain chip incorporated 10 GaInAs/GaAs/GaAsP quantum wells and it was cooled via diamond heat spreader attached to a water-cooled copper mount. The V-shaped cavity included a birefringent filter and an etalon for wavelength tuning and linewidth narrowing. The frequency conversion was achieved using a temperature controlled non-critically phase-matched lithium triborate (NCPM LBO) crystal, placed close to the beam waist. The frequency doubled light was then extracted through the cavity folding mirror.

The maximum frequency doubled output power achieved was 20 W which corresponded to an emission spectrum centered at ~588 nm (with FWHM < 0.5 nm), an optical-to-optical conversion efficiency of ~27 %, and a mount temperature of 8.3 °C. The maximum conversion efficiency obtained was ~28 % for 16 W of output power. The VECSEL had a tuning bandwidth of ~26 nm ranging from about 576 to 602 nm.

8966-15, Session 5

High power electrically pumped VECSELs and arrays *(Invited Paper)*

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VECSELs are characterized by an outstanding brightness of 100kW/mm?/ster and a small spectral width. Electrical pumping and the potential to combine many of them in arrays allow for highly integrated and easy to manufacture laser sources which can be scaled towards high power. This almost ideal value proposition is affected by the penalty in efficiency which reduces the output power from VCSELs towards multimode VECSELs and finally single mode VECSELs. The root causes for this lower performance are optical losses in the extended cavity, a mismatch of pump and mode profile and losses related to the oxide aperture which is used for current confinement. The reduction of losses requires a careful design of doping distributions in the epitaxially grown layers as these losses have to be balanced against the requirement of low electrical resistance across the many hetero-interfaces in the DBR mirrors. The mismatch of pump and mode profile and the aperture related losses are addressed by an improved current injection enabled by a tailored electrical contact. In this paper optimized structures will be presented which enable a significant increase of efficiency and output power towards more than 150mW in a single mode and more than 300mW in multimode operation. The optical concept of the extended cavity can use a plane mirror in the simplest case thus facilitating the power scaling

in arrays with many individual VECSEL apertures combined on a single chip.

8966-16, Session 5

Coaxial tunnel junctions: a novel approach to reduce the current crowding effect in electrically-pumped VECSELs

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The numerical investigation of the current injection into the active region of the electrically-pumped vertical-external-cavity surface-emitting lasers (E-VECSELs) will be presented. The main drawback of E-VECSELs is the multiple transversal mode operation induced by strong current crowding effect. To reduce this effect we propose a novel approach based on selectively etched tunnel junctions in the form of the coaxial rings. We show a significant improvement of the higher order modes suppression for high emitting powers as a result of this unique geometry.

To achieve high output power in E-VECSEL a broad aperture of at least 35 ?m is necessary and thus the problems of current crowding at the edge of the active region appear. This is a drawback resulting in non-Gaussian-like profile of carrier concentration and hence an optical gain distribution favours higher order modes. Therefore the optimal geometry of tunnel junction is necessary to ensure desired distribution of the current injected into the active region. In this case a nonstandard tunnel junction patterning is proposed in the form of several coaxial rings of different width. It assures the desired Gaussian-like distribution of the optical gain profile, very close to one achieved by the optical pumping in standard VECSELs. The optimization of the tunnel junction geometry and specific resistivity aimed for the reduction of the current crowding effect will be shown. The presented results are of great importance for the efficiency of E-VECSELs and also for high power VCSELs of narrow spectral width.

8966-17, Session 5

SESAM-modelocked electrically pumped VECSELs emitting 6.3-ps pulses

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Optically pumped vertical external cavity surface emitting lasers (OP-VECSELs) evolved to high-power laser sources offering excellent beam-quality, wavelength flexibility and low-noise properties in a compact and simple cavity. Passively modelocked with a semiconductor saturable absorber mirror (SESAM), VECSELs demonstrated fs-pulses with multi-Watt average output powers at gigahertz repetition rates.

Electrical pumping (EP) is an obvious step to make these semiconductor lasers even more compact and suitable for chip integration, potentially enabling access to applications such as data communication or optical clocking. With SESAM-modelocked EP-VECSELs, 57-ps pulses with an average output power of 40 mW and 9.5-ps pulses with 7.6 mW have been obtained. However, due to the intrinsic trade-off between electrical and optical properties in the design of EP-VECSELs, short pulses at high average output power are difficult to achieve. This challenge was previously addressed in our theoretical guidelines for power scaling and modelocking optimization and later experimentally verified.

Here, we report on the successful implementation of an improved design and fabrication scheme for EP-VECSELs, grown and fabricated at ETH Zurich. These lasers enabled a further decrease in pulse duration to 7.3 ps while increasing the average output power to 13.1 mW at 1.46-GHz repetition rate. The shortest pulse duration measured was 6.3 ps with an average power of 6.2 mW.

In addition to the modelocking experiments, we present a thorough cw-characterization of our EP-VECSELs of different sizes and in different cavity configurations, pointing out the inevitable trade-off between high-power multi-mode and low-power single-mode operation thus limiting the modelocking performance.

8966-18, Session 5

216 MHz repetition rate passively mode-locked electrically-pumped VECSEL

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Electrically pumped vertical external cavity surface emitting laser (EP-VECSEL) in mode-locked regime is an attractive source for applications were ps pulses with average output power below few hundred mW in compact laser configuration are required. To date mode-locked EP-VECSELs with average output power up to 40mW and pulses as short as 14.8 ps were demonstrated. Here we report a significant reduction of laser repetition rate down to 216 MHz. It is five times reduction as compared with previous reports and it will enable the scaling of laser peak power.

The active region of EP-VECSEL sample (provided by dr. A. Mooradian) was based on strain compensated InGaAs/GaAsP quantum wells designed for 980 nm emission. Quantum dot based semiconductor saturable absorber mirror was used to mode-lock the laser allowing low pulse fluence and relieved cavity design. The laser was realized in multi-folded cavity configuration. Active region was pumped with 730 mA current for stable operation. Average output power of 8 mW during the mode-locked operation was achieved at a repetition rate of 216 MHz, with the pulse duration of 24 ps. The further reduction of repetition rate resulted in unstable operation due to the short few-ns level carrier lifetime in EP-VECSEL. Output power could be improved up to 34 mW with pulse duration of 42 ps at a repetition rate of 499 MHz.

Although the achieved peak power of 1.5 W is low comparable to alternative laser sources, a further scaling of average output power and pulse compression will enable higher values of >10 W in further development.

8966-19, Session 6

Generation of high-purity microwave signals from a dual-frequency OP-VECSEL *(Invited Paper)*

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Coherent population trapping (CPT) is an interesting technique for the development of compact atomic frequency references. We describe an innovating laser source for the production of the two cross-polarized coherent laser fields which are necessary in CPT-based atomic clocks.

It relies on the dual-frequency and dual-polarization operation of an optically-pumped vertical external-cavity semiconductor laser. This particular laser emission is induced by intracavity birefringent components which produce a controllable phase anisotropy within the laser cavity and force emission on two cross-polarized longitudinal modes. The laser emission is tuned at the Cs D2 line (? = 852.14 nm), and the frequency difference ∆? between the two laser modes is tunable in the microwave range.

The laser line wavelength is stabilized onto an atomic hyperfine transition, and concurrently the frequency difference is locked to an ultra-low noise RF oscillator at 9.2 GHz. The high spectral purity of the optically-carried microwave signal resulting from the beatnote of the two cross-polarized laser lines is assessed through its narrow spectral linewidth (<30 Hz) as well as its low phase noise (≤ -100 dBrad2/Hz). The performance of this laser source is already adequate for the interrogation of atoms in a CPT atomic clock, and should result in an estimated relative stability of 3.10-13?-1/2 – one order of magnitude better than commercial atomic clocks.

8966-20, Session 6

Experimental and theoretical study of noise in a dual-frequency VECSEL

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We investigate, both experimentally and theoretically, the spectral behavior of the intensity noises as well as the phase noise of the radio frequency (RF) beatnote generated by optical mixing of two orthogonally polarized modes of a dual-frequency VECSEL. To be more specific, we measure the relative intensity noises (RINs) and the correlation between the intensity noises between 10 kHz and 50 MHz of the two laser modes for different nonlinear coupling strengths between them. Moreover, we explore the spectral behavior of the RF phase noise and its dependence on the strength of non-linear coupling between the two laser modes. The theoretical model considers pump intensity fluctuations as the only source of noise. The pump fluctuations, entering into the two spatially separated laser modes on the active medium, are approximated to be white noises of identical amplitudes, partially correlated, and in phase. To model the RF phase noise, we take into account two different physical mechanisms: (i) the thermal fluctuations of the refractive index of the semiconductor active medium induced by pump intensity fluctuations and (ii) the phase-intensity coupling due to large Henry factor of the semiconductor gain medium. For all the results, theory shows very good agreement with the experiment.

8966-21, Session 6

Systematic investigation of single- and multi-mode operation in vertical-external-cavity surface-emitting lasers

Matthias Wichmann, Mohammad K. Shakfa, Philipps-Univ. Marburg (Germany); Maik Scheller, College of Optical Sciences, The Univ. of Arizona (United States) and Desert Beam Technologies LLC (United States); Arash Rahimi-Iman, Bernd Heinen, Philipps-Univ. Marburg (Germany); Jerome V. Moloney, College of Optical Sciences, The Univ. of Arizona (United States) and Desert Beam Technologies LLC (United States); Stephan W. Koch, Philipps-Univ. Marburg (Germany) and Desert Beam Technologies LLC (United States); Martin Koch, Philipps-Univ. Marburg (Germany)

Due to their ability for high power operation, excellent beam quality and wavelength diversity, vertical-external-cavity surface-emitting lasers (VECSELs) are interesting for a variety of research fields. Most applications require single-frequency emission which can be enforced by using a birefringent filter placed inside the cavity. Without intra-cavity filters, a VECSEL usually operates in a longitudinal multi-mode regime, at least if the resonator is sufficiently long. Moreover, it has been show that by inserting an etalon inside the cavity, the VECSEL can be forced into a two-color operation which can be utilized for the generation of continuous wave terahertz radiation. In this case, the spectrum is condensed into two wavelengths packages, typically spaced by a few nm and at least two longitudinal modes are present (one at each color). However, for the generation of terahertz waves, the total number of longitudinal modes matters as their beat signal is transformed into the THz spectrum.

Here, we present a systematic study of the longitudinal single- and multi-mode emission of VECSELs using streak camera measurements and interferometric measurement techniques. The laser emission is analyzed in dependence of the pump power, employing various cavity designs as well as different output couplers. We observe a steep increase of the emission bandwidth close to the laser threshold with only minor variance at higher pump powers. Additionally, we show that a stable two-color lasing – with both lasing colors sharing the same gain region – is intrinsically connected to a high number of longitudinal modes participating in the laser emission.

8966-22, Session 6

Picosecond MIXSEL for clocking applications

Mario Mangold, Valentin J. Wittwer, Christian A. Zaugg, Sandro M. Link, Matthias Golling, Bauke W. Tilma, Ursula Keller, ETH Zurich (Switzerland)

Applications such as optical clocking and sampling benefit from sub-10-ps high-power lasers with repetition rates in the high gigahertz regime. A promising source is the modelocked integrated external-cavity surface emitting laser (MIXSEL), which combines the gain of vertical-external-cavity surface-emitting lasers (VECSELs) with the saturable absorber of a semiconductor saturable absorber mirror (SESAM) in one semiconductor structure. This allows for passive modelocking using a compact straight cavity, additionally offering a remarkably simple method to perform repetition rate scaling by translating the output coupler in beam-direction. With a MIXSEL based on a quantum-dot absorber, record-high average output power levels at a repetition rate of 10 GHz were demonstrated already, a further increase was inhibited by the pulse duration of 17 ps.

Here, we present a high-power MIXSEL delivering shorter picosecond pulses at even higher gigahertz repetition rates. A modified top-coating together with the new saturable absorber leads to significantly shorter pulse durations than realized before with a MIXSEL. At a repetition-rate of 5.1 GHz an output power of 1.05 W in 2.4 ps-pulses was achieved. This is a decrease in pulse duration of a factor seven compared to previously published watt-level MIXSELs. Furthermore, we confirm the simple repetition-rate scaling up to 10 GHz with 3.9-ps-pulses at 1.29 W output power and even up to 20.7 GHz with a pulse duration of 2.35 ps at 607 mW average output power. The coverage of a broad range of high gigahertz repetition rates makes this MIXSEL a unique high-power ultrafast laser.

8966-23, Session 7

Femtosecond mode-locked red AlGaInP-VECSEL *(Invited Paper)*

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Advantageous properties such as high output power and bandgap engineering have made vertical external-cavity surface-emitting lasers (VECSELs) an important category of continuous-wave power-scalable semiconductor lasers. Furthermore, the introduction of a semiconductor saturable absorber mirror (SESAM) into the cavity has proved to allow mode locking with excellent results. Since most research has been limited to the infrared spectral range from 830 nm to 1.5 µm, only in 2013 a mode-locked VECSEL was realized in the visible spectrum.

We present passive mode locking of an AlGaInP-VECSEL emitting at around 665 nm. Both the gain structure and the SESAM are fabricated by metal-organic vapor-phase epitaxy and include a Bragg mirror consisting of 55 ?/4 pairs of Al0.45GaAs/AlAs. The active region contains 20 GaInP quantum wells arranged in a 5x4 resonant periodic gain structure. The absorber is fabricated in a resonant design with two GaInP quantum wells close to the surface and an additional SiO2 coating for low group delay dispersion. We use a V-shaped cavity with a concave output coupler serving as folding mirror and an overall length of around 185 mm resulting in a repetition frequency of 810 MHz. The achieved FWHM pulse duration is below 250 fs with a spectral FWHM of 2.8 nm which is around 1.5 times the Fourier limit. Due to the plane diamond heatspreader bonded onto the gain chip, we observe side pulses with the delays corresponding to the thickness of the diamond. Further research towards all quantum dot mode locking of VECSELs in the red spectral range is made to reach lower wavelength ranges.

8966-24, Session 7

Passively mode-locked VECSELs at 675 nm and 2 µm *(Invited Paper)*

Antti Härkönen, Tomi Leinonen, Soile Suomalainen, Sanna Ranta, Jonna Paajaste, Tampere Univ. of Technology (Finland); Uwe Griebner, Günter Steinmeyer, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany); Mircea Guina, Tampere Univ. of Technology (Finland)

During the past few years, passively mode-locked vertical-external-cavity surface-emitting lasers (VECSELs) have developed rapidly. Excellent results have been obtained in the field of ultra-short pulse generation, high average power, and high repetition rate, for example. Most of the heroic results have been achieved using mature InGaAs/GaAs technology for 1 µm wavelength. In our work we have extended the wavelength coverage of mode-locked VECSELs to visible part of the spectrum (675 nm) using GaInP/AlGaInP/GaAs material and towards the mid-IR (2 µm) using InGaSb/GaSb material.

In both cases we have used SESAMs for passive mode-locking. At 675 nm we have obtained 5 ps pulses with 45 mW average power and 973 MHz repetition rate. At the 2 µm wavelength we were able to produce sub-400 fs pulses with 25 mW average power and 890 MHz repetition rate. In this paper we will review the red VECSEL results and the latest developments clarifying the dynamical properties of GaSb-based SESAM used for mode-locking at 2 µm. The results show that the intrinsic wavelength flexibility of VECSELs can be applied for the short-pulse generation in a rather large spectral range, making this laser type even more attractive for many applications.

8966-25, Session 7

Femtosecond pulse mode-locked VECSELs *(Invited Paper)*

Keith G. Wilcox, Univ. of Dundee (United Kingdom) and Univ. of Southampton (United Kingdom)

Here, I will review our recent work on femtosecond pulse mode-locked VECSELs. I will summarise the key performance advances and will discuss the design criteria for the gain structure and SESAM necessary to achieve femtosecond pulse durations as well as discuss the approaches we are using to scale the average power to multi-Watt levels through thermal management of both the gain structure and the SESAM.

8966-11, Session 8

Generation of new spatial and temporal coherent states using VECSEL technology: VORTEX, high order Laguerre-Gauss mode, continuum source *(Invited Paper)*

Mohamed Sellahi, Mohamed Seghilani, Univ. Montpellier 2 (France); Isabelle Sagnes, Grégoire Beaudoin, Xavier Lafosse, Luc Legratiet, Lab. de Photonique et de Nanostructures (France); Philippe Lalanne, Institut d'Optique (France); Mikhaël Myara, Arnaud Garnache, Univ. Montpellier 2 (France)

Since years, the VeCSEL concept is pointed out as a technology of choice for beyond-state-of-the-art laser light sources, demonstrating wavelength flexibility, high power, high spatial and temporal coherence, linear polarization state, CW or pulsed operation, compacity and functionnalities. The targeted coherent state is typically the common gaussian TEM00, single frequency, linearly polarized lightstate.

In this work, we take advantage of the VeCSEL technology for the generation of other kinds of coherent states, thanks to the insertion of intracavity functions. These new kinds of coherence target many applications including optical tweezers, telecommunications, fundamental physics, sensors, …

A first part of this work aims at demonstrating new spatial coherence. For this purpose, we developed a semiconductor technology for transverse phase and intensity control inside the cavity. The intensity control is obtained thanks to sub-wavelength metallic masks deposited on the surface of the semiconductor chip. For the phase control, we developed an ultra low-loss photonic-crystal planar technology. All this technological development permitted the generation of high purity single high order Laguerre-Gauss mode (degenerated or non generated, including VORTEX), preserving the coherence properties (propagation factor, noise) of more usual TEM00 VeCSELs. It also paves the way for the generation of other coherences (Bessel beams) or new functionnalities (wavelength filtering, …).

In a second part, we explore new time domain coherence : owing to a high gain semiconductor chip design and the insertion of intracavity AOM, we demonstrated the first Frequecy-Shifted-Feedback VeCSEL, with a broadband coherence state as wide as 300 GHz.

8966-26, Session 8

Recent advances in the development of high power optically pumped semiconductor lasers *(Invited Paper)*

Jill D. Berger, Andrea Caprara, Juan L. Chilla, Sergei V. Govorkov, Arnaud Y. Lepert, Wayne Mefferd, Qi-Ze Shu, Luis Spinelli, Coherent, Inc. (United States)

Optically-pumped semiconductor (OPS) lasers with intra-cavity frequency doubling and tripling provide wavelength-flexible, efficient, low noise, CW laser sources in the visible and ultraviolet. We report on lasers combining InGaAs gain media with LBO nonlinear crystals to produce single and multi-transverse mode lasers at wavelengths of 355 nm in the ultraviolet and from 460 – 590 nm in the visible. Designs for maximum efficiency enable ultra-compact packages in the 1-5W visible power range, while designs scaled for higher power achieve more than 25W in the visible.

The lasers are environmentally robust and reliable, and are useful for medical, life sciences, light show, and scientific applications.

8966-27, Session 8

2-µm high-brilliance micro-cavity VECSEL with >2W output power *(Invited Paper)*

Sebastian Kaspar, Marcel Rattunde, Christian Schilling, Peter Holl, Steffen Adler, Andreas Bächle, Christian Manz, Rolf Aidam, Klaus Köhler, Joachim Wagner, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany)

VECSEL are attractive laser sources for many applications, as they simultaneously offer a multiple-Watt output power and an excellent beam quality [1]. On the other hand the external cavity configuration makes conventional VECSEL modules rather bulky compared to e.g. semiconductor diode lasers, limiting their use in applications requiring a small footprint.

To circumvent this problem, the concept of micro-cavity VECSELs (µC-VECSEL) has been introduced, where the external cavity mirror is placed in close proximity to the surface of the VECSEL semiconductor chip. GaSb-based µC-VECSELs have been demonstrated first by Ouvrard et al. with an output power of up to 3.5 mW [2].

Here, we present GaSb-based µC-VECSELs with Watt-level output power. The SiC heatpreader bonded to the VECSEL chip for efficient heat-removal was HR-coated, constituting that way the outcoupling mirror of a 400-µm long cavity. This cavity is rendered stable by the thermal gradient index lens, which is generated in the heatspreader and VECSEL chip by pump absorption.

The effect of thermal lensing on the performance of 2-µm emitting GaSb-based µC-VECSELs was studied using different VECSEL structures optimized for either 980-nm pumping, i.e. a large quantum deficit and thus strong thermal lensing, or 1.5-µm pumping. For a given pump photon flux, the latter results in a thermal lens with reduced dioptric power, and thus a larger cavity mode diameter. Using 1.5-µm pumping, we achieved an output power of 2.2 W at M2=3.5 and 700 mW in TEM00 emission, compared to 750 mW (100 mW TEM00) for 980 nm pumping.

References

[1] M. Kuznetsov et al., IEEE J. Sel. Topics in Quantum Electron. 5, pp. 561-573 (1999).

[2] A. Ouvrard et al. IEEE Photon. Technol. Lett. 17, 2020 (2005).

8966-29, Session 8

Industrial integration of high coherence tunable VECSEL in the NIR and MIR

Laurence Ferrieres, Innoptics SAS (France); Attia Benselama, Institut d'Electronique du Sud (France); Isabelle Sagnes, Lab. de Photonique et de Nanostructures (France); Mikhaël Myara, Univ. Montpellier 2 (France); Vincent Lecocq, Innoptics SAS (France); Laurent Cerutti, Univ. Montpellier 2 (France); Stéphane Denet, Innoptics SAS (France); Arnaud Garnache, Univ. Montpellier 2 (France)

Demanding applications like LIDAR, velocimetry, gas analysis, atomic clock... rely on a highly coherent laser. Owing to high coherence at high power, flexible wavelength, the GaAs- and Sb-based VeCSEL technologies seem to be a well suited path to fulfill the required specifications. Till now, technical and physical knowledge of high power high coherence single frequency compact diode-pumped VECSELs have been developed at IES [1], with low intensity and frequency noise, but this promising technology is still today at laboratory stage. The expertise built up in this field, allows considering the realization of a user-friendly marketable product, with performances that do not exist on the market today at 1µm and 2.3µm. The goal of this project is to develop a diode-pumped VeCSEL, intracavity element free, with those desired performances, and to integrate this component into a compact module. The VECSELs prototypes developed in the frame of this work exhibit exciting features compared to diode-pumped solid-state lasers, they combine high power high coherence in a single TEM00 mode emission, free running narrow line-width with high SMSR, a linear polarization, broadband continuous tunability, and compact design without any movable intracavity elements. All these specifications can be reached because the VECSEL technology is based on high finesse cavity, associated to ideal homogeneous laser QW gain behavior. [1] A. Laurain, M. Myara, G. Beaudoin, I. Sagnes, and A. Garnache, "Multiwatt–power highly–coherent compact single–frequency tunable Vertical–External–Cavity–Surface–Emitting–Semiconductor–Laser," Opt. Express 18, pp.14631 (2010).

8966-30, Session 8

Demonstration of an in-phase, coherently-coupled 37-element VECSEL array

Alec C. Sills, Gavin N. West, Rose-Hulman Institute of Technology (United States); Eryn A. Fennig, Univ. of Rochester (United States); Joseph W. Braker, DILAS Diode Laser, Inc. (United States); Manoj Kanskar, Mike Grimshaw, nLIGHT Corp. (United States); Matthew T Johnson, University of Illinois at Urbana-Champaign (United States); Kent D. Choquette, Univ. of Illinois at Urbana-Champaign (United States); Paul O. Leisher, Rose-Hulman Institute of Technology (United States)

Electrically-injected vertical external cavity surface emitting laser (VECSEL) arrays are an attractive source for low-cost, high-brightness applications. Optical pumping can be used to investigate the emission properties of such devices without undergoing complex device fabrication. The design of such arrays is based on a single VECSEL chip, a 2D lens array, and a flat output coupling dichroic mirror. In this work, we report on the demonstration of an optically pumped, coherently-coupled VECSEL array. The lasing spectrum indicates single-mode operation. Near-field characterization reveals 37 individual lasing elements in a hexagonal array. Far-field measurements show an interference pattern which is consistent with in-phase coherent coupling, with >60% of the total output power present in the on-axis central lobe. The physical origin of coherent coupling is attributed the Talbot self-imaging effect wherein photons generated in each emitter are reflected to all other emitters in the array. The simplicity of the optical cavity design suggests scalability to much larger arrays, making the result of particular interest to the development of low-cost, high-brightness diode laser sources.

8966-31, Session PTue

Graphene saturable absorbers for VECSELs

Valentin J. Wittwer, Univ. of Cambridge (United Kingdom); Christian A. Zaugg, ETH Zurich (Switzerland); Zhipei Sun, Daniel Popa, Silvia Milana, Tero Kulmala, Ravi S. Sundaram, Univ. of Cambridge (United Kingdom); Mario Mangold, Matthias Golling, ETH Zurich (Switzerland); Y. Lee, Jong-Hyun Ahn, Sungkyunkwan Univ. (Korea, Republic of); Ursula Keller, ETH Zurich (Switzerland); Andrea C. Ferrari, Univ. of Cambridge (United Kingdom)

Graphene is at the centre of an ever growing research effort. The linear dispersion of the Dirac-electrons leads to a broadband absorption. This, combined with the ultrafast recombination dynamics, makes graphene a promising saturable absorber for passive modelocking of various lasers, such as fiber, solid state bulk and waveguide. Here we report mode-locking of an optically pumped VECSEL using a graphene-based

saturable absorber mirror (GSAM). Self-starting and stable modelocked operation is demonstrated with 473 fs pulses at 1.5 GHz repetition rate and 949 nm center wavelength. Wavelength tuning is achieved over a 46 nm bandwidth with the same GSAM. This consists of a single layer of graphene transferred on a mirror with a SiO2 layer. The thickness of this layer is varied in the fabrication of different GSAMs in order to control their absorption properties. Here we discuss the mirror design, the fabrication and the characterization of the GSAMs, and we give an outlook on further optimization of the design, including dielectric top coatings to protect the graphene and to increase the flexibility in the design.

8966-32, Session PTue

Beam combination of multiple vertical external cavity surface emitting lasers via volume Bragg gratings

Chunte A. Lu, William P. Roach, Air Force Research Lab. (United States); Genesh Balakrishnan, The Univ. of New Mexico (United States); Jerome V. Moloney, College of Optical Sciences, The Univ. of Arizona (United States); Alexander R. Albrecht, The Univ. of New Mexico (United States); Leonid B. Glebov, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

To achieve beam combining and/or power scaling with VECSELs, we conduct experimental study using volume Bragg gratings (VBGs). The specific VBGs is designed to reflect near 1020nm wavelength at approximately 0 degree incident angle. The VECSELs used in the experiment are pumped with 808nm diodes and consist of InGaAs MQW with emission wavelength centered on 1020nm at the specific pump power level. The beam combining/power addition setup is perfromed in a W cavity, the VECSELs are placed at the two adjacent apexes of the W with the VBGs works as the output coupler at the one end of the cavity. Several lenses are placed inside the cavity to ensure matching of cavity mode size and pump spot size on the VECSELs. Preliminary results show >80% beam combining efficiency with M2 of 1.2 at mW level output power and >70% combining efficiency with M2 of 1.6 at watt level output. The degradation of the combining efficiency and beam quality is primary due to spectral broadening and shifting and higher order mode excitation at high pumping power. An alternative beam combining scheme involves additional polarizer will be part of the discussion during presentation.

8966-33, Session PTue

Injection-locked optically-pumped vertically external cavity surface emitting laser (VECSEL)

Yi-Ying Lai, Kevin Winn, J. Michael Yarborough, Yevgeny A. Merzlyak, Yushi Kaneda, College of Optical Sciences, The Univ. of Arizona (United States)

We report a novel single-frequency, injection-locked vertical external-cavity surface-emitting lasers (VECSELs) for the first time to the best of our knowledge. The wavelength of the injection locked output can be tuned with the master laser. A lower power single-frequency VECSEL served as the master oscillator that provides wavelength tunability with frequency selective elements such as a birefringence filter, and/or an etalon. The master laser was mode-matched to the slave VECSEL ring resonator. By varying the injecting power and wavelength of the master VECSEL oscillator, we investigated the locking range of the laser. With 150 mW of the injection power, we generated above 4W of stable output in single frequency. With the ability to provide narrow linewidth, good beam quality, and stable output with sufficient power at specific wavelengths, such laser sources can be useful in many laser applications, such as precision spectroscopy.

Conference 8967: Laser Applications in Microelectronic and Optoelectronic Manufacturing (LAMOM) XIX

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8967-1, Session 1

Black and colored metals and applications *(Invited Paper)*

Chunlei Guo, Univ. of Rochester (United States)

Recently, we developed a number of techniques that allow us to dramatically alter the properties of materials using high-intensity femtosecond lasers. The techniques led to the creation of the so-called black and colored metals. In this talk, I will discuss these studies and various applications of the black and colored metals, from making more efficient light sources to turning regular materials superwicking.

8967-2, Session 1

Processing of nano-porous film based on plasmonic excitation of Au nanoparticles *(Invited Paper)*

Yasuyuki Tsuboi, Osaka City Univ. (Japan)

Recently, we proposed a novel technique for processing nanoholes (d?100 nm) on a polymer film. The technique is based on resonant excitation of localized surface plasmon of Au nanoparticles that are embedded in a polymer film. After pulsed laser excitation at ?=532 nm in a single-shot-mode, Au nanoparticles are superheated, immediately followed by explosive vaporization. As a result, small nanoholes (d ?100 nm) was produced on the polymer film, overcoming the diffraction limit of laser light (d <?). The next challenging issue of the study is to increase the density of nanoholes with homogeneous dispersion on the film. In the present study, we propose a new method for creating such a nano-porous film based on a microphase separation of a diblock copolymer. Glass substrates integrated with Au nanoparticles (d~30 nm) were prepared by a microphase separation of a diblock copolymer. Au nanoparticles ware integrated with homogeneous dispersion on the surface of glass substrate without any aggregatio. Then, substrates were spin-coated with a thin poly(methyl methacrylate) (PMMA) film (thickness~ 20 nm). The sample film was exposed to a nanosecond 532 nm laser pulse in a single-shot-mode. In the processed film, numerous nanoholes (d <?) were formed on the surface polymer film, i.e., porous film. The diameter of the nanohole showed a narrow size distribution (40 nm < d < 60 nm). Moreover, we can roughly control of the density and size of the nanoholes by varying the experimental conditions (sample preparation procedures and laser parameters).

8967-3, Session 1

real-time adaptive optimization of laser induced nano ripples by laser pulse shaping

Pornsak Srisungsitthisunti, King Mongkut's Univ. of Technology North Bangkok (Thailand); Marian Zamfirescu, Liviu P. Neagu, National Institute for Lasers, Plasma and Radiation Physics (Romania); Nicolas Faure, Lab Hubert Curien, Université Jean MONNET (France); Razvan Stoian, Lab. Hubert Curien (France)

We propose a control technique for laser induced sub- micron ripples on titanium and silicon using femtosecond laser pulse shaping. This is based on a real-time observation method of nano ripples by diffraction of UV laser beam and programmable pulse temporal design. The feedback signal provided information of ripples? period, area, direction, and uniformity. By using a genetic algorithm optimization, ripples formation were optimized for their period tuning ability and their uniformity. The diffraction signals were validated with scanning electron microscope (SEM) images. Using polarized Ti:sapphire femtosecond laser (wavelength 800 nm), ripples on titanium has periods from 610 nm to 680 nm, and ripples on silicon has periods from 710 ? 770 nm. Laser pulse energy affects optimization due to transient energy deposit on material with pulse form effects in the threshold fluence and ripple areas.

8967-4, Session 2

Laser-induced patterns on metals and polymers for biomimetic surface engineering *(Invited Paper)*

Anne-Marie Kietzig, Jorge Lehr, McGill Univ. (Canada); Luke Matus, McGill University (Canada); Fang Liang, McGill Univ. (Canada)

One common feature of many functional surfaces found in nature is their modular composition often exhibiting several length scales. Prominent natural examples for extreme behaviors can be named in various plant leaf (rose, peanut, lotus) or animal toe surfaces (Gecko, tree frog). Influence factors of interest are the surface's chemical composition, its microstructure, its organized or random roughness and hence the resulting surface wetting and adhesion character. Femtosecond (fs) laser micromachining offers a possibility to render all these factors in one single processing step on metallic and polymeric surfaces. Exemplarily, studies on Titanium and PTFE are shown, where the dependence of the resulting feature sizes on lasing power, translation speed and scan line overlap is investigated. While Ti surfaces show rigid surface patterns of micrometer scaled features with superimposed nanostructures, PTFE exhibits elastic hairy structures of nanometric diameter, which upon a certain threshold tend to bundle to larger features. Both surface patterns can be adjusted to mimic specific wetting and flow behaviour as seen on natural examples. Therefore, fs-laser micromachining is suggested as an interesting industrially scalable technique to pattern and fine-tune the surface wettability of a surface to the desired extends in one process step. Possible applications can be seen with surfaces, which require specific wetting, fouling, icing, friction or cell adhesion behaviour.

8967-5, Session 2

Growth evolution of high spatial frequency LIPSS on SiC crystal surfaces

Go Obara, Hisashi Shimizu, Taira Enami, Keio Univ. (Japan); Meng-Ju Sher, Benjamin Franta, Harvard Univ. (United States); Eric Mazur, Harvard School of Engineering and Applied Sciences (United States); Mitsuhiro Terakawa, Minoru Obara, Keio Univ. (Japan)

Multiple pulse irradiation of femtosecond laser can form Low Spatial Frequency LIPSS (LSFL) and High Spatial Frequency LIPSS (HSFL), depending upon the irradiation parameters. The periodicity? of LSFL is smaller than the laser wavelength (0.4<?/?<1), while that of HSFL is much smaller than the laser wavelength (?/?<0.4) The LSFL is formed by interference of long range surface plasmon and laser irradiation. However, the fundamental physics of HSFL formation is not reported in detail yet.

We present evolution of HSFL fabricated on SiC crystal surfaces by irradiation with femtosecond laser pulses. At early stages the initial defects in the crystal are mainly induced by successive laser pulse irradiation, leading to the reduction in the ablation threshold fluence. By observing the evolution of these structures growth under illumination with successive laser pulses, the initial nanocraters are made by nanoablation at defects in the SiC crystal surface. The Mie scattering by the nanoablated craters grows the periodic ripples. The number of HSFL is enhanced with increasing pulse number. The SiC semiconductor crystal surface becomes a metal-like phase in the center of the laser irradiated spot so that LSFL is fabricated mainly by plasmonic scattering. While the Mie scattering process is still dominant in the fringe region of the laser spot, causing the generation of HSFL, being explained by 3D FDTD method. In the fringe area SiC remains a semiconductor state because the electron number density in the crystal by laser irradiation is low. HSFLs grow during femtosecond laser irradiation at low laser fluence under Mie scattering regime.

8967-6, Session 3

Optothermal response of plasmonic nanofocusing lens under picosecond laser irradiation *(Invited Paper)*

zhidong Du, Chen Chen, Purdue University (United States); Dennis Tsao, University of California, Los Angeles (United States); Luis Traverso, Purdue University (United States); Adrienne Lavine, University of California, Los Angeles (United States); Xianfan Xu, Purdue University (United States); Liang Pan, Purdue Univ. (United States)

Nanomanufacturing provides the crucial engineering supports for many current and emerging applications, including semiconductor, data storage, alternative energy, biology and healthcare. There have been many exciting and significant findings in this field, however many scientific and engineering challenges have to be tackled in order for them to enter real world applications. At nanoscale many classical laws and theories start to break down and some other effects start to arise, bringing much of great opportunities and challenges in engineering research, particularly in the size range of 1~100 nm according to current trend of technology progression.

This seminar reports a new low-cost high-throughput maskless nanomanufacturing approach, aiming as the enabling technique for breaking optical diffraction limits in the future applications, which uses arrays of plasmonic lenses (PLs) that “fly” above the rotating surface to be thermally processed, concentrating short wavelength surface plasmons into deep sub-wavelength scales. A self-spacing air-bearing surface was designed to carry the array just a few nanometers above a substrate at linear speeds of tens of meter per second. Experimental results showed feature sizes far smaller than the far-field diffraction limit reaching state-of-the-art 22-nm half-pitch direct material processing capability using ultra-fast laser assisted nanoscale heat management and progressive multistage PL designs.

This nanomanufacturing scheme has the potential of a few orders of magnitude higher throughput than current maskless techniques, and opens a new cost effective route towards the next generation nano-manufacturing. Besides patterning and material processing, this nearfield technique can also lead to niche applications such as data storage, nanoscale metrology and imaging, and alternative energy.

8967-7, Session 5

Femtosecond laser 3D nanofabrication in glass: enabling direct write of integrated micro/nanofluidic chips *(Invited Paper)*

Ya Cheng, Yang Liao, Shanghai Institute of Optics and Fine Mechanics (China); Koji Sugioka, RIKEN (Japan)

We report on fabrication of 3D micro- and nanofluidic structures directly buried in glass using a femtosecond laser. Our technique mainly consists of two steps: (1) femtosecond laser direct writing in a porous glass immersed in water to form hollow micro- and nanofluidic channels buried in the glass; and (2) postannealing of the fabricated glass sample for consolidating the porous glass by collapsing the nanopores at a temperature close to the melting point of the glass. In particular, we find that when the polarization of the femtosecond laser pulses is perpendicular to the direction of laser writing, with the peak intensity of the pulses being near (i. e., slightly above) the ablation threshold, high-aspect-ratio (~1,000) nanofluidic channels with widths down to ~30 nm (i. e., 1/25th of the wavelength of the femtosecond laser) and lengths of tens of microns can be formed in the porous glass. The mechanism of fabrication of such nanochannels with widths much smaller than that allowed by diffraction limit is a combined contribution from a threshold effect and formation of femtosecond-laser-induced nanogratings. The nanofluidic channels can be easily incorporated into the microfluidic networks pre-written in glass, which are obtained using the same femtosecond laser beam but of higher pulse energies. We show that DNA analysis, e. g., DNA molecule stretching, can be realized using a fully integrated micro-/nanofluidic biochip. Our technique opens a new avenue to develop 3D micro-/nanofluidic systems for investigation of nanofluidics and lab-on-a-chip applications.

8967-8, Session 5

Flexible metal patterning in glass microfluidic structures using femtosecond laser direct-write ablation followed by electroless plating

Jian Xu, Katsumi Midorikawa, Koji Sugioka, RIKEN (Japan)

Integration of metallic micro/nanostructures into microfluidic systems enables us to introduce many practical functionalities such as on-site temperature control, electrical manipulation and plasmonic detection of very small quantities of biological samples, which is useful for developing highly functional biomicrochips. To realize such integration, conventional metal patterning strategies such as planar photolithography processes combined with metal deposition techniques are usually employed during the fabrication procedure of microfluidic systems. Their flexibilities are always limited due to the complexity arising from the multiple steps including microfluidics fabrication, metal deposition and patterning, and stacking and bonding of substrates, in particular, for fabrication of the microfluidic structures with three-dimensional configuration.

In this paper, we propose a simple and flexible strategy for metal patterning in three-dimensional glass microfluidic structures. First, we used the femtosecond laser direct writing combined with selective wet chemical etching to fabricate three-dimensional microfluidic structures such as microchannels and microreservoirs in photosensitive glass. Then we employed femtosecond laser direct-write ablation to modify the internal walls of microfluidic structures in space-selective manner and metalized the ablated areas by the succeeding electroless plating process. Not only the top and bottom walls of glass microfluidic structures but also the sidewalls can be selectively metalized using this technique. Therefore, this technique allows us to form continuous metal patterns from the inside to the outside of microfluidic structures, which is very important to control the electrical microdevices integrated inside the microfluidics by the external power supply.

To demonstrate the application of this technique, microreactors based on integration of microheaters and microfluidic structures have been fabricated and used for controlling the temperature in microchannels and enhancing the in-channel chemical reaction. Moreover, electrical manipulation such as electro-orientation of aquatic microorganisms based on integration of microelectrodes and microfluidic structures by using this technique has been realized.

8967-9, Session 5

Nanosecond laser-induced back side wet etching of fused silica with a copper-based absorber liquid

Pierre Lorenz, Leibniz-Institut für Oberflächenmodifizierung e.V. (Germany); Sarah Zehnder, Berner Fachhochschule Technik und Informatik (Switzerland); Martin Ehrhardt, Frank Frost, Klaus-Peter Zimmer, Leibniz-Institut für Oberflächenmodifizierung e.V. (Germany); Patrick Schwaller, Berner Fachhochschule Technik und Informatik (Switzerland)

Laser-patterning of dielectric surfaces with high-precision, low-roughness and cost-effective machining for industrial applications is still challenging. Laser etching allows the fabrication of well-defined, free-form surfaces with low surface roughness needed e.g. for of optical elements. This presentation points to summarize the current and to highlight the latest achievements status of laser etching.

The different laser-etching and laser-ablation approaches of dielectrics are discussed in relation to the involved processes and the achievable precision of the etching with pulsed UV-laser sources. These results are compared to current achievements in etching of different glass materials with near-infrared laser pulses using copper based solutions as backside etching agent.

Nano- and picosecond Nd:YAG, as well as femtosecond Ti: Sapphire laser were used for etching of different glass materials like soda lime glass, fused silica and sapphire with saturated CuSO4 solutions. The etching rate and the surface quality depend from the pulse length, the laser fluence and the pulse number. Only at very specific laser etching conditions precise laser-etching with low etching rates and low surface roughness are found. The analysis of the chemical/physical material properties of the etched surface show low modification of the glass material and almost no contaminations by the used liquid.

The experimental results were compared with different mechanistic approaches including the temperature field, the chemical processes in the liquid and the generated shock waves. Finally, the etching of functional surfaces by direct writing and mask projection are shown.

8967-10, Session 5

Picosecond-laser bulk modification, luminescence and Raman lasing in single-crystal diamond

Beat Neuenschwander, Berner Fachhochschule Technik und Informatik (Switzerland); Sergei M. Pimenov, A. M. Prokhorov General Physics Institute (Russian Federation); Beat Jaeggi, Valerio Romano, Berner Fachhochschule Technik und Informatik (Switzerland)

Bulk modification and micro-structuring of diamonds using ultra-short laser pulses is of great interest due to its potential in photonic applications and diamond gem marking. We will report on bulk micro-structuring and stimulated Raman scattering (SRS) in type IIa single crystal diamond with multipulse irradiation by picosecond-laser pulses at the wavelengths 355nm (10ps) and 532nm (10ps & 44ps). The experiment is expanded by additional setups for on-line video imaging and spectroscopic measurements during laser irradiation and structure growth in the bulk diamond from the backside of the crystal. We will discuss the influence of the crystal orientation ([100] and [110]) relative to the laser beam onto (i) the optical breakdown threshold, (ii) the character of the structural modifications and (iii) generation of SRS during irradiation. It will be shown that the formation of bulk microstructures dramatically influences the behavior of the SRS and that the structure growth and the laser-induced breakdown in the bulk are governed by the dielectric breakdown mechanism. We will present the conditions for efficient SRS lasing depending on the different pulse durations. Based on the Stokes-to-anti-Stokes intensity ratio in the recorded SRS spectra we will further propose a method of local temperature measurements in the bulk of diamond to determine the “pre-breakdown” temperature.

8967-11, Session 5

Dynamics of interference of femtosecond laser-induced stress waves and crack formation inside a LiF single crystal

Masaaki Sakakura, Naoaki Fukuda, Yasuhiko Shimotsuma, Kiyotaka Miura, Kyoto Univ. (Japan)

If laser-induced cracks in solid materials can be controlled, the speed and accuracy of material scribing can be improved. In our previous study, we observed the generation of a stress wave after tightly focusing a femtosecond laser pulse inside a solid material, and elucidated that the generation and propagation of cracks were accompanied by the laser-induced stress wave inside some single crystals. In particular, inside a LiF single crystal, tensile stresses in a laser-induce stress wave at the crack tips drove the propagation of the cracks. This finding gives us an idea to control the propagation of cracks by interference of a number of laser-induced stress waves, which can be generated simultaneously by simultaneous multispots’ laser irradiation system with a spatial light modulator. We have already reported that the lengths of some laser-induced cracks inside a LiF single crystal become shorter or longer, depending on the distribution of photoexcited points. We explained the photoexcited-spots-dependence of the crack lengths in terms of the interference of laser-induced stress waves. However, there has been no experimental evidence of the explanation. In this paper, we will report the observation of interference of fs laser-induced stress waves inside a LiF single crystal. The observation shows that the interference of two stress waves generated a compressive stress at the crack tip and the compressive stress prevents the crack from propagating further. This observation clearly shows that the crack propagation can be controlled by the interference of stress waves.

8967-12, Session 6

Spatial and temporally focused femtosecond laser pulses for material processing *(Invited Paper)*

Jeffrey A. Squier, Jens U. Thomas, Erica K. Block, Charles G. Durfee III, Colorado School of Mines (United States); Sterling J. Backus, Kapteyn-Murnane Labs., Inc. (United States)

Simultaneously spatially and temporally focused pulses (SSTF) can be used to mitigate nonlinear effects, such as self-focusing, when processing with low numerical aperture, femtosecond beams. This enables precise targeted ablation or material modification deep within optically transparent materials. We demonstrate the utility of this processing technique for both material processing, and medical applications. For example, high-aspect ratio channels can be created in materials as SSTF facilitates backside ablation. Similarly, precise targeted ablation is possible within biological materials making it possible to rapidly cut up to sensitive barriers. Detailed analysis of the focusing characteristics of this pulse geometry as applied to these processing

methods is presented. Finally, for the first time, we demonstrate a watt level, high repetition rate (10 kHz), chirped pulsed amplification system that has an integrated SSTF compressor. The novel femtosecond micromachining workstation powered by this new amplified system is described.

8967-13, Session 7

Dynamic optics for laser direct writing *(Invited Paper)*

Patrick Salter, Martin J. Booth, Univ. of Oxford (United Kingdom)

We present new methods that use dynamic optical elements – deformable mirrors and liquid crystal spatial light modulators – to control focal fields for material processing using ultrafast lasers. Adaptive aberration correction maintains focal quality when focusing deep into high refractive index materials. Dynamic parallelisation methods permit independent control of up to hundreds of fabrication spots, enabling increases in fabrication speed. Adaptive methods for control of pulse front tilt are also presented. These methods are combined with 3D microscopy for online measurement of fabrication performance. Applications include waveguide circuits, photonic crystals, and fabrication in diamond.

8967-14, Session 7

Femtosecond laser processing and spatial light modulator *(Invited Paper)*

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The use of the femtosecond laser enables generation of small spot sizes and ablation features. Ablation of the small features usually requires only a small amount of laser power to be delivered to the ablation spot. When using only a one beam for the ablation of the small features this process is bound to be time consuming. The spatial light modulator (SLM) can be used to create computer generated holograms (CGH) that can be used for manipulating and shaping of the laser beam in various applications. When using laser with relatively high power the original beam can be divided up to hundreds beams and still have the energy of the individual beam above the ablation threshold of the material. This parallel laser processing enables the utilization of all laser power regardless of the machining task.

CGHs together with SLM enable simultaneous control over various parameters in laser ablation. For example, laser beam can be divided to several hundred beams and intensity of the each individual beam can be controlled with great accuracy. This can be used to speed up the processing time considerably. Using SLM it is also possible to generate 3-dimensional intensity patterns which will be novel feature in laser micromachining. Feature sizes of the parallel laser processing can be diminished down to a few microns using very simple optical setup. Various laser micromachining applications, for example engraving, drilling and marking, can benefit from this technique.

8967-15, Session 7

Focal length stabilization of a tunable lens integrated focus shifting unit

Gregory Eberle, Benjamin Boesser, Konrad Wegener, ETH Zurich (Switzerland)

A focus shifting unit integrated with a tunable lens allows for rapid response times, high accuracy, no moving parts, small footprint and simple controllability. The focus shifting unit is designed for laser material microprocessing applications where tolerances of a few micrometers are required. However, the polymer membrane of the tunable lens can be severely altered by long term thermal influences from the environment and high powered laser beams. Utilizing the working principles of a cylinder lens, a discrete proportional-integral-derivative controller with an anti-reset-windup is simulated and designed for offline regulation of the focal length of the tunable lens. This allows for integration into a three-dimensional scanhead system to reliably deflect the focused laser spot at the workpiece level over long periods of time, i.e. > 8 hours. Deviation of the focal length of the tunable lens is identified by the cylinder lens through ellipticity of a probe laser beam. The focal length is subsequently corrected by altering the input current into the tunable lens by means of the control system which is based on numerical methods. The thermal behavior of the tunable lens, system identification and synthesis of the controller, design of the focus shifting optical system and validation of the controller are studied.

8967-16, Session 8

Influence of Laser Parameters on Quality of Microholes and Process Efficiency

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To enable the direct-spinning process of super-micro fibres (< 0.5 dtex) suitable for novel medical, hygienical and technical products microhole arrays with diameters down to 25 µm in very high quality are required. Hence, the attention was turned to microholes with diameters below 30 µm processed in 0.3 mm stainless steel. Using ultrashort pulses together with a helical drilling optics microholes with high accuracy can be manufactured in metals. However, the required process time for a single microhole ranges up to several ten seconds. Simple energy balance considerations show that higher averaged powers - either achieved with larger pulse energies or an increased repetition rate - considerable reduce the process time. In this case plasma formation and heat accumulation show increased formation of melt and recast. Thus, the objective is to increase the productivity while maintaining consistent quality of the microholes.

With this aim, the influence of pulse energy and repetition rate on the borehole geometry, processing quality and process efficiency was investigated for helical drilling. In the present research work a TruMicro 5250 (tp=8 ps, ?=515 nm, fR=800 kHz) was used. To determine the process time of the microhole the transmitted laser radiation was recorded. A systematic evaluation of the process quality and process time dependent on pulse energy and repetition rate will be presented in this contribution.

First laser manufactured spinning nozzles with microhole diameters down to 25 µm processed in 0.24 mm thick AuPt alloy were used to fabricate unique super-micro fibres with yarn counts down to 0.2 dtex.

8967-46, Session PTue

Spot size dependence of LIPSS formation threshold using femtosecond laser

Hisashi Shimizu, Go Obara, Mitsuhiro Terakawa, Keio Univ. (Japan)

Many papers have been published on the surface ripples (Laser induced periodic surface structures: LIPSSs) formation on various materials by multiple pulses irradiation of femtosecond laser with lower fluences

compared to the single-shot ablation threshold. The period of the LIPSS is as approximately same as the incident wavelength ? (Low spatial frequency LIPSS), and harmonic periodicity ripples ?/2 (High spatial frequency LIPSS) are formed under some particular experimental conditions. The interference of the plasmon polaritons with the incident wave resulted in the modulation of the optical intensities for LSFL formation. On the other hand, HSFL formation process is still under investigation.

In this paper, we report the spot size dependence of LIPSS-formation threshold on the silicon carbide (SiC: bandgap 3.2 eV approximately), based on the idea that HSFLs originate in surface defects on a crystalline sample irradiated by femtosecond laser pulses. The threshold of LIPSS formation changed clearly in the range of 100 ?m < ?0 < 20 ?m, which was evaluated by the D2 method in the 1/e2 beam radius ?0. We fitted the threshold with the two ablation thresholds, Fd (ablation threshold at defect site) and Fi (intrinsic ablation threshold), and probability of hitting a defect area. With 100 pulses of 80 fs, 800 nm laser of spot radius ?0 = 25 ?m at 600 mJ/cm2 (nearly equal to HSFL formation threshold), HSFLs are not formed uniformly in the laser spot, but are randomly distributed, suggesting that HSFLs could originate in surface defects on crystals.

8967-47, Session PTue

Laser radiation attenuator on the basis of four Dove's prisms

Jan A. Owsik, Military Univ. of Technology (Poland); Anatoly A. Liberman, Alexander A. Kovalev, Alexey S. Mikryukov, Sergey A. Moskalyuk, Michail V. Ulanovsky, All-Russian Research Institute for Optical and Physical Measurement (Russian Federation); Janusz Noga, Military Univ. of Technology (Poland); Anna Z. Rembielinska, LOT Polish Airlines (Poland); Joanna Walczuk, Agencja Restrukturyzacji i Modernizacji Rolnictwa (Poland)

The study [1] presents the design of attenuator with weakening factor ~ 10-3, based on two Dove's prisms, rigidly mounted on a turntable. The main peculiarity of the attenuator lies in the adjustment methodology, allowing to determine the unknown parameters of attenuator, calculate the adjustment angles at which the attenuation factor is independent of polarization of the incident radiation as well as to clarify the size of the attenuation factor. This methodology bases on the geometric properties of the angle between the edges of the prism, which consists in the fact that there is only one pair of the radiation incidence angle at which the plane of reflection from each of its planes are perpendicular to each other. For ideal Dove prisms, angle between the reflecting planes is 60°, but for real prisms can vary by few degrees [1]. The main disadvantage of this attenuator is the unpredictability of the direction of output radiation. In an ideal configuration it is directed perpendicular to the incident radiation, but due to the deviation of angle from ideal value between the edges of the prism, its direction moves. Therefore, successive use of two such attenuators to achieve attenuation factor of 10-6 is very difficult, because for the second attenuator, mounted on a different turntable, the entire adjustment procedure needs to be done again.

[1] Owsik J., Avdeev Y., Liberman A. A. Kovalev A. A., Mikryukov A. S., Moskalyuk S. A., Noga J., Rembieli?ska A., Walczuk J.,"Fresnel attenuator of laser radiation power", Proc. SPIE 8607, 8607 1F (2013).

8967-49, Session PTue

High precision laser forming for micro actuation

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For assembly of micro-devices, such as photonic devices, alignment of components is often critical for their performance. Laser forming, also known as laser-adjusting, can be used to create an integrated micro-actuator to align the components with sub-micron precision after bonding. In this paper, an analytical model and a 3-D Finite Element (FE) model are validated by experiments. The models are used to identify the optimal parameter settings for a high precision actuator. A so-called three-dam planar manipulator was used to study the laser-material interaction and thermal and mechanical behavior of the laser forming mechanism.

With the experimental setup we measure the deformation, surface temperature and the reflected laser radiation in real-time. The time-dependent thermal and mechanical FE models match with experimental results. Parameter studies based on the FE model show that the magnitude of the deformation is most sensitive to variations in absorbed laser power, plate thickness, dam width, and initial stresses.

Experimentally, a positioning resolution of 0.1µm was achieved, with a total stroke exceeding 5µm. A spread of 10% in the temporal temperature cycles was found, which was attributed to a spread in the surface absorptivity. Combined with geometric tolerances, the spread in deformation can be as large as 20%. This implies that feedback control of the laser power, in combination with iterative learning during positioning, is required for high precision alignment. However, the 3-D FE model predicts the trend in deformation sufficiently accurate to use it for design optimization of high precision 3-D actuators using laser adjusting.

8967-50, Session PTue

Laser texturing glass substrates for light in-coupling in silicon thin-film solar cells

Kambulakwao Chakanga, Ortwin Siepmann, Oleg Sergeev, Karsten von Maydell, Carsten Agert, Next Energy (Germany)

The aim of this work is to compare the effect of laser texturing on three different multi-component glasses (SCHOTT Eco, Corning Eagle XG and Saint Gobain Diamond White) for the application as light scattering structures in thin-film silicon solar cells.

Due to the low absorption coefficient in the infrared and thin film thicknesses required in silicon thin film solar cells, methods of enhancing light absorption are important. In this work we take an approach of using a 1064 nm pico second laser to texture the glass surface to reduce the reflection losses and achieve light scattering in the solar cells.

By varying the laser parameter, different degrees of texture and dielectric modification of the glass surface can be achieved. It is therefore possible to tune the degree of scattering of the glass surface as required in the solar cell. However, given the same laser parameters, the three glass types show different behavior. The morphological and optical variations are analyzed in this work. The surface texture is characterized by atomic force microscopy (AFM) and scanning electron microscopy (SEM). The optical characteristics are analyzed by UV-VIS Spectroscopy using an intergraded sphere. The light scattering capability of the textured substrates is analyzed by angular resolved measurements with an Absolute Reflectance Transmittance Analyzer (ARTA).

8967-51, Session PTue

Smart optical writing head design for laser-based manufacturing

Muhammad Junaid J. Amin, Nabeel A. Riza, Univ. College Cork (Ireland)

Proposed and demonstrated is a smart laser writing head design suited for industrial laser-based manufacturing. The design uses an Electronically Controlled Variable Focus Lens (ECVFL) which enables the highest achievable spatial resolution of writing head spot sizes for axial target distances reaching 8 meters. A proof-of-concept experiment

is conducted using a visible wavelength laser with a collimated beam that is coupled to beam conditioning optics which includes an electromagnetically actuated deformable membrane liquid ECVFL cascaded with a bias convex lens of fixed focal length. Electronic tuning and control of the ECVFL keeps the laser writing head far-field spot beam radii under 1 mm that is demonstrated over a target range of 20 cm to 800 cm. System smartness is achieved by controlling the size of the laser writing spot that can be varied to suit the desired manufacturing specification in industrial laser based cutting/writing applications. Furthermore, this laser writing head design allows beam optical power density control using the changing beam spot size without laser source current driver adjustments. This optical power density control helps reduce striation effects during cutting and unrestrained material damage due to insufficient or over-sufficient writing head laser power. Applications for the proposed writing head design, which can accommodate both continuous wave and pulsed wave sources, include laser machining, high precision industrial moulding of components, as well as materials processing requiring material sensitive optical power density control.

8967-52, Session PTue

High quality ZnO film formation by CO2 laser annealing of buried films in SiO2 matrix

Kota Yamasaki, Hiroshi Ikenoue, Tetsuya Shimogaki, Yousuke Watanabe, Daisuke Nakamura, Tatsuo Okada, Kyushu Univ. (Japan)

Zinc Oxide is a wide-bandgap semiconductor of the II-VI semiconductor group and has a direct band gap of 3.37 eV. ZnO has been considered a promising material for highly efficient optoelectronic device applications because of its exciton binding energy (60 meV) which is much larger than the room- temperature thermal energy. However, it is still difficult to realize applications because ZnO has native defects which decrease the luminescence efficiency. Therefore, high quality ZnO film formation is needed to realize highly efficient optoelectronic devices. A ZnO thin film was deposited on the quartz substrate by the pulsed laser deposition and a SiO2 thin film was deposited on the ZnO film by physical vapor deposition. The ZnO film was annealed by Q-switched CO2 laser. The laser has 10 ns pulse duration and 10 – 100 kHz repetition rate. We think that this annealing process doesn't cause defects such as oxygen vacancy, zinc vacancy, antisite defect, etc. because the ZnO film is buried in SiO2 matrix. The quality of a film was evaluated by the photoluminescence. The ZnO film before annealing had a dominant visible light luminescence which comes from defects. The ZnO film after annealing had a dominant ultraviolet luminescence which comes from band-edge emission. The result suggested that the annealed film had fewer defects and the quality of the film was improved. In conclusion, the high quality ZnO film was formed by the CO2 laser annealing of buried films in SiO2 matrix.

8967-53, Session PTue

Selective realignment of the exchange-biased magnetization direction in spintronic layer stacks using continuous and pulsed-laser radiation

Isabel Berthold, Hochschule Mittweida (Germany)

We report on selective realignment of the magnetization direction of the exchange biased ferromagnetic layer in two different spintronic layer stacks using laser radiation.

The exchange bias effect occurs in an antiferromagnetic/ferromagnetic bilayer system when cooled in an external magnetic field below the Néel temperature and results in a shift of the ferromagnetic hysteresis loop. The effect is utilized to pin the magnetization direction of the reference ferromagnetic layer in spin valve systems. We investigated the realignment of the pinned magnetization direction in a spin valve system with in plane exchange bias and in a Co/Pt multilayer with perpendicular exchange bias.

The layer stacks were heated above the Néel temperature in a defined lateral area by using rapidly deflected laser radiation. During laser annealing, the sample was subjected to an external magnetic field in order to selectively realign the magnetization direction of the pinned ferromagnetic layer. Two different laser assisted annealing techniques were investigated applying either continuous or pulsed laser radiation. After laser annealing, the magnetic properties were investigated using a magneto optical Kerr effect set up (MOKE). The impact of the processing parameters peak intensity, pulse duration, scan speed (continuous wave) and magnetic field strength on the resulting reversed exchange bias field was evaluated.

8967-54, Session PTue

Shape-controlled ZnO nanocrystals using multi-beam interference irradiation

Daisuke Nakamura, Tetsuya Shimogaki, Yuki Muraoka, Shihomi Nakao, Kosuke Harada, Mitsuhiro Higashihata, Kyushu Univ. (Japan); Yoshiki Nakata, Osaka Univ. (Japan); Tatsuo Okada, Kyushu Univ. (Japan)

ZnO nanocrystals have received much attention due to their unique morphologies, electronic and optoelectronic properties. In order to apply the ZnO nanocrystals to the practical optoelectronic applications, control of the growth density, shape and position is required. We have achieved density-controled ZnO nanowires and periodic ZnO nanostructures using a ZnO buffer layer and interference laser irradiation. Various shape of ZnO nanostructure, such as mirco-cylinder and aligned wall, are grown using interference patterns. In this presentation, morphological and optical characteristics of the ZnO nanocrystals will be discussed.

8967-55, Session PTue

Performance optimization of electronics circuits laser repair

Ram Oron, Orbotech Ltd. (Israel)

Electronics circuits are susceptible to production defects. Yield improvement can be obtained by in-process inspection and repair of these defects. Automated optical inspection is widespread, and became in many cases a standard procedure. However, repair solutions are not as advanced. In some cases (such as printed circuit boards); the common repair method is manual, which is very limited in performance. This calls for efficient automated repair solutions. Here, we shall describe an automated laser repair system, and discuss how to optimize it to obtain best performance in terms of throughput and quality.

The laser repair system is based on a pulsed laser and a fast steering mirror. It can repair excess conductor defects (e.g., shorts) by an ablation process. The impingement point of the laser beam is accurately set by the angle of the two-dimensional fast steering mirror. The fast steering mirror also controls the ablation path, which needs to be designed according to the defects geometry. The path is also optimized to avoid damaging of the non-conductor substrate, which may be more sensitive than the metallic conductor. Moreover, a feedback loop is obtained by capturing images of the repaired area, using a co-aligned imaging system.

We will present the automated laser system design and repair process. Repair performance shall be discussed and analyzed with respect to the process parameters. Examples of optimization of these parameters shall be shown.

8967-56, Session PTue

Femtosecond laser production of mixed metal oxides for efficient water oxidation

Kasey C. Phillips, Jin Suntivich, Cynthia M. Friend, Harvard Univ. (United States); Eric Mazur, Harvard School of Engineering and Applied Sciences (United States)

We present a novel method for producing mixed metal oxides using femtosecond laser doping of metallic foil in the presence of oxygen and another metallic dopant. We discuss doping titanium dioxide (TiO2) and other oxides for above bandgap absorptance by irradiating titanium metal with an evaporated thin film of metal. As a wide bandgap, TiO2 most strongly absorbs in the UV range (? < 387 nm). We explore the possibility of creating intermediate states in the band gap by doping with metals, such as chromium, manganese, and nickel. Using femtosecond laser doping, we produce laser-induced periodic surface structures on a variety of transition and mixed metal oxide surfaces. We present compositional data from X-ray photoelectron and Raman spectroscopy and structural data from scanning electron microscopy. Using a three-electrode setup, we present photoelectrochemical results and show enhanced water oxidation under illumination. Our research presents an innovative approach using laser scanning techniques to create new materials for visible-light watersplitting.

8967-57, Session PTue

Study of fast laser-induced cutting of silicon materials

Sebastian Weinhold, Hochschule Mittweida (Germany)

We report on a fast machining process for cutting silicon wafers using laser radiation without melting or ablating and without additional pretreatment.

For the laser induced cutting of silicon materials a defocused Gaussian laser beam has been guided over the wafer surface. In the course of this, the laser radiation caused a thermal induced area of tension without affecting the material in any other way. With the beginning of the tension cracking process in the laser induced area of tension emerged a crack, which could be guided by the laser radiation along any direction over the wafer surface. The achieved cutting speed was greater than 1 m/s. We present results for different material modifications and wafer thicknesses. The qualitative assessment is based on SEM images of the cutting edges.

With this method it is possible to cut mono- and polycrystalline silicon wafers in a very fast and clean way, without having any waste products. Because the generated cracking edge is also very planar and has only a small roughness, with laser induced tension cracking high quality processing results are easily accessible.

8967-17, Session 9

Development of high Tc superconducting coated conductors based on laser processing technologies *(Invited Paper)*

Takanobu Kiss, Kyushu Univ. (Japan); Teruo Izumi, International Superconductivity Technology Ctr. (Japan); Yasuhiro Iijima, Fujikura Ltd. (Japan); Yuh Shiohara, International Superconductivity Technology Ctr. (Japan)

In this talk, we will review recent progress in long-length production of rare-earth (RE) based high Tc superconducting (HTS) tapes based on advanced laser processing technologies. HTS tape conductors are now produced commercially on an industrial scale with lengths of several 100's meters to kilometers. On a flexible metal tape substrate, functional multi-layers including highly textured thick RE1Ba2Cu3O7-d (RE-123) superconducting layers are deposited continuously with deposition rate of typically 80 m/h for each layer by use of the multi-plume and multi-lane pulsed laser deposition (PLD) system. Columnar growth by the PLD is also suitable to introduce artificial nano-rods in the superconducting layer for further enhancement of in-field current carrying capability. This improves practical performance of the RE-123 coated conductor significantly. Furthermore, laser slitting is essential to obtain narrow tape strands without degradation. It has been demonstrated that these processing are crucial to realize high energy-efficiency electric devices such as superconducting power transmission cables and transformers.

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8967-18, Session 9

Laser cutting of carbon fiber reinforced plastics (CFRP) by single-mode fiber laser irradiation

Hiroyuki Niino, Yoshizo Kawaguchi, Tadatake Sato, Aiko Narazaki, AIST (Japan) and Advanced Laser and Process Technology Research Association (Japan); Ryozo Kurosaki, AIST (Japan); Mayu Muramatsu, Yoshihisa Harada, AIST (Japan) and Advanced Laser and Process Technology Research Association (Japan); Kenji Anzai, Mitsuaki Aoyama, Miyachi Corp. (Japan) and Advanced Laser and Process Technology Research Association (Japan); Masafumi Matsushita, Koichi Furukawa, Shin Nippon Koki Co. Ltd. (Japan) and Advanced Laser and Process Technology Research Association (Japan); Michiteru Nishino, Mitsubishi Chemical Corp. (Japan) and Advanced Laser and Process Technology Research Association (Japan); Akira Fujisaki, Taizo Miyato, Takashi Kayahara, Furukawa Electric Co., Ltd. (Japan) and Advanced Laser and Process Technology Research Association (Japan)

We report on the laser cutting of carbon fiber reinforced plastics (CFRP) with a single-mode cw IR fiber laser (average power: 350W). CFRP is a high strength composite material with a lightweight, and is increasingly being used various applications. A well-defined cutting of CFRP which were free of debris and thermal-damages around the grooves, were performed by the laser irradiation with a fast beam galvanometer scanning on a multiple-scan-pass method.

8967-19, Session 9

Laser trepanning of CFRP with a scanner head for IR and UV lasers

Kenji Anzai, Mitsuaki Aoyama, Miyachi Corp. (Japan) and Advanced Laser and Process Technology Research Association (Japan); Akira Fujisaki, Taizo Miyato, Takashi Kayahara, Furukawa Electric Co., Ltd. (Japan) and Advanced Laser and Process Technology Research Association (Japan); Yoshihisa Harada, Hiroyuki Niino, National Institute of Advanced Industrial Science and Technology (Japan) and Advanced Laser and Process Technology Research Association (Japan)

The CW-350W single-mode near-IR fiber laser and nanosecond-pulsed-35W UV laser were used in the experiments for the optimization of processing parameters in the cutting performance. The laser beam on

the sample surface was scanned with a galvanometer scanner and focused with the f-theta lens of 400mm focal length for IR and UV laser irradiations. A prototype remote scanner head for the multiple laser irradiations has been developed for a high-quality and high-speed laser processing of carbon fiber reinforced plastics (CFRP). In this paper, we report on the laser trepanning of circular patterns on CFRP.

8967-20, Session 9

Ablation dynamics and shock wave expansion during laser processing of CFRP with ultrashort laser pulses

Margit Wiedenmann, Univ. Stuttgart (Germany); Christoph Haist, Universität Stuttgart (Germany); Christian Freitag, Volkher Onuseit, Rudolf Weber, Thomas Graf, Univ. Stuttgart (Germany)

Carbon fibre reinforced plastics (CFRP) have a large potential in the automotive lightweight construction due to their low density and high mechanical stability. Compared with today's laser processing methods of metals the main issues in laser processing of CFRP are the very differing thermal, optical and mechanical properties of the components. To understand the process in detail, the ablation process of CFRP with ultrashort laser pulses was investigated. The shock wave and the detached CFRP-particles resulting from single laser pulses were recorded. Shadow photography with an ultra-high-speed camera was used to show the ablation process with a temporary resolution of up to 3ns. The field of view was 250 µm x 250 µm. An ultrashort laser pulse with a pulse duration of 6 ps and a wavelength of 800 nm was focused on the workpiece. The energy content of the shock wave was calculated from the resulting images. The energy content of the shockwave was about 10% of the incident energy and the speed of propagation of the shock wave was more than 2000 m/s. The ablated particles reached velocities up to 800 m/s. The high intensities in the range of 1013 W/cm? lead to formation of a plasma plume which was clearly seen in the shadow photography images. In addition, the ablation dynamics of each of the components of CFRP, i.e. particle and shock wave expansions of the carbon fibres and of the matrix material separately will be presented.

8967-21, Session 9

Analysis on laser ablation dynamics of CFRP with IR and UV pulse lasers

Yuji Sato, Masahiro Tsukamoto, Kazuki Nakai, Osaka Univ. (Japan); Tatsuya Nariyama, Kinki Univ. (Japan); Kenjiro Takahashi, Shinichiro Masuno, Osaka Univ. (Japan); Hitoshi Nakano, Kinki Univ. (Japan); Tomomasa Ohkubo, Tokyo Institute of Technology (Japan)

A carbon fiber reinforced plastic [CFRP], which has high strength, light weight and weather resistance, is widely applied for automobile, aircraft and so on. The laser processing of CFRP is one of suitable way to machining tool. However, heat affected zone (HAZ) was caused at the exposure part because of the difference in laser absorbance and thermal properties of carbon fiber and matrix resin in the CFRP. The laser wavelength is an important factor for reduction of HAZ since formation of HAZ might be related to laser absorption of CFRP.

In this study, we tried to cut the CFRP with two different nanosecond pulse lasers, whose wavelengths were 1064 nm and 266 nm respectively. The ablation plumes were investigated by spectroscopic analysis and ultra-high speed camera observation. As the results, the ablation depth for 1064 nm laser was 3.79 ?m/pulse larger than that for 266 nm to 1.00 ?m/pulse. SEM analysis was conducted to evaluate the HAZ. The results revealed that the HAZ formation also differ with the laser wavelength. The HAZ for 266nm laser was smaller than that for 1064 nm laser.

8967-22, Session 10

Application of a laser heterodyne technique to characterize surface acoustic waves generated via a pulsed laser excitation

Anthony J. Manzo, Henry Helvajian, The Aerospace Corp. (United States)

A CW laser heterodyne spectrometer has been assembled with time resolved data acquisition for probing surface acoustic waves (SAWs) generated by the interaction of a pulsed laser and surface. Literature suggests that SAWs can enhance chemical catalysis, nucleation and surface chemical mobility. Pulsed lasers are known to induce SAWs with bandwidth that is inversely proportional to the pulse width. The goal of this experiment is to apply laser heterodyne spectroscopy to understand the photophysical interactions that promote the formation of laser induced SAWs. The experiment explores the effects produced by a 100 Hz repetition rate UV (355nm) laser with a 6 ns pulse width and a 1 kHz repetition rate visible (532nm) laser where the pulse width can be varied from 3-170ns. The pulse width is varied using a pulse slicer based on a BBO crystal and explores a range of SAW bandwidths from 6 - 330 MHz. Silicon (111) is the substrate material under investigation because of the potential applications to MEMS and microelectronics fabrication. We will discuss the development of the heterodyne spectrometer and the time resolved data acquisition and software analysis tools developed that monitor the small, transient surface deflection events and their concomitant spectral signature. In addition, we present results from a 2D pulsed laser thermal heating model which sets a limit for the duration of the pulsed laser/surface interaction and the duty cycle of the subsequent SAW bursts. Initial results show that it is possible to measure and analyze laser induced SAWs many centimeters away from the laser induced source, and substrate dispersion affects the spectral properties of the propagating SAWs. Understanding how the SAW packet evolves will be critical to utilizing SAWs for material modification.

Keywords: laser heterodyne, surface acoustic wave,

8967-23, Session 10

Maximizing laser ablation efficiency of silicon through optimization of the temporal pulse shape

Alain Cournoyer, David Gay, INO (Canada); Pascal Turbis, Univ. de Montréal (Canada); Emmanuel Lorin de la Grandmaison, Carleton Univ. (Canada); Martin Briand, Yves Taillon, INO (Canada)

The commercial availability of fiber lasers based on MOPA architectures with arbitrary temporal pulse shaping capabilities offers completely new possibilities for laser material processing. Energy deposition over time within one laser pulse can be controlled and adapted to the specific material and/or process to be optimized. Hence, for given laser pulse energy and duration in the nanosecond regime, it has been demonstrated that the temporal pulse shape has an influence on the material removal rate of metals, semiconductors and ceramics.

In this study, based on both numerical modelling and experimental results in the nanosecond regime for the case of silicon at 1064 nm wavelength, we show that not only the single pulse laser ablation efficiency depends on the temporal pulse shape but, we also demonstrate how a stochastic approach can be applied in order to reach an optimized pulse shape maximizing the material removal rate for given laser pulse energy and duration. In particular, burst trains of short laser pulses within a temporally shaped envelope of a tens of nanoseconds reach the best results in terms of material removal rate.

In addition, we present results on multiple pulse laser ablation of silicon at 100 kHz. In that case of figure, cumulative thermal effects appear and their interaction with pulse shaping effects is analyzed. Differences

between the resulting optimized pulse shapes for both single pulse and multiple pulse laser ablation of silicon at 1064 nm are discussed.

8967-24, Session 10

Laser Thin Film Ablation with Multiple Beams and Tailored Beam Profiles

Stefan Rung, Univ. of Applied Sciences Aschaffenburg (Germany); Christian Bischoff, Udo Umhofer, Erwin E. Jäger, TOPAG Lasertechnik GmbH (Germany); Ralf Hellmann, Univ. of Applied Sciences Aschaffenburg (Germany)

For thin film ablation one can often not take full advantage of the relatively high output power and high pulse energy of lasers. A solution might be the use of parallel processing technique with multiple beams which help to increase process speed and to save process costs. Within this contribution we demonstrate thin film scribing of GZO and ITO which shows the potential of parallel processing combined with Top-hat beam shaping. The beam shaping optic provides process optimized beam profiles leading to a more efficient process and an improved ablation quality.

8967-25, Session 10

High-throughput and high-precision laser micromachining with ps-pulses in synchronized mode with a fast polygon line scanner

Beat Neuenschwander, Beat Jaeggi, Markus Zimmermann, Berner Fachhochschule Technik und Informatik (Switzerland); Lars Penning, Ronny DeLoor, Next Scan Technology B.V. (Netherlands)

High precision laser micromachining requires an exact synchronization of the laser pulse train with the mechanical axes of the motion system to ensure for each single pulse a precise control of the position of the laser spot on the target. For ultra-short pulsed laser systems this was already demonstrated with a conventional galvo scanner. But this solution is limited by the scanner architecture to a marking speed of about 10m/s with a maximum scan line length about 100mm. Additionally it was shown in earlier works that the removal rate per average power can be maximized when the correct fluence is applied. For many materials this optimum fluence is quite low i.e. using high average powers will only be possible at high repetition rates demanding marking speeds in the range of 100 m/s and single pulse gating possibilities in the MHz range.

We will report on the results of application tests like decoating, perforation and 3d patterning on large areas with a LSE170 polygon line scanner. This scanner has a maximum marking speed of 100m/s, a scan line length of 170mm and spot diameters of 50µm (1064nm) and 25µm (532nm). The precise control of the laser spot position i.e. the synchronization of this scanner with a FUEGO 50W ps laser system is realized via the new SuperSyncTM technology. Additionally results of scan-strategy optimization studies dealing with surface roughness, minimum structure dimensions etc. will be presented as well.

8967-26, Session 11

Formation of corrosion-resistant iron thin films by F2 laser-induced surface modification

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Iron is the most practical material in various metals; however, pure iron is actually difficult to be used without surface coating or alloying technologies because of its poor corrosion resistance. If pure iron thin film has high corrosion resistance, essential properties of iron such as magnet, electrically conductive and bio-compatible properties can be used to fabricate microdevices for electronic and industrial applications. Previously, we used the F2 laser for the surface modification of aluminum thin films into Al2O3 resistant to KOH aqueous solution. In this work, instead of aluminum, iron (Fe) thin films were photochemically modified into Fe3O4 by the F2 laser for developing a corrosion resistant Fe thin film.

The Fe thin films were deposited on a slide by an electron beam evaporation of Fe wires. A three-slit metallic mask made of stainless steel was set on the Fe thin films before laser irradiation. The F2 laser irradiated the Fe thin films through the metallic mask. The single pulse fluence of F2 laser was 40 mJ/cm2. The pulse repetition rate and irradiation time were 10 Hz and 60 min, respectively.

An electrochemical test of the nonirradiated and F2 laser irradiated Fe thin films on silica glass was conducted in pseudo seawater . The anode potential was measured to be -680 mV for the nonirradiated sample. In the case of the F2 laser irradiated sample, the potential was successfully shifted to -315 mV, which means that the surface of the F2 laser irradiated sample showed high corrosion resistance to pseudo seawater.

We also observed the surface of the F2 laser irradiated sample after the 0.01 wt% HNO3 chemical etching for 60 min. Three lines of 100-?m-wide Fe thin films, in accordance with the shape of metallic mask, were clearly formed on slide glass substrate. This result indicates that the F2 laser could induce the strong oxidation reaction to form thick Fe3O4 layer on the Fe thin films. The formed Fe3O4 was confirmed by the X-ray photoelectron spectroscopy. Thus, the combination of F2 laser and HNO3 chemical etching is useful for the micro-patterning of Fe thin films.

8967-27, Session 11

Precision laser annealing of silicon devices for enhanced electro-optic performance

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We present results from laser annealing experiments in Si using a passively Q-switched Nd:YAG microlaser. Operating the laser at fluence values above the damage threshold of commercially available photodiodes results in electrical damage (as measured by an increase in photodiode dark current). We show that increasing the laser fluence to values in excess of the damage threshold can result in annealing of a damage site and a reduction in detector dark current by as much as 100x in some cases. A still further increase in fluence results in irreparable damage. Thus we demonstrate the presence of a laser annealing window over which performance of damaged detectors can be at least partially reconstituted. Moreover dark current reduction is observed over the entire operating range of the diode indicating that device performance has been improved for all values of reverse bias voltage. Additionally, we will present results of laser annealing in Si waveguides. By exposing a small (<10 um) length of a Si waveguide to an annealing laser pulse, the longitudinal phase of light acquired in propagating through the

waveguide can be modified with high precision, <150 milliradian per laser pulse. Phase tuning by 180 degrees is exhibited with multiple exposures to one arm of a Mach-Zehnder interferometer at fluence values below the morphological damage threshold of an etched Si waveguide. No reduction in optical transmission at 1550 nm was found after 220 annealing laser shots.

8967-28, Session 11

Laser annealing and simulation of amorphous silicon thin films for solar cell applications

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A picosecond DPPS laser and a nanosecond Nd:YAG laser were employed for the annealing and partial crystallization of an amorphous silicon layer, in order to improve its solar cell efficiency. In addition, simulation of the annealing effect was performed in terms of temperature distribution evolution, for the determination of optimum annealing conditions. The structural properties of the annealed materials were studied by means of, XRD, SEM and micro-Raman techniques. The use of picosecond pulses offers optimum crystallization's ratios and larger nano-crystallites compared to the case of poly-Silicon layer developed by PECVD.

8967-29, Session 11

Novel industrial laser etching technics for sensors miniaturization applied to biomedical: a comparison of simulation and experimental approach

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The aim of this work is to demonstrate the feasibility of sensor's integration into millimeter-sized needles by a new industrial laser etching technique for biomedical applications.

Multiple lasers sources, from nanosecond to femtosecond pulse duration range and from infrared to ultraviolet wavelength are compared in order to evaluate benefits and disadvantages of each laser source for the etching purpose. Precise pulse shape, duration and quality factor of the different industrial laser beams are obtained by specific measurements. In order to supply the required energy to the sensor and the related electronics, a blind hole has to be drilled to insert an optical fiber in the silicon substrate. The ablation needs to be a non-thermal process, in order to avoid any electronic components degradation. Moreover, the light conversion of a PN junction is optimized thanks to a fine control of the ablation depth.

Numerical simulations of the laser-matter interaction process in various conditions of wavelength and pulse duration are achieved in order to have a better understanding of the experimental results.

8967-30, Session 11

Surface structuring of zirconium-based bulk metallic glasses using ultrashort laser pulses

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Laser processing of bulk metallic glasses using ultrashort laser pulses in the femto- to picosecond time regime are carried out. Single and multipulse ablation in a pulsewidth range of tP = 100 fs to 5 ps and its influence on amorphous material properties is investigated. Amorphous properties are analyzed via x-ray diffraction (XRD) and differential scanning calorimetry (DSC). Surface characteristics due to ultrashort laser processing are evaluated using white light interferometry (WIM) as well as scanning electron microscopy (SEM) and energy dispersive x-ray spectroscopy (EDX). Material modifications with pulse energies just above ablation threshold to high fluence processing with thermal effects are under discussion.

8967-31, Session 12

Study of direct writing of heavily doped Al and Bi heterojunctions on Si by laser transfer doping

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For the production of integrated electronic or photonic devices, distinct areas need to be arranged in heterojunctions, and controlled diffusion of dopants on homogeneous semiconductor substrates is the preferred method. Lithographic masking and thermal diffusion doping is the established path for mass production of electronic, photonic and MEMS devices.

As low cost device prototyping, direct manufacturing or mass customization gain importance as new paradigms of manufacturing, alternative fabrication methods are being explored for direct writing of heterojunctions, including ion implantation or laser doping. A process based on simultaneous dopant feed and diffusion is studied here, combining Laser Induced Forward Transfer (LIFT) of the dopant and laser melting of the substrate, in a single nanosecond laser pulse.

This paper explores direct writing of heavily doped and highly localized heterojunctions, by means of laser transfer-doping. Solid dopant sources (Aluminium and Bismuth) are explored in the form of glass and polymer supported thick films or metal foils, and the effect of the dopant source on the result is studied. Doping profiles and spatial distribution of dopants is analysed by mass spectroscopy. Electrical properties of the produced junctions are measured and a miniature transistor is fabricated to demonstrate single step device prototyping.

8967-32, Session 12

High-resolution imaging of ejection dynamics in laser-induced forward transfer

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Laser-induced forward transfer (LIFT) is a 3D direct-write method suitable for precision printing of various materials. As the ejection mechanism of picosecond LIFT has not been visualized in detail, the governing physics are not fully understood as yet. Therefore, this article presents an experimental imaging study on the ejection process of gold-based LIFT. The LIFT experiments were performed using a 6.7 picosecond Yb:YAG laser source equipped with a SHG. The beam was focused onto a 200 nm thick gold donor layer. The high magnification images were obtained using bright field illumination by a 6 ns pulsed Nd:YAG

laser and a 50? long-distance microscope objective that was combined with a 200 mm tube lens. For laser fluences up to two times the donor-transfer-threshold, the ejection of a single droplet was observed. The typical droplet radius was estimated to be <3 µm. A transition of ejection features towards higher fluence, indicate a second fluence-regime in the ejection process. For higher laser fluence, the formation of an elongated gold jet was observed. This jet fragments into multiple relatively small droplets, resulting in a spray of particles on the receiving substrate.

8967-33, Session 12

Pump-probe investigations and numerical simulation of the confined laser ablation of thin molybdenum films

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The transient behaviour of the laser lift-off of thin molybdenum films, initiated by glass substrate side irradiation with a 660 fs laser pulse, is investigated from the femtosecond to the microsecond range. For this purpose, a pump-probe microscopy setup is utilized to measure the transient relative reflectivity change of the irradiated spot at the molybdenum/glass interface. Moreover, the setup enables to measure the dynamic mechanical movement of the film by interferometry. In addition, a multi-physics and multi-time scale simulation was performed to simulate the electron and lattice temperature, the phase transitions, and the mechanical movement of the film. The experiment and the simulated data suggest that the film bulging is mainly driven by a volume expansion of about 10 % that occurs during the phase transition from solid to liquid. The acceleration of the film is in the order of 1010 m/s?. The film then bulges to a dome at a constant velocity of about 70 m/s. The bulging continues for approximately 20 ns. Then an intact Mo disk shears, if the tensile stress limit is exceeded.

8967-34, Session 13

Short pulse laser-induced switching of phase change materials studied by time-resolved X-ray scattering

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Phase change materials (PCMs) exhibit rapid and reversible phase transitions between an amorphous and a crystalline state, which can be triggered by short light or electrical pulses. Since the structural changes are associated with large differences in the electronic and optical properties of the two phases, PCMs are widely used in rewritable optical data storage technology and also considered for future non-volatile electronic memory applications.

We have applied time-resolved X-ray scattering using the XPP-instrument of the Linear Coherent Light Source (LCLS) to directly probe the structural dynamics in PCMs after laser irradiation over an extended time range from fs to µs. Thin films of the PCMs GST225, AIST, and GeSb deposited on free-standing Si_3N_4-membranes were irradiated with fs optical laser pulses. The structural changes during the laser-induced transitions were monitored by scattering of a time-delayed 50 fs X-ray probe pulse at 9.5 keV from the LCLS in normal-incidence transmission geometry.

We find that with fs excitation both transitions (amorphous-to-crystalline and crystalline-to-amorphous) involve melting of the material. Depending on the excitation strength melting can occur very fast on a sub-ps time-scale as a non-thermal process driven by the strong laser-induced electronic excitation. However, it takes ns up to tens of µs for the material to reach its final amorphous or crystalline state. While these time-scales imply purely thermal mechanisms, determined by the nucleation and growth kinetics for a given material and sample geometry, the final state in some cases exhibits unusual structural properties.

8967-36, Session 13

Synchronized videography of plasma plume expansion during femtosecond laser ablation

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Femtosecond lasers are gaining industrial interest for surface patterning and structuring because of the reduced heat effects to the surrounding material, resulting in a good quality product with a high aspect ratio. Analysis of the plasma plume generated during ablation can provide useful information about the laser-material interactions and thereby the quality of the resulting surface patterns. As a low-cost alternative to rather complicated ICCD camera setups, presented here is an approach based on filming the laser machining process with a high speed camera and tuning the frame rate of the camera to slightly higher than the laser pulse frequency. The delay in frequency between the laser and camera results in frames taken from sequential pulses. Each frame represents a later phase of plume expansion although taken from different pulses. Assuming equal plume evolution processes from pulse to pulse, the sequence of images obtained completes a plume expansion video. To test the assumption of homogeneity between sequential plumes, the camera can be tuned to the frequency of the laser, as to capture consecutive plumes at the same phase in their evolution. This approach enables a relatively low-cost, high resolution visualization of plasma plume evolution suitable for industrial micromachining applications with femtosecond lasers. Using this approach we illustrate differences in plume expansion at the example of machining homogeneous surface patterns in different liquid and gaseous processing environments.

8967-37, Session 13

Ultrafast imaging of highly efficient submicron fabrication using nondiffractive Bessel beams

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Nonlinear propagation of intense ultrafast laser pulses inside transparent materials has a strong influence on fabrication quality and accuracy for 3D laser-material processing. Due to their ability to maintain near-constant fluence profiles over an appreciable distance along the propagation direction in linear and nonlinear media, ultrafast Bessel beams are ideal source for high aspect ratio submicron structuring applications. We report here on the interaction of transparent materials, especially fused silica with ultrafast nondiffractive beams of moderate and high cone angle at various laser energy and pulse duration and define their impact on photoinscription regimes, i.e. formation of isotropic and non-isotropic refractive index structures. The laser pulse duration was observed to be a key in deciding the type of the structures. In particular, high aspect ratio voids with submicron cores are produced when using laser pulse of longer pulse duration highlighting the important contribution of delayed ionization and light carrier diffusion. On the contrary, for the same energy, only smooth refractive index modified structures are produced for short laser pulse. To understand the formation mechanisms of these structures, we studied their ultrafast dynamics around the ablation threshold using time-resolved microscopy and spectral imaging technique. We reveal various relaxation mechanisms leading to permanent refractive index changes accompanied by structural characteristic defect markers, namely fast carrier trapping in structural matrix deformations and long living carriers characteristic of phase transition. Also we compare the ultrafast laser material interaction mechanisms in terms of energy deposition and relaxation in fused silica associated with Gaussian and Bessel beams.

8967-38, Session 14

Time-resolved microscopy studies at fs laser-irradiated surfaces

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Time-resolved microscopy (TRM) combines ultrafast pump-probe techniques with optical microscopy. It represents a very versatile tool to monitor modifications of the optical properties of laser irradiated materials both in space and time. TRM avoids the spatial averaging effects of usual pump-probe apporaches, which can lead to severe misinterpretation of experimental data for a surface exhibiting strong inhomogeneities in its optical properties. On the other other hand, a TRM-experiment allows to obtain information over an extended excitation range in a single time-resolved image by employing the spatial intensity variation of the focused pump beam. In this contribution we present a setup for ultrafast TRM and discuss two examples for its application: (1) Femtosecond laser-induced switching of so-called phase change materials and (2) Investigation of the ablation dynamics of materials used in thin-film solar cells. In (1) the results of the TRM-experiments are compared to time-resolved X-ray scattering experiments performed on the same materials.

8967-39, Session 14

Rapid composition analysis of compound semiconductor thin film solar cell by laser induced breakdown spectroscopy

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The characteristics of laser-induced breakdown spectroscopy (LIBS) such as short measurement time and no sample preparation provide clear advantages over other analytical techniques for rapid elemental analysis at manufacturing sites where the composition of products need to be determined in real-time for process monitoring or quality control. Thin film solar cells based on Cu(In,Ga)Se2 (CIGS), polycrystalline compound semiconductor material, have unique advantages of high efficiency (~20%), long-term stability, and low manufacturing cost over other types of solar cell. The electrical and optical properties of the thin CIGS films are closely related to the concentration ratios among its major constituent elements Cu, In, Ga and Se such as Ga/(Ga + In) and Cu/(Ga + In), and thus an accurate measurement of the composition of CIGS thin films has been an issue among CIGS solar cell researchers, requiring a fast and reliable technique for analytical analysis. This paper presents the results of nanosecond (ns) and femtosecond (fs) laser based LIBS analysis of thin CIGS films. The critical issues for LIBS analysis of CIGS thin films such as self-absorption and fractionation is discussed in comparison with ns- and fs-LIBS measurement results. The calibration of LIBS signal intensity ratios with respect to reference concentration data is carried out and the issues of surrounding gas effects, depth profiling capability, and reproducibility are to be discussed with experimental and analytical results.

8967-40, Session 14

Modeling of laser patterning of thin-film solar cells

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We report on theoretical models of the interaction of ultra-short laser pulses with semiconductor-based multilayer structures. Those models may be used to optimize the ablation process used for structuring of thin-film solar cells.

A finite-difference based optical model of light propagation within the thin-film system is used to determine the 3D-distribution of absorbed laser power in the thin-film cell under investigation. The model takes into account the measured dielectric properties of the different materials. Depending on the excitation wavelength absorption occurs in different depths of the structure which has a large effect on the efficiency of the laser ablation process. The results show a qualitative agreement with ablation experiments carried out at different laser wavelengths.

The model also takes into account the evolution of the density of charge carriers which may be driven either by direct absorption of the laser radiation or multi-photon absorption and impact ionization of highly excited carriers, depending on the wavelength of excitation.

The modification of the optical properties of the materials by plasma screening results in a feedback on the laser beam propagation. In particular, the percentage and distribution of absorbed power evolves in time. This process is driven primarily by the energy which was already absorbed.

An additional finite-element based thermo-mechanical model is used to evaluate the effect of the absorbed laser power on the generation of internal stresses, ablation behavior and the size of heat-affected zones.

Comparison with experimental results on the ablation of Mo-layers for P1-structuring show good agreement with experimental results.

8967-41, Session 14

Optimizing process time of laser drilling processes in solar cell manufacturing by coaxial camera control

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In Emitter Wrap Through (EWT) solar cells, laser drilling is used to increase the light sensitive area by removing emitter contacts from the front side of the cell. For a cell area of 156 x 156 mm?, about 24000 via holes with a diameter of 60 µm have to be drilled into silicon wafers with a thickness of 200 µm. The processing time of 10 to 20 s is determined by the number of laser pulses required for safely opening every hole on the bottom side. Therefore, the largest wafer thickness occurring in a production line defines the processing time. However, wafer thickness varies by roughly ±20 %.

To reduce the processing time, a coaxial camera control system was integrated into the laser scanner. It observes the bottom breakthrough from the front side of the wafer by measuring the process emissions of every single laser pulse. To achieve the frame rates and latency times required by the repetition rate of the laser (10 kHz), a camera based on cellular neural networks (CNN) was used where the images are processed directly on the camera chip by 176 x 144 sensor–processor–elements. One image per laser pulse is processed within 36 µs corresponding to a maximum pulse rate of 25 kHz. The laser is stopped when all of the holes are open on the bottom side.

The result is a quality control system in which the processing time of a production line is defined by average instead of maximum wafer thickness.

8967-48, Session 14

Silver-free solar cell interconnection by laser spot welding of thin aluminum layers: analysis of process limits for ns- and µs-lasers

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Damage-free contacting of thin metal layers on solar cells for interconnection is a challenge in silicon photovoltaics. Two to 20-µm-thick metal layers on the solar cell have to be contacted to interconnectors. To reduce material consumption and mechanical stress, the metal layer thickness should be minimized but without inducing crystal damage during the interconnection. Additionally, the mechanical contact needs to be sufficiently strong and the electrical contact resistance low. The laser process presented here welds a 10-µm-thick Al-film deposited on a borosilicate glass directly to the Al-metallization on the solar cells and therefore avoids the use of silver. The mirco-weld spots are formed by focusing the laser beam through the transparent substrate in the interface of both Al-layers. Two types of laser processes are used; one uses one to eight 20-ns-laser pulses at 355 nm with fluences between 6 and 23 J/cm? and the other single 1.2-µs-laser pulses at 1064 nm with 28 to 72 J/cm?. We analyze the limiting thickness of the Al-layer on the cell in dependence on the laser parameters. The laser induced damage is investigated by analyzing the degradation of effective charge carrier lifetime of SiNx passivated silicon wafer metallized with 1 to 20 µm aluminum. Furthermore, the mechanical properties are measured by perpendicular tear-off and electrical contact resistance of the laser welds is determined. Samples with down to 1-µm-thick aluminum can be contacted using ns-pulses, whereas 2 µm is the limiting Al-thickness for the single µs-pulses due to the larger thermal diffusion length.

8967-43, Session 15

Optimized laser patterning for high performance Cu(In,Ga)Se2 thin-film solar modules

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Solar cells based on Cu(In,Ga)Se2 absorbers show the highest efficiencies among all thin-film technologies. Despite a recent slowdown of the thin-film market growth CIGS production capacity is increasing and the technique is maturing.

Apart from the cell technology itself, module patterning is a major critical point in the production process. The scribing tool of choice is the laser but finding the right process parameter has proven to be difficult for this complex material system.

In the past years we conducted a comprehensive study on laser sources and parameters for selective ablation of photovoltaic thin-films. Various aspects have been analyzed in-depth and were presented at previous conferences. Among the many scribing processes studied we identified a reliable and robust "workhorse" process which has a high potential for use in an industrial production line. The selected picosecond laser process is well controllable and can be competitively implemented in an industrial environment.

In the present study we show the successful realization of functional CIGS mini modules on glass substrate with optimized dead-zone. We demonstrate reproducible scribing of interconnects smaller than 70 ?m on 8-cell modules. This translates into a productive area loss due to scribing of considerably less than 2 percent. The produced mini modules achieved certified conversion efficiencies of up to 16.61 percent.

8967-44, Session 15

Investigations of laser ablation processes in thin-films for photovoltaic applications

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The thin-film Cu-chalcopyrite-based solar cell technologies are becoming more attractive due to their lower cost and optimal performance. Serial interconnect formation in these devices is one of the most promising technology for laser applications. Laser processing of thin-films is still challenging due to thermal nature of the layer ablation mechanisms. Previous investigations revealed possible thermal damage of thin layers even processing with ultra-short laser pulses. Minimization of laser affected area after thin-film processing is the most important step for future development of this technology. Optimizing processing conditions such as pulse duration is crucial for accomplishing this goal. Therefore we were concentrating on optimizing the pulse duration and also investigated the possibility of using the laser induced ablation for the P3 type laser processing of thin-film solar cells. We used industrial femtosecond laser with possibility to tune the pulse duration from 320 fs to 16 ps. Ablation of craters in CIGS solar cell using different processing conditions and laser pulse durations was investigated. The relationships between the laser pulse duration and melt area formation was studied and the results will be presented. We also present our results on picosecond and femtosecond laser induced material lift-off effect investigations in the CZTSe thin-film solar cell structures, which can be applied for the damage-free front-side scribing processes. This approach helped to minimize the thermal effects since the laser-affected material was removed mechanically from the ablation zone.

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8968-2, Session PTue

Influence of Sn impurities as enhancement mechanism of the laser ablation process of commercial soda-lime glass

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Commercial soda-lime float glass exhibits the incorporation of tin impurities during the fabrication process. The influence of these impurities as enhancements in terms of energy reduction for the laser ablation process is reported here. Different ablation thresholds identified correspond to 110 J/cm2 for the side with Sn impurities and 920 J/cm2 for non Sn impurities, which means a reduction of one order of magnitude. Based to this approach, a laser based technique for fabricating microfluidic microchannels, microlens arrays and microholes on commercial soda-lime glass with an IR nanosecond laser is presented. The versatility of this technique for the development of new microgeometries on glass is also demonstrated. Features around depth 1.5 µm and diameter 10 µm were obtained. By using a noncontact profilometer, the surface roughness of the microchannels has been measured obtaining values of Ra of approximately 450 nm. The technique is inexpensive and is capable to obtain quality elements using a low cost infrared laser widely implemented in industry which makes this technique attractive in comparison with other more expensive methods.

8968-34, Session PTue

CO2-laser based fiber coating process for high-power fiber applications

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The generation of high-power beams in active fiber application and also the transmission of high laser power via fiber cables need a protection against misdirected laser light. A new approach to remove undesired parts of light is given. The coating of fused silica material on the fiber cladding, applied with CO2-laser processes, provides a robust and high-power suitable cladding-light stripper. Among others, the relation between coated fiber length and numerical aperture of the coupled laser light, results of the removed high laser power, and tensile strength measurements are shown for the coated fiber. CO2-laser processes are easy to apply, do not require dangerous materials and provide more mechanical stability in handling and assembly of high-power fiber application.

8968-35, Session PTue

Surface transmission enhancement of ZnS via continuous-wave laser microstructuring

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Fresnel reflectivity at dielectric boundaries between optical components, lenses, and windows is a major issue for the optics community. The most common method to reduce the index mismatch and subsequent surface reflection is to apply a thin film or films of intermediate indices to the optical materials. More recently, surface texturing or roughening has been shown to approximate a stepwise refractive index thin-film structure with a gradient index of refraction change from the bulk material to the surrounding medium.

Short-pulse laser ablation is a recently-utilized method to produce such random anti-reflective structured surfaces (rARSS). Typically, high-energy femtosecond pulsed lasers are focused on the surface of the desired optical material to produce periodic or quasi-periodic assemblies of nanostructures which provide reduced surface reflection. This technique is being explored to generate a variety of structures across multiple optical materials. However, femtosecond laser systems are relatively expensive and more difficult to maintain.

We present here a low power and low-cost alternative to femtosecond laser ablation, demonstrating random antireflective structures on the surface of Cleartran ZnS windows produced with a continuous-wave laser. In particular, we find that irradiation with a low-powered (<10 mW), defocused, CW 325nm laser produces a random surface with significant roughness on ZnS substrates. The transmission through the structured ZnS windows is shown to increase by up to 9% across a broad wavelength range from the visible to the near-infrared.

8968-36, Session PTue

Compact probing system using remote imaging for industrial plant maintenance

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Laser induced breakdown spectroscopy (LIBS) and endoscope observation were combined to design a remote probing device. We use this probing device to inspect a crack of the inner wall of the heat exchanger. Crack inspection requires both speed and accuracy. Once eddy current testing finds a crack with a certain signal level, another method should confirm it visually. We are proposing Magnetic particle Testing using specially fabricated the Magnetic Particle Micro Capsule(MPMC)[1].

For LIBS, a multichannel spectrometer (the slit width is 100?m, and the grating is 900lines/mm.) and a Q-switch YAG laser (wavelength: 1064nm, pulse duration: 4-6ns, laser repetition: 10Hz) were used. Irradiation area is 270?m, and the pulse energy was 2mJ. This pulse energy corresponds to 5-2.2MW/cm2. A composite-type optical fiber was used to deliver both laser energy and optical image. Samples were prepared to heat a zirconium alloy plate by underwater arc welding in order to demonstrate severe accidents of nuclear power plants. A black oxide layer covered the weld surface and white particles floated on water surface. Laser induced breakdown plasma emission was taken into the spectroscope using this optical fiber combined with telescopic optics. As a result, we were able to simultaneously perform spectroscopic measurement and observation.

For MT, The MPMC which gathered in the defective area is observed with this fiber. The MPMC emits light by the illumination of UV light from this optical fiber. The size of a defect is estimated with this amount of emission. Such technology will be useful for inspection repair of reactor pipe.

[1] F. Ito,et. al, E-Journal of Advanced Maintenance, 4, 2, p57, (2012).

8968-37, Session PTue

Laser-induced processes on the back side of dielectric surfaces using a CuSO4-based absorber liquid

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Laser-induced back side wet etching LIBWE is a promising process for microstructuring the surface of dielectric materials. In this work LIBWE and related processes were studied using aqueous CuSO4 in form of a tartrate complex with formaldehyde as absorber liquid. This solution is known as precursor for laser-induced deposition of Cu. However, in standard configuration the absorber liquid is placed on top of the dielectric surface.

We performed experiments using the aforementioned absorber in the – unusual – back side configuration using different laser wavelengths and pulse durations. The reason for this back-side configuration was to study the possibility of ablating dielectric material in combination with deposition of conducting Cu only by varying experimental parameters. This could generate possible application in the field of microsensors.

It turned out that depending on the specific parameters either well-defined compact Cu deposits, micro- or nano-scaled Cu droplets or ablation of the dielectric substrate can be observed. For example, crystalline and conducting Cu structures can be produced using ns pulses at 532nm wavelength whereas with UV excimer laser droplet formation can be achieved.

Detailed results for different wavelengths ranging from UV up to Near-IR and pulse durations from cw to fs will be presented and possible mechanisms for the observed surface modifications will be discussed as a function of the specific parameters.

8968-38, Session PTue

Synthesis of graphene pattern using laser-induced chemical vapor deposition

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Graphene will be the core material for flexible and transparent electronics, including displays, solar cells, sensors, and electrodes. Up to now, high quality graphene can be obtained through several different approaches such as mechanical exfoliation, annealing of SiC, and chemical vapor deposition (CVD). CVD is the most promising method due to the benefits of large-scale production of high quality graphene and transfer the graphene to arbitrary substrates for various applications. Especially, large-scale patterns can be achieved by patterning of catalytic metal films before growth or direct patterning of graphene after growth. Although the CVD method can achieve large production volume using a roll-to-roll method, the fabrication of graphene patterns by CVD methods is a multi-step process which is time-consuming and costly.

In this study, Graphene patterns using laser-induced chemical vapor deposition (LCVD) with a visible CW laser (? = 532 nm) irradiation at room temperature was investigated. Optically-pumped solid-state laser with a wavelength of 532 nm irradiates a thin nickel foil to induce a local temperature rise, thereby allowing the direct writing of graphene patterns about ~10 μm in width with high growth rate on precisely controlled positions. It is demonstrate that the fabrication of graphene patterns can be achieved with a single scan for each graphene pattern using LCVD with no annealing or preprocessing of the substrate. The scan speed reaches to about ~200 μm/s, which indicates that the graphene pattern with an unite area (10?10 μm) can be grown in 0.05 sec. The number of graphene layers was controlled by laser scan speed on a substrate. The fabricated graphene patterns on nickel foils were directly transferred to desired positions on patterned electrodes. The position-controlled transfer with rapid single-step fabrication of graphene patterns provides an innovative pathway for application of electrical circuits and devices.

8968-39, Session PTue

Direct selective metallization of AIN ceramics induced by laser radiation

Arkadiusz J. Antonczak, Pawel E. Koziol, Bogusz D. Stepak, Patrycja Szymczyk, Krzysztof M. Abramski, Wroclaw Univ. of Technology (Poland)

Aluminum nitride (AIN) ceramics has a unique characteristic, namely the ability to form conductive structures on its surface direct by laser-induced decomposition of the base material. There were carried out studies on obtaining low-ohmic structures depending on process parameters such as a laser power, scanning speed of the sample, overlap of subsequent pulses and the type of shielding gas (air, nitrogen and argon). This paper focuses on explaining which factors mainly determine the resistance (resistivity) value of obtained structures. In order to clarify the effect of the laser fluence (below and above the ablation threshold of the aluminum) on the chemical structure of the conductive layers, qualitative EDX analysis were conducted. Optimization of the process allowed to obtained a resistivity of the conductive layers at the level of ? = 0.64?10-6 ?m, with a thickness of aluminum up to 10 ?m (sheet resistance Rs < 0.1 ?/sq). This technology can be useful in making printed circuit boards (PCB), a various type of sensors as well as radio-frequency identification (RFID) and lab on a chip (LOC) structures.

8968-40, Session PTue

Investigations on laser transmission welding of absorber-free thermoplastics

Viktor Mamuschkin, Alexander Olowinsky, Simon W. Britten, Fraunhofer-Institut für Lasertechnik (Germany)

Laser transmission welding of thermoplastics has been established in several industrial applications, but it has not yet been able to weld transparent thermoplastics without an IR-absorber. New diode lasers provide a broad variety of wavelengths which allows exploiting intrinsic absorption bands of thermoplastics. The use of a proper wavelength in combination with special optics enables laser welding of two transparent polymer parts without absorbers, which can be utilized in a large number of applications primarily in the medical and food industry, where the use of absorbers entails costly and time-consuming authorization processes. To generate a heat source in the joining area, the intensity distribution and the wavelength of the laser must be aligned to the absorption characteristics of the polymer. The usage of special optics with high numerical aperture keeps the laser intensity on top of the material and below the melting threshold. Only in the welding area does the intensity reach the necessary value to determine the welding of the transparent components. In this paper among others the influence of the focus position is first considered, which is crucial when both joining partners have equal optical properties. After a theoretical consideration, an evaluation is carried out based on welding trials.

Further aspects as gap bridging capability are considered as well. In contrast to conventional laser transmission welding, where no gaps are allowed, welding of absorber-free parts enables bridging of relatively large gaps, since a higher volume of material is molten.

8968-1, Session 1

Quantized structuring of transparent films with femtosecond laser interference *(Invited Paper)*

Peter R. Herman, Kitty Kumar, Kenneth K. C. Lee, Jianzhao Li, Jun Nogami, Nazir Kherani, Univ. of Toronto (Canada)

Our paper presents novel findings on the use of a femtosecond fiber laser interactions as a method for highly resolved internal structuring of transparent dielectric films. We harness the femtosecond laser to drive strong nonlinear interactions within Fabry-Perot interference fringes that are favorably formed by a thin film interference effect. In this way, narrow nano-length scale interaction zones are shown to have formed precisely at the fringe maxima positions which, in turn, cleave open into sub-wavelength internal cavities at single or multiple periodic depths or can be driven harder to eject a fractional film segment at various controllable depths. Prior to this work, the evidence of spatially localized laser interaction and internal structuring has never been directly observed inside a dielectric film. This sub-wavelength structuring is particularly surprising considering the high temperature and high electron density that were calculated to form in the film in 45 nm thick optical interference fringe positions. The observations verify that strong ablation dynamics are driven from these thin interaction zones before thermal diffusion would otherwise wash out and diminish the localized interaction.

This paper therefore introduces a new way for lasers to interact with transparent films, to scribe open nanovoids, or lift up thin 100-nm freestanding membranes, or eject partial film layers, all at quantized depths. We present a detailed study of the laser-film interaction physics, confirming the basic phenomenon of optical interference responsible for the quantized processing inside the film. As a new fabrication method, the paper further explores the technological potential of the reported interaction towards high resolution axial processing of transparent dielectric films and demonstrates several application examples such as forming multilevel micro- and nano-fluidic channels inside the film or selective segment ejection for three-dimensional surface structuring, coloring, marking, and printing.

These diverse examples confirm a precise laser interaction control that will be highly attractive to a broad community of laser-physicists through to thin-film material engineers as they seek further means for high resolution material structuring, especially within the thickness of the film for the first time. This new opportunity holds a promise to further improve the functionality of CMOS microelectronics and photonics, photovoltaics, MEMS, LED, lab-on-a-chip devices where thin films are widely deployed during their manufacture. Further, it opens directions for developing flexible electronic or display films and a concept of ‘lab-in-a-film’. Hence, we believe the present laser scribing results will be of great interest to the attendees of the Laser-based Micro- and Nano-Processing Conference who are seeking new research and applied directions.

8968-3, Session 1

In situ structural analysis of direct laser written waveguides

Patrick Salter, Univ. of Oxford (United Kingdom); Alexander Jesacher, Innsbruck Medical Univ. (Austria); Xiang Liu, Martin J. Booth, Univ. of Oxford (United Kingdom)

We present a suite of optical techniques for the structural characterisation of direct laser write (DLW) waveguides. DLW waveguides are finding increasing application in a wide range of photonic circuits. In order to completely characterise the waveguide network, it would be useful to map the refractive index profile at every point in the circuit in a non-destructive manner. A single method alone may not be sufficient to achieve this, but a range of techniques used together can be successful. This is demonstrated on ultrashort-pulsed-laser fabricated waveguides embedded several hundred microns below the surface of fused silica. Quantitative phase microscopy, based on the transport of intensity equation, is used to measure the cumulative refractive index change through a waveguide perpendicular to its axis. Results are verified through comparison with interferometry. We show how an existing laser fabrication system may be simply modified to incorporate this measurement during processing. The computational time required is less that the camera acquisition time allowing a live measurement of every point of the circuit during fabrication. Since the cross-section for DLW waveguides may not be assumed symmetric about the waveguide axis, an additional measurement is required to fully characterise the refractive index profile. We present two complimentary techniques for inferring the waveguide cross-section: (i) tomographic measurements using illumination from a high numerical aperture condenser lens; and (ii) third harmonic generation microscopy. The measurements are then combined to give a full structural characterisation of the waveguide.

8968-4, Session 1

High resolution multiphoton ablation with negligible thermal effects in transparent materials using Q-switched microchip lasers with 300 picosecond pulses at 532nm

Patrice L. Baldeck, Taghrid Mhalla, Univ. Joseph Fourier (France)

Self-Q-switched microchip lasers are attractive alternative to femtosecond lasers for micromachining in transparent materials. They can easily reach pulse peak powers needed to trigger ablation in all materials, including diamond, ceramics, plastics, and glasses. In addition, there are low cost with compact, and rugged design. In this work, we report on using microchip lasers for micro-engraving and marking different types of transparent materials. Sub-micron resolution embedded marking is demonstrated inside borosilicate glass. Microfluidic channels for optical sensor are engraved on BK-7 glass microchips with ion-doped waveguides. Pearl nacre are identified with marks invisible by naked-eye. Arrays of dense microchannels are fabricated at the surface of thermoplastics with a zone affected by thermal effects limited to the micron range.

8968-5, Session 1

Fs-laser microstructuring of laser-printed LiMn2O4 electrodes for manufacturing of 3D microbatteries

Johannes Pröll, Karlsruher Institut für Technologie (Germany); Heungsoo Kim, U.S. Naval Research Lab. (United States); Melanie Mangang, Hans J. Seifert, Karlsruher Institut für Technologie (Germany); Alberto Piqué, U.S. Naval Research Lab. (United States); Wilhelm Pfleging, Karlsruher Institut für Technologie (Germany)

Further improvement of the cycling behavior of electrode materials for lithium-ion microbatteries at high discharging rates can be achieved, e.g. by enhancing the contact surface area in between the active particles and the electrolyte. Therefore, a porous structure and small particle sizes are favourable resulting in short lithium-ion pathways which can be achieved by laser-printing. The porous structure of the laser-printed composite cathode consisting of active powder, binder, carbon black, and graphite enables ionic and electronic transport through 50 - 60 µm thick cathodes due to its high intrinsic active surface area. Within a new approach, laser structuring techniques have been developed for manufacturing three-dimensional cathode architectures directly into laser-printed porous cathodes. In order to further improve the cycling behavior of the laser-printed thick film cathodes with discharging rates up to 1 C (a 1 C rate will discharge the entire battery in one hour), cathodes were first calendered and then structured using ultrafast femtosecond

laser radiation (pulse length: 350 fs). Laser-printed, calendered, and laser-structured lithium manganese oxide thick films were electrochemically tested by using the Swagelok design. Cyclic voltammetric measurements and galvanostatic testing were performed using an Arbin Instruments BT2000 battery cycler. It is shown that calendered/laser-structured cathodes in the form of rectangular three-dimensional grids exhibit improved discharge capacity retention at a 1 C rate.

8968-6, Session 2

Laser surface micro-texturing to enhance the frictional behavior of lubricated steel *(Invited Paper)*

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Surface micro-texturing has been widely theoretically and experimentally demonstrated to be beneficial to friction reduction in sliding contacts under lubricated regimes. Several microscopic mechanisms have been assessed to concur to this macroscopic effect. In particular, the micro-textures act as lubricant reservoirs, as well as traps for debris. Furthermore, they may produce a local reduction of the shear stress coupled with a stable hydrodynamic pressure between the lubricated sliding surfaces. All these mechanisms are strongly dependent both on the micro-texturing geometry and on the operating conditions.

Among the various micro-machining techniques, laser ablation with ultrashort pulses is an emerging technology to fabricate surface textures, thanks to the intrinsic property of laser light to be tightly focused and the high flexibility and precision achievable. In addition, when using sub-ps pulses, the thermal damage on the workpiece is negligible and the laser surface textures (LST) are not affected by burrs, cracks or resolidified melted droplets, detrimental to the frictional properties.

In this work several LST geometries have been fabricated by fs-laser ablation of steel surfaces, varying the diameter, depth and spacing of micro-dimples squared patterns. We compared their frictional performance with a reference non-textured sample, on a range of sliding velocities from the mixed lubrication to the hydrodynamic regime. The measured Stribeck curves data show that the depth and diameter of the microholes have a huge influence in determining the amount of friction reduction at the interface. Different theoretical interpretations to explain the experimental findings are also provided.

8968-7, Session 2

Non-digitized diffractive beam splitters for high-throughput laser materials processing

Jun Amako, Toyo Univ. (Japan); Eiichi Fujii, Seiko Epson Corp. (Japan)

In laser material processing, high throughput can be achieved using an array of beams, as it enables simultaneous access to multiple process pointes on a work piece. Such arrayed beams can be generated using a diffractive beam splitter (DBS) with high splitting efficiency and uniformity. We report a non-digitized DBS with split counts of 45, a measured efficiency of 95%, and a measured uniformity of 0.90. The splitter was iteratively designed through a simulated-annealing method and was created on a fused silica substrate through laser writing lithography. Anti-reflection (AR) coats were added on the splitter surfaces to ensure high efficiency. This splitter arranged with a focusing lens has been applied to the manufacture of inkjet printer heads, in which silicon wafers are drilled using a 532-nm, nanosecond pulse laser with a 10-W average output and are wet-etched to produce micro-fluidic channels. The resultant drilling throughput has increased more than threefold as compared to the value obtained in our initial experiments several years ago, which involved 13 split counts with a 3-W average output. With consideration of the use of KW-class pulse lasers in the future, we have investigated subwavelength structures for AR, which are formed on the splitter through liquid-immersion laser interference lithography. The formation of these structures is affected by the large curvature on the corrugations. The steps required to further increase the split counts will be discussed with regard to the laser source, design and fabrication of splitters, and focusing lens.

8968-8, Session 2

Fabricating fiber Bragg gratings using phase modulated direct UV writing

Christopher Holmes, Chaotan Sima, Paolo L. Mennea, Lewis G. Carpenter, James C. Gates, Peter G. R. Smith, Univ. of Southampton (United Kingdom)

Fiber Bragg gratings (FBGs) are ubiquitous in the fields of telecommunications and sensing. Traditionally, fabrication is approached using either a phase mask or a dual beam interferometric arrangement to define 100's of grating planes per exposure. Recent developments using direct femtosecond writing allows greater control over design through implementing a point-by-point technique that defines grating planes through individual modulated exposures. In this work the authors present a different approach that combines the concept of dual beam UV interferometry with direct writing. This direct UV writing approach uses two focused coherent beams from a 244nm continuous wave UV laser. At their point of intersection the beams are focused to ~7 µm diameter spot where they form an interference pattern consisting of only several periods. Bragg gratings are achieved by aligning this interference pattern into a waveguide and traversing it along a length of waveguide using a combination of CNC precision stages and positional synchronized firing of a phase modulator located on one of the incident beam arms. As only several grating planes are defined on exposure greater design flexibility compared to traditional approaches that use a much larger number of fringes is achievable. In addition, as fewer grating planes are defined per exposure detuning results in a significantly larger accessible spectral range that spans telecom bands E to U. The authors will present the concept of direct UV writing to fabricate FBGs in a variety of optical fibers and demonstrate the enhanced performance inherent through exposing with a small spot.

8968-9, Session 2

Laser micromachining and modification of bioabsorbable polymers

Bogusz D. Stepak, Arkadiusz J. Antonczak, Pawel E. Koziol, Krzysztof M. Abramski, Konrad Szustakiewicz, Wroclaw Univ. of Technology (Poland)

Bioabsorbable polymers such as polylactide and its copolymers are commonly used for manufacturing non-permanent biomedical devices: orthopedic implants, vascular stents or scaffolds for tissue engineering. The laser machining of such thermally sensitive polymers can lead to degradation or alteration of their properties. We wanted to investigate the modification of material properties caused by CO2 laser (10.6 um) and KrF excimer laser (248 nm) treatment and define usability of those lasers in terms of micromachining and intentional modification of polylactide-based polymers. A different kind of laser source was applied to show potential differences in material modification at UV and IR spectral range. The irradiated samples were examined using X-ray photoelectron spectroscopy (XPS) and infrared spectroscopy. Additionally, differential scanning calorimetry (DSC) and contact angle measurements were performed.

8968-10, Session 3

High speed surface functionalization using direct laser interference patterning, towards 1 m?/min fabrication speed with sub-?m resolution *(Invited Paper)*

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Periodic patterned surfaces can be used to provide unique surface properties in applications, such as biomaterials, surface engineering, photonics and sensor systems. Such periodic patterns can be produced using laser processing tools, showing significant advantages due to a precise modification of the surfaces without contamination, remote and contact-less operation, flexibility, and precise energy deposition.

On the other hand, the resolution of sequential laser based surface structuring methods, like direct laser writing, is generally inversely proportional to the fabrication speed. Therefore, the development of new laser structuring technologies is necessary to achieve both high fabrication speed and resolution at low cost.

In this paper, different approaches for the large area fabrication of repetitive surface structures using Direct Laser Interference Patterning (DLIP) will be introduced. The procedures offer not only the possibility to process planar surfaces but also complex three dimensional components. In the case of planar surfaces, structuring strategies to achieve sub-micrometer resolution at fabrication speeds up to 1 m?/min will be also described.

After that, different application examples of structured surfaces on different materials will be presented. The applications include the development of thin film structured electrodes to improve the efficiency of organic light emitting diodes (OLEDs) and organic solar cells (OSOL) as well as the direct fabrication of low friction surfaces on technological steels and diamond like coatings (DLC).

8968-11, Session 3

Laser generated microstructures in tape cast electrodes for rapid electrolyte wetting: new technical approach for cost efficient battery manufacturing

Wilhelm Pfleging, Robert Kohler, Johannes Pröll, Karlsruhe Institute of Technology (Germany)

Three dimensional (3D) battery architectures are under current scientific investigation since they can achieve large areal energy capacities while maintaining high power densities. A main goal of surface patterning is to enhance lithium-ion diffusion which is of often a critical factor in lithium-ion cells. By using a rather new approach, laser material processing of thick film electrodes has been investigated for the precise adjustment of 3D surface topography. Besides lithium-ion diffusion in electrode materials as an electrochemically limited process, a critical step in lithium-ion pouch cell manufacturing itself is the electrolyte wetting of stacked electrodes and separators which is a cost expensive and time-consuming vacuum and storage processes at elevated temperatures. The new and cost efficient laser process has been successfully applied in order to significantly improve the electrode wetting. Preliminary investigations for testing the process on pouch cell geometry revealed higher capacities and increased cycle times compared to standard cells without storage processes at elevated temperatures. The process can be applied to commercial electrode materials and integrated into existing production lines.

8968-12, Session 3

Understanding the formation of self-organized micro/nanostructures on metal surfaces from femtosecond laser ablation using stop-motion SEM imaging

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In recent years, a growing number of unique micro/nanostructures created using femtosecond laser surface processing have been demonstrated. Although researchers have provided insight into the formation processes for distinctive morphologies on specific materials, there is a need for a broader understanding of the physics behind the formation of a wide range of morphologies and what parameters affect their formation in order to fine tune the morphologies for a wide range of applications. In this work, we make significant strides towards this goal using a stop-motion scanning electron microscope (SEM) technique, not previously utilized in this field. The sample was imaged in the SEM at various pulse counts in the microstructure development process. Between SEM imaging sets, the same location on the sample was irradiated with further pulses by precisely aligning the sample to the same location in the laser setup. The result is a series of images showing the pulse by pulse development of individual structures. Using these images, we show that by only changing the fluence three unique morphologies develop on nickel; above surface growth mounds, below surface growth mounds and nanoparticle covered pyramids. The structures are formed using 800 nm, 50 fs pulses, and are self-organized, with structure dimensions much smaller than the spot size of the pulses. Each morphology forms through a combination of fluid flow of the surface melt formed during irradiation, preferential ablation of regions between structures, and material/nanoparticle redeposition. The pulse fluence determines the balance of these formation mechanisms, and therefore which morphology develops.

8968-13, Session 3

Laser-induced periodic surface structures: modelling, experiments, and applications

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Laser-induced periodic surface structures (LIPSSs) consist of regular wavy surface structures, also referred to as ripples. This paper presents a summary of LIPSSs we observed as well as our model with attempts to explain their origin.

If the surface of the material is irradiated at normal incidence with linearly polarized cw or pulsed laser light, LIPSSs with a periodicity close to the laser wavelength, and direction orthogonal to the polarization, can develop. Typical amplitudes are in the sub-micrometer range.

Ripples with a periodicity (much) smaller than the wavelength of the laser occur when applying laser pulses with ultra-short durations in the femtosecond and picosecond regime. The direction of these smaller ripples is either parallel or orthogonal to the polarization direction of the laser radiation. Finally, when applying numerous laser pulses, structures with periodicities larger than the wavelength of the laser light can form and are referred to as "grooves".

The physical origin of LIPSSs is still under severe debate. The strong correlation of the ripple periodicity to the laser wavelength, suggests that their formation can be explained by an electromagnetic approach. Recent results from a numerical electromagnetic model, predicting the spatially modulated absorbed laser energy below the surface, are discussed. This

model can explain several geometrical features occurring at the surface after laser irradiation, including features parallel or perpendicular to polarization.

Finally, bio-medical and industrial applications of LIPSSs will be discussed.

8968-14, Session 3

IR and green femtosecond laser machining of heat sensitive materials for medical devices at micrometer scale

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In medical device manufacturing there is an increasing interest to enhance machining of biocompatible materials on a micrometer scale. Obviously there is a trend to generate smaller device structures like cavities, slits or total size of the device to address new applications. Another trend points to surface modification, which allows to control selective growth of defined biological cell types on medical implants.

In both cases it is interesting to establish machining methods with minimized thermal impact, because biocompatible materials often show degradation of mechanical properties under thermal treatment. Typical examples for this effect is embrittlement of stainless steel at the edge of a cutting slit, which is caused by oxidation and phase change. Also for Nitinol (NiTi alloy) which is used as another stent material reduction of memory-shape behavior is known if cutting temperature is too high. For newest biodegradable materials like Polylactic acid (PLA) based polymers, lowest thermal impact is required due to PLA softening point of 65°C and ~170 °C melting temperature respectively.

Laser machining with ultrashortpulse lasers is a solution for this problem. In our work we demonstrate clean laser cut as well as laser surface roughening of NiTi and PLA based polymers with a high repetition-rate 1025 nm, 400-800 fs laser source at a pulse energy up to 50 µJ and laser repetition rate of up to 500 kHz. We further demonstrate effects of machining with SHG frequency-doubled femtosecond laser on feature size.

8968-15, Session 4

Black silicon and the quest for intermediate band semiconductors *(Invited Paper)*

Eric Mazur, Harvard School of Engineering and Applied Sciences (United States)

Shining intense, ultrashort laser pulses on the surface of a crystalline silicon wafer drastically changes the optical, material and electronic properties of the wafer. The process has two effects: it structures the surface and incorporate dopants into the sample to a concentration highly exceeding the equilibrium solubility limit. This femtosecond laser “hyperdoping technique” enables the fabrication of defect- and bandgap engineered semiconductors, and laser texturing further enhances the optical density through excellent light trapping. Hyperdoped silicon opens the door for novel photodectors and for Earth-abundant, semiconductor-based solar energy harvesters with the potential for both low cost and high photoconversion efficiency.

The same technique can be used to form nanostructured and doped TiO_2 and non-stoichiometric TiN films. We show that oxygen, nitrogen, and chromium incorporation occurs in these films when the laser fluence exceeds the ablation threshold. Our research offers an innovative approach to alter the surface and structure of TiO_2 to generate new materials with applications in visible-light water splitting.

8968-16, Session 4

Control of multiphoton and avalanche ionization using an ultraviolet-infrared pulse train in femtosecond laser micro-/ nano-machining of fused silica

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We report on the experimental results of microstructures fabricated on the surface of fused silica by a train of two femtosecond laser pulses, a tightly focused 266 nm (ultraviolet, UV) pulse followed by a loosely focused 800 nm (infrared, IR) pulse. By controlling the fluence of each pulse below the damage threshold, microstructures are fabricated using the combined beams when the delay between the UV and IR pulse is within ~1 ps. The damage threshold of UV beam is 88% lower for pulse trains than for the single UV beam when the UV pulse is leading the IR pulse by ~60 fs. The microstructure linewidth is close to the focal spot size of the UV pulse. These results suggest that the UV pulse generates seed electrons through multiphoton absorption and the IR pulse utilizes these electrons to cause damages by avalanche process. A single rate equation model based on electron density can be used to explain these results. It is further demonstrated that structures with dimensions of ~200 nm can be fabricated on the surface of fused silica by this technique with UV energy density below its single beam damage threshold using a high numerical aperture (NA) objective. This provides a possible route to XUV (or even shorter wavelength) laser nano-machining with reduced damage threshold.

8968-17, Session 4

Femto-second laser micro-machined structures for light harvesting applications in optofluidics

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Miniaturization of optical elements like lenses and light guiding structures is essential for the ease of their integration for lab-on-chip applications. Integration of various functionalities in the same device leads to versatile devices. Realizing such devices is possible thanks to techniques like femtosecond laser micromachining (FLM). The FLM technique involves tight focusing of femtosecond laser pulses and translating the substrate at the focal point for device direct “writing”. The non linear nature of the processes involved allows one to exploit the technique in most materials. Unlike most conventional techniques for device fabrication, like lithography, FLM offers several advantages. Firstly, there are no masking steps involved like in lithography, which enables fast prototyping due to reduced number of steps. Secondly, as FLM is inherently 3D, it allows the fabrication of 3D structures in the bulk of transparent materials and on the surface for opaque materials. Very precise micromachining, restricted only to the focal volume is possible. Moreover, FLM followed by Chemical Etching (FLICE) leads to the fabrication of microfluidic networks for lab-on-chip applications. We demonstrate light harvesting in two different optofluidic configurations viz. a) Binary Fresnel lenses (BFL) fabricated

on polymer 1D photonic crystal (1D-PC) can be used as reflecting lenses, where the 1D-PC filters unwanted wavelength while the BFL focuses the required wavelength. b) Waveguide arrays in the vicinity of micro channels can be used for fluorescence light harvesting for further manipulation.

8968-18, Session 4

A new method for tempered glass cutting

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The paper presents a new method for cutting tempered glass. Surface tempered glass, with its tempered layer on the surface of the glass, is extensive applied in the area of touch panel display. In order to make the manufacturing process more convenient, industry is working on processing the glass after tempering. However because it has thin thickness and untempered layer between tempered layers on surface, it is easy to break or generate cracks during the presented processing. In this method, ultra-short pulse laser was used to ablate the tempered glass layer, which requires that the ablate traces on both sides are strict positional parallel. In addition the etching depth should exceed the tempered thickness. With ultra-fast laser, the chipping could be controlled in a small range. After that, computer numerical control operate grinding rod cut or drill the untempered glass and polish the cutting edge to make the smaller chipping further. This method would avoid too much laser energy accumulating, which would lead to glass breakup. For mechanical grind, it needs slow process speed in order to avoid cracks on the glass. Combination of laser process and mechanical grind could integrate either advantages and achieves better process efficiency than either processing. With the help of ultra-fast laser such as pico-second laser and high number grinding rod, it could achieve excellent chipping and roughness effect.

8968-19, Session 4

How to capitalize the laser direct writing and holographic lithography match: looking for a high quality tunable microfluidic dye laser driven by liquid crystals orientation properties

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The development of simple and low-cost miniaturized fabrication methods has been very important for the advancement of microfluidics technology. Although planar micro-fabrication approach based on photolithography is well established and is suitable for surface micro-fabrication, multilayer and multistep processes, including stacking and bonding of different substrates, are required to form true three-dimensional (3D) microstructures.

An innovative, simple and maskless technique is the femtosecond laser micromachining, which allows a 3D fast prototyping thanks to its inherent ability to locally modify the substrate in correspondence of the focal spot. Since the circuit design is fabricated by the same tool, it is easy to create integrated and vibration-free optofluidic devices.

Taking advantage from this new fabrication technique, we report an investigation on novel optofluidic laser microcavities with the aim to obtain an easy optical tuning driven by liquid crystal orientation properties. DBR (distributed Bragg reflector) lasers geometry have been fabricated combining the pulsed laser direct writing with the holographic lithography, to realize high quality factor microcavities within the microfluidic chip. Two Bragg reflectors have been imprinted close to the dye recirculation microchannel, recording a periodic refractive index change in a photopolymerizable mixture by means of two beams interference. An integrated broad band fiber optic completes the microcircuit design in order to monitor the Bragg reflection efficiency and outcouple the emitted light. In order to pump the laser action the second harmonic of Nd:YAG pulsed laser has been used while to get tuning driven by liquid crystal orientation properties different configurations have been investigated.

8968-20, Session 4

3D hydrodynamic focusing fabricated by femtosecond laser micromachining

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Hydrodynamic focusing is a powerful technique frequently used in microfluidics that allows focusing the sample flowing in the device to a narrow region in the center of the microchannel. In fact thanks to the laminarity of the fluxes in microchannels it is possible to confine the sample solution with a low flow rate by using a sheath flow with a higher flow rate. This in turn allows the flowing of one sample element at a time in the detection region, thus enabling analysis on single particles. One of the main issues is connected with the 2D nature of the lithographic techniques frequently used in microfluidics, which do not allow having a 3D focusing of the sample in microfluidic devices unless complicated and expensive multi-step fabrication processes are exploited.

Femtosecond laser micromachining represents a powerful tool to easily obtain hydrodynamic focusing thanks to the intrinsic 3D nature of this technique. Furthermore, because of the possibility to fabricate optical waveguides with the same technology, it is possible to obtain extremely compact optofluidic devices characterized by a precise alignment between the fluidic and the optical components, to perform optical analysis of the sample. Here we show the fabrication and the fluidic characterization of monolithic devices having only two inlets for 2D (either in vertical or in horizontal planes) as well as full 3D symmetric hydrodynamic focusing. In addition we show the fabrication and the validation of a monolithic cell counter, obtained by integrating optical waveguides in the 3D hydrodynamic focusing device.

8968-21, Session 5

Laser-printed/structured thick-film electrodes for Li-ion microbatteries *(Invited Paper)*

Heungsoo Kim, U.S. Naval Research Lab. (United States); Johannes Pröll, Robert Kohler, Wilhelm Pfleging, Karlsruher Institut für Technologie (Germany); Alberto Piqué, U.S. Naval Research Lab. (United States)

There is an increasing demand for rechargeable micropower sources for the development of microelectronic devices. Thin film Li-ion microbatteries are being studied as a potential micropower source due to their high power density and long cycle life. However, the thickness of these thin film systems (normally prepared by sputtering techniques) is limited to a few microns (< 5 ?m) due to high internal resistance of the dense electrodes. One way to achieve high discharge capacity per active electrode area is to develop thick-film electrodes deposited by laser induced forward transfer (LIFT). In this work, various thick-film electrodes (up to ~115 um) are laser-printed onto metallic current collectors and assembled into functional Li-ion microbatteries. Microbatteries based on these thick-film electrodes demonstrate significantly higher discharge capacities than those made by sputter-deposited thin film techniques. This increased performance is attributed to the porous structure of the

laser-printed electrodes that allows improved diffusion of the Li-ions without a significant increase in internal resistance. The packaged microbatteries exhibited discharge capacities in excess of 2500 ?Ah/cm2 at a constant charge/discharge rate of 100 ?A/cm2. In this talk, we will present details on the fabrication of Li-ion microbatteries with various cathodes and anodes in terms of electrode thickness, discharge capacity, charge/discharge rate, and cycling performance. In addition, we will also present the use of an ultrafast laser ablation process to prepare three-dimensional grid microstructures to further improve performance by increasing the active surface area in the laser-printed and then laser-structured thick-film electrodes.

8968-22, Session 5

Ultrafast laser microstructuring of LiFePO4 cathode material

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LiFePO4 is a very promising material to be used as positive electrode for future lithium-ion batteries. Nevertheless, a reduced rate capability at high discharging and charging currents is in general a main drawback.

In this work, a 3D topography was realised in the surface of a LiFePO4 composite electrode by applying ultrafast laser microstructuring. The impact of laser-generated cathode surface structures on to the electrochemical performance in a lithium-ion half-cell was studied in detail and will be discussed. The main challenging goal was to significantly improve the capacity retention as a function of laser pulse length and surface microstructure.

For microstructuring of electrode materials an ultrashort pulse laser (Tangerine, Amplitude Systemes) and a ns fiber laser system (IPG Photonics) were used. The pulse length was varied in the range from 350 fs up to 200 ns. With ultrashort laser radiation it was possible to obtain defined structures in composite electrode materials without thermal damage or melt formation. Electrochemical characterisations were performed using an Arbin Instruments BT2000 battery cycler. For this purpose Swagelok® test cells with lithium metal as counter electrode were assembled. Main electrochemical parameters such as specific capacity and cycle stability were determined for the cells with structured and non-structured cathodes. It was shown that the rate capability for the cells with structured cathodes in comparison to cells with unstructured cathodes was significantly enhanced, especially for high charging and discharging rates. Up-scaling to pouch cell format (5x5cm?) was realised and electrochemical tests were performed with unstructured and structured cathodes.

8968-23, Session 5

Polarization selectable nano-pattern formation on diamond surfaces by 2-photon ultraviolet desorption

Andrew Lehmann, Christopher Baldwin, James E. Downes, Richard P. Mildren, Macquarie Univ. (Australia)

Diamond's extreme properties are of intense interest in applications such as quantum information processing, spin sensing, and Raman lasers [1]. However, there is a lack of effective techniques for creating structures with the required resolution and without simultaneously introducing collateral damage to the surrounding material. Recently, we showed that exposure of diamond surfaces to sub-ablation fluences of ultraviolet radiation desorbs carbon from the surface at well defined rates and without inducing damage to the crystal structure [2]. Although the phenomenon is promising for sculpting this most challenging of materials, many of the details of the process have not been investigated including the nano-scale properties of the machined surface that are critical in many applications.

Here we report a detailed study into the morphology and roughness of the UV treated surfaces as a function of laser parameters. Electron microscope imaging reveals that regular nano-structured features are produced that have morphologies strongly dependent on the polarization of the incident beam. Facetted ridge, grid, and wave-like patterns, are obtained for polarizations parallel to low-miller index directions on {100} and {110} diamond surfaces. Periodicity of 50-250 nm is observed for etch depths up to approximately 500 nm. We show that the etching provides a rapid, controllable, and area-scalable method for nano-patterning diamond surfaces. Of more fundamental significance, these observations comprise mesoscopic evidence for polarization dependent coupling of photons with localized and directional surface states associated with carbon - carbon bonds. We show that this has implications for nano-scale manipulation of atoms on diamond and potentially other covalently bonded materials.

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8968-24, Session 5

Microstructuring of resist double layers by a femtosecond laser ablation and UV lithography hybrid process

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We report on recent results on selective structuring of photoresist with femtosecond laser pulses in combination with conventional UV photolithography. The advantages of both processes could be combined to generate structures covering lateral dimension from the micron scale up to patterns of millimeter size with high quality in a photoresist double layer system. The fabrication process is based on a photoresist multilayer system where a negative photoresist is placed on a thick SU-8 layer. The negative resist layer is patterned by photolithography and the SU-8 layer by means of selective laser ablation, respectively. An additional thin sacrificial layer of photoresist on the top surface serves as a protective coating and enables the removal of debris which is deposited on the top surface during laser structuring.

After resist structuring the process parameters of the femtosecond laser is adapted to enable processing of the glass substrate where drilling of through vias and the formation of cavities within the glass substrate is carried out, respectively. This enables resist patterning and substrate processing within one laser step offering a fast and flexible process. Laser processing experiments were carried out with a pulse duration of 400 fs and a wavelength of 520 nm. Photolithography was carried out with a standard mask aligner (MA6, SUESS).

8968-25, Session 6

Formation and properties of nanostructured amorphous polymer films by MAPLE *(Invited Paper)*

Rodney D. Priestley, Princeton Univ. (United States)

A major theme in materials engineering is the development of materials with new and unusual properties from the same atoms or molecules by uniquely manipulating their organization at the atomic or molecular level. For instance, carbon atoms can be arranged into numerous structures resulting in a range of materials including diamond, graphite and nanotubes. In starting from the gas phase to make glassy materials via MAPLE, we are able to generate nanostructured amorphous materials formed via the assembly of molecular-scale building blocks, i.e., nanoglobules. In comparison to the conventional material, these nanostructured materials can have superior thermal stability (40 K enhancement in glass transition temperature), factor of 300 increase in kinetic stability as well as a 40 % reduction in density. Individually, each of these property changes is exceptional. When viewed as a whole, the combination of properties for these amorphous materials makes them truly unique. The origin of film formation is understood by investigating the nanostructure of sub-monolayer and monolayer films via short time MAPLE. The structure is quantified by analyzing the size distribution of polymer nanoglobules as a function of deposition parameters: time and polymer concentration. Two deposition regimes are observed in the early stages of MAPLE deposition, with a transition at a critical time. The observed distribution of nanoglobule sizes that is present after the critical time agrees well with prior molecular dynamics simulations of the MAPLE process. Based on these findings, we propose a mechanism for the formation of nanostructured coatings by MAPLE.

8968-26, Session 6

Transparent conductive films based on the laser sintering of metal and metal oxide nanoparticles

Akira Watanabe, Gang Qin, Tohoku Univ. (Japan)

such as evaporation or sputtering is desired to reduce the energy consumption and the environmental impact. A printing technique based on a wet process using metal and semiconductor nanoparticle inks is one of the candidates on innovation. One of the problems in the wet process using metal and semiconductor nanoparticles is a rather high temperature for the sintering and crystallization of the inorganic nanoparticles, which is sometimes a limiting factor in the application to glass or polymer substrates with a low heat resistance. In previous papers, we have reported the laser sintering of metal nanoparticle dispersed film and the laser direct writing using metal nanoparticle inks, where the laser energy confined in a nanoparticle causes the fast and efficient conversion of the light energy to the thermal energy. In this paper, we applied the laser sintering to the fabrication of transparent conductive metal and metal oxide films using the nanoparticles. The laser sintering of a silver nanoparticle (Ag nanoparticle) thin film gave a transparent conductive film (1.8 ohm/sq) with a thickness of 12 nm whereas such a thin film fabricated by conventional heat treatment using an electronic furnace was insulator because of the formation of isolated Ag grains during the slow heating process. The laser sintering of Ag/ZnO hybrid and layered films was studied to enhance the transparency. Transparent conductive micropatterns were also fabricated by laser direct writing of Ag and Ag/ZnO thin films.

8968-27, Session 6

Tailoring liquid/solid interfacial energy transfer: fabrication and application of multiscale metallic surfaces with engineered heat transfer and electrolysis properties via femtosecond laser surface processing techniques

Troy Anderson, Craig A. Zuhlke, Corey Kruse, Chris Wilson, Univ of Nebraska-Lincoln (United States); Anton Hassebrook, Isra Somanas, Univ. of Nebraska-Lincoln (United States); Sidy Ndao, George Gogos, Univ of Nebraska-Lincoln (United States); Dennis Alexander, Univ. of Nebraska-Lincoln (United States)

Femtosecond Laser Surface Processing (FLSP) is a powerful technique for the fabrication of self-organized multiscale surface structures on metals that are critical for advanced control over energy transfer at a liquid/solid interface such as heat transfer and electrolysis. Precise control over the surface geometry enables the tailoring of interfacial phenomena such as wettability and wicking to achieve both superhydrophobic and superhydrophilic surfaces for heat transfer and lab-on-chip systems. Multiscale surfaces are characterized by micrometer and nanometer roughness and are formed via multipulse illumination through a combination of ablation, redeposition of ablated material, and fluid flow of molten material. Recent studies have demonstrated variations in the density and shape of surface features via modication of laser fluence, pressure, and atmospheric composition.

We fabricate an undocumented range of multiscale surface features on stainless steel and nickel using FLSP. Specifically, up to seven distinct classes of multiscale surface features are fabricated solely through precise control of the laser fluence and number of pulses incident on the sample. These classes of structures are distinguished either by their dominant surface features or the physical mechanisms that govern their production.

In addition, we present a series of studies that utilize this wide range of multiscale surfaces to tailor and optimize energy transfer at liquid/solid interfaces. For example, the onset of film boiling (characterized by the Leidenfrost temperature) can be increased by over 175°C, droplets on a surface can be propelled uphill via directional boiling, and the production efficiency of hydrogen gas via electrolysis can be increased.

8968-28, Session 6

Femtosecond laser sintering of nanoparticle based metallic inks on flexible substrates for organic electronics applications

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Laser sintering is on the verge of becoming a standard tool in manufacturing sectors like 3D printers for mechanical parts, roll to roll printing technologies for optoelectronic devices on flexible substrates . In particular femtosecond laser sintering (FLS) of nanoparticles is gaining importance both for fundamental research of the sintering process and also for its applications. FLS has advantages as it is a 'maskless' technology enabling cost efficient rapid prototyping. Moreover it is compatible with low temperature thermal treatment process as required by the flexible polymer substrates. The devices with feature sizes of high resolution are possible with FLS as compared continuous wave laser sintering as in case of FLS the diffraction limits can be overcome as it is multiphoton driven process. Our results on FLS of silver nanoparticle based inks will be presented; various fabrication parameters and initial characterization will also be presented. We report the use of laser sintered Ag patterns as electrodes in high mobility organic field-effect transistors (OFETs), demonstrating the possibility to adopt this direct-writing technique to develop downscaled OFETs for logic circuits.

8968-29, Session 6

Joining of ultra thin sheets using a beam shaping optic

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Joining of ultra thin foils in the order of 100 micrometer and below is gaining importance in applications such as electrical contacting. The materials used for electrical contacts

commonly have good electrical conductivity and hence also good thermal conductivity and a high thermal expansion. As a consequence, these factors give rise to undesired effects such as high thermal gradients and distortion of the foils largely affecting the quality of the joints.

We investigate using a pulsed Nd:YAG laser to generate spot joints of overlapping ultra thin foils. Simply linearly downscaling laser power and spot size known from macro joining seems not to be sufficient as it is leading to very small laserspots of high intensity. While this may work well for seam joining with a large joining area due to the length of the seam it is likely to fail for spot joining with reduced joining area in both surface dimension. Hence, the process becomes further complicated by the conflicting desire to realize high mechanical strength of the connection while maintaining a stable process.

We present the use of a beam shaping optic to tailor the temperature profile during laser spot joining of ultra thin foils. Different configurations are examined and discussed mainly in terms of their general impact on micro joining process, in terms of process stability and mechanical strength.

8968-30, Session 7

New strategies in laser processing of TCOs for light management in thin-film silicon solar cells *(Invited Paper)*

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Light confinement strategies in thin-film silicon solar cells play a crucial role in the performance of the devices. One way to reduce these optical losses is the texturing of the transparent conductive oxide (TCO) acting as front contact. On the other hand other losses arise from the mismatch between the incident light spectrum and the spectral properties of the absorbant material. This implies that low energy photons (below the bandgap value) are not absorbed, and therefore can not generate photocurrent. Upconversion techniques, in which two sub-bandgap photons are combined to give one photon with a better matching with the bandgap, has been proposed to overcome this problem.

In particular this work studies two strategies to improve light management in thin film silicon solar cells using laser technology. The first one addresses the problem of TCO surface texturing using fully commercial fast and ultrafast solid state laser sources. In particular AZO and ITO samples has been laser processed and the results has been optically evaluated measuring the haze factor of the treated samples. A comparison of the experimental results with those obtained through numerical modelling of the optical behaviour can lead to a full optimization of the morphological characteristics of the laser treated surface. On the other hand, laser annealing experiments of TCOs doped with rare earth ions are presented as a potential process to produce layers with upconversion properties, opening the possibility of its potential use in high efficiency solar cells

8968-31, Session 7

Quasi-simultaneous laser soldering for the interconnection of back-contact solar cells with composite foils

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Back-contact solar cells allow an increase of the electrical efficiency compared to conventional solar cells because the electrical front contact is placed on the back side and therefore shading by interconnectors on the front side is prevented. The design of the back-contact solar cell challenges the interconnection process in regard to the geometrical position and required isolation of the punctual contacts on the back side. Today's interconnection processes need to result in a high joining quality and require a process time in the range of 3s per solar cell. In this contribution we evaluate the minimal process time for the interconnection of the 31 electrical contacts of a MWT-back contact solar cell with a quasi-simultaneous laser scanning strategy. The selective energy deposition with a laser system allows the minimization of thermal stress. The laser scanning process is applied in combination with a composite foil as an interconnector and a pre-dispensed solder paste. This approach is evaluated regarding the joining quality of the interconnection as function of the process time. An analysis of the thermal distribution on the solar cell by thermography is used for the optimization of the laser scanning strategy in regard to thermomechanical stress in the joining zone.

8968-32, Session 7

Utilizing the transparency of semiconductors via backside machining with a nanosecond 2 um Tm:fiber laser

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Semiconductors such as Si and GaAs are transparent to long wavelength near-IR lasers with wavelengths >1.2 µm. As such, it seems as though it should be a simple matter to utilize this transparency for materials processing in the bulk or the rear surface of the material without damaging the front surface. However, in previous experiments with ultrashort laser pulses we have found that nonlinear absorption makes it impossible to sufficiently concentrate the optical intensity to the point of material modification far below the front surface. Using a recently developed Tm:fiber laser system producing pulses as short as 7 ns with peak powers exceeding 100 kW, we have demonstrated it is possible to ablate the "backside" surface of 500-600 µm thick Si and GaAs wafers.

We will report on the nonlinear absorption in Si and GaAs for pulses with 7 and 100 ns pulse duration. Over this pulse duration range, we see a significant increase in nonlinear absorption for shorter nanosecond pulses in Si, which has a significant effect on the energy required for and the morphology of backside modification. This unique processing regime has the potential to enable novel applications such as semiconductor welding for microelectronics, photovoltaic, and consumer electronics.

8968-33, Session 7

Study of a-Si crystallization dependence on power and irradiation time using a cw green laser

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INTRODUCTION

Crystallization and grain growth technique of thin film silicon are among the most promising methods for improving efficiency and lowering cost of solar cells.

A major advantage of laser crystallization over conventional heating methods is its ability to limit rapid heating and cooling to thin surface layers. This is mainly controlled by the pulse duration time and the absorption depth of the laser light used in the material. Laser energy is used to heat the amorphous silicon thin film, melting it and changing the microstructure to polycrystalline silicon as it cools.

EXPERIMENTAL PROCEDURE

Thin film samples of a-Si, deposited by physical vapor deposition on a glass substrate, were irradiated with a cw-green laser source.

In order to control the energy input, laser irradiated spots were produced by using different laser powers and irradiation times.

The structural properties were studied by micro-Raman spectroscopy. In order to analyze the crystalline fraction of the irradiated area, the Raman spectra were fitted by three Gaussian line profiles.

RESULTS

The laser power and the irradiation time are identified as key variables in the crystallization process. In the study, the power threshold for crystallization is reduced as the irradiation time is increased (reaching 90 mW for 15 ms of irradiation time). Once this power threshold is reached crystalline fraction increases lineally with power for each irradiation time until a new threshold for material damage is reached.

Acknowledgements

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Conference 8969: Synthesis and Photonics of Nanoscale Materials XI

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8969-1, Session 1

In situ Raman spectroscopy studies of single-walled carbon nanotube growth *(Invited Paper)*

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We report progress on our study of single-walled carbon nanotubes (SWNT) growth using a unique setup that combines situ Raman spectroscopy with chemical vapor deposition. We have used our system to link the initial growth rate of a SWNT to its chirality [1]. We showed experimentally that higher chiral angle nanotubes grew faster than lower chiral angle nanotubes. This was originally predicted in a theoretical treatment by Ding and Yakobson [2].

We also compared the growth kinetics of SWNTs from iron and nickel catalysts over a range of temperature (750?-1200? C) [3]. Here we found that, while for nickel the lifetime of the catalyst decayed as temperature increased, the iron catalyst underwent a discontinuous increase in catalyst lifetime. We explain this using the binary Fe-C and Ni-C phase diagrams, showing that the jump in lifetime around 1000? C correlates well the Fe-C eutectic temperature modified for the nano-size of the catalyst. In contrast, no jump is seen for nickel, which is explained by the higher eutectic temperature in the Ni-C phase diagram.

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8969-2, Session 1

Laser-assisted growth of carbon nanotubes inside sealed fluidic microchannels

Yoeri van de Burgt, Audrey Champion, Yves Bellouard, Technische Univ. Eindhoven (Netherlands)

Carbon Nanotubes (CNTs) form interesting organized nanostructures that find a variety of applications as diverse as field effect transistors, interconnects, saturable absorbers in laser cavities, AFM tips or filters with nanoscale pores for water purifications.

A major challenge in producing CNTs that are embedded in devices is to cope with the high temperature requirements (typically well above 500 deg. C) necessary for synthesizing their peculiar crystallographic structures. These requirements dramatically limit the CNT-growth process integration with possible other manufacturing techniques or elements.

Here, we present a method to directly grow vertically-aligned carbon nanotube structures within a sealed micro-channel by means of a feedback-controlled laser-assisted chemical vapor deposition technique.

To do so, we use a CW infrared laser to locally heat up the inner surface of a channel on which a catalyst (Fe / 1.5 nm and Al2O3 / 20 nm) is deposited. The channel is sealed and part of it is fabricated using femtosecond laser exposure combined with chemical etching. To achieve a precisely controlled and constant temperature necessary for the efficient growth of CNTs, we use feedback control based on emitted thermal radiation and reflected unabsorbed light from the laser growth site. The gas containing the carbon load - in our case ethylene - is flown directly through the channel.

This process is compatible with virtually any micro-channel fabrication process and bypasses the need for usually costly post-process packaging and assembly. It opens new opportunities for CNTs embedded in fluidic devices.

8969-3, Session 1

Revealing growth mechanism of graphene induced by CVD and PLD using real-time optical diagnostics

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A combination of real-time Raman spectroscopy, optical imaging, and optical reflectivity were used to characterize the growth kinetics of graphene by pulsed chemical vapor (CVD) and pulsed laser deposition (PLD) at different growth temperatures. The key parameters relevant to energy applications – defects, nucleation density, crystallinity, and number of layers – depend critically on the growth mechanisms and kinetics. However, very few in situ characterization studies have been performed to understand the nucleation and growth kinetics of this important material under typical growth conditions. For graphene growth on Ni, fundamental synthesis questions are addressed including the timescales for rapid nucleation and growth and whether growth occurs at high temperature or upon cooling. The fractional precipitation upon cooling has been measured for the first time using in situ Raman spectroscopy, revealing the growth parameters for isothermal graphene formation, which is crucial for understanding the growth mechanism and controlling the number of layers. Temperature dependent growth kinetics clearly showed two completely different nucleation and growth mechanisms, i.e., surface nucleation and growth at low temperatures and segregation from the bulk of a Ni film at high temperatures. The growth model based on our in situ measurements of the growth kinetics will be presented. The described approach combining CVD (PLD) and real-time optical diagnostics opens new opportunities to understand and control graphene growth on various substrates.

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8969-4, Session 1

Laser-based synthesis of nanoparticles: role of laser parameters and background conditions

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Laser ablation (LA) is a unique tool for nanoparticle synthesis [1]. The main advantages of this method are in its green character and in the possibility of a control over particle size.

In this study, we examine nanoparticle formation by laser ablation under different experimental conditions and analyse the results based on the developed models [1-4]. The dynamics of the laser plume expansion is examined revealing the role of the background pressure and laser pulse duration (fs, ns). As a result, the ablated material is compressed and a part of it becomes supersaturated. The so-called “primary” nanoparticles are formed at this stage. Then, nanoparticle aggregation/fragmentation enters into play leading to the formation of the secondary particles. In addition, laser-assisted fragmentation of nanopraticles is also examined. Based on numerical modeling we shed light on the above mechanisms by using different numerical approaches, such as molecular dynamics, DSMC [4], numerical hydrodynamics [3] and analytical analysis [2]. Calculations are performed mostly for metallic targets and for carbon under different background conditions. The obtained results explain recent experimental findings and help to predict the role of the experimental parameters. The performed analysis thus indicates ways of a control over nanoparticle synthesis.

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8969-5, Session 1

Understanding the formation of nanostructures and thin films using nanoparticles as ‘building blocks’ in pulsed laser deposition

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Ultrasmall nanoparticles (UNPs, ~ 3 nm) synthesized in pulsed laser vaporization (PLV) are investigated as “building blocks” in the growth of larger nanostructures, and into thin films. Here we primarily study the synthesis conditions, size distribution, and atomic structure of TiO_2 UNPs as a test material due to its extraordinary optical and photocatalytic properties. Temporally- and spatially-resolved gated-ICCD imaging, spectroscopy and ion probes are employed as in situ diagnostics to understand and control the plume expansion conditions for synthesis of various TiO_2 UNPs. Atomic-resolution Z-contrast scanning TEM and EELS are described to characterize the stoichiometry and atomic structure of individual UNPs. In Situ and Ex-situ annealing experiments are used to understand how UNPs are integrated into larger nanostructures and thin films. These findings are crucial to understand stoichiometry transfer and film growth modes in PLD, catalyst-assisted nanotube and nanowire growth in PLV, and catalyst-free nanorod synthesis in NA-PLD.

Research sponsored by the U.S. Dept. of Energy, Basic Energy Sciences, Materials Science and Engineering Div. (synthesis science) and Scientific User Facilities Div. (characterization science).

8969-6, Session 1

Catalytic nanoparticles for carbon nanotube growth synthesized by through thin film femtosecond laser ablation

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Alloy nanoparticles synthesized by femtosecond laser ablation of multilayer films are combined with carbon nanotube synthesis to understand the extent of intermixing of multilayer films in femtosecond ablation, the factors determining particle size, the catalytic activity of the particles, and the influence of the particles on carbon nanotube growth. Here, nanometer-scale films deposited on a quartz substrate are ablated in vacuum and Ar gas using a through-thin-film configuration, and ejecta is collected on TEM grids in millimeter proximity to understand the influence of layer thickness and collection location on particle size. Gated-ICCD imaging is employed as an in situ diagnostics to understand plume transport, while ex situ TEM -- both conventional and atomic-resolution Z-contrast -- is used to characterize particle size distributions, stoichiometry, and atomic structure. A computational modeling approach is described to understand particle size distributions and layer intermixing, and experiments involving film thickness gradients are presented to understand the influence of particle size and alloy composition on nanotube growth. These findings may open new opportunities to understand and control nanotube diameter, wall number, and chirality through the design of new catalysts.

Research sponsored by the U.S. Dept. of Energy, Basic Energy Sciences, Materials Science and Engineering Div. (synthesis science) and Scientific User Facilities Div. (characterization science).

8969-7, Session 2

Demonstration of enhanced surface mobility of adsorbate cluster species by surface acoustic wave excitation-induced by a pulsed laser

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Fluorescence microscopy is being used to explore the efficacy of surface acoustic waves (SAWs), generated by a pulsed laser “tapping” a surface, to enhance the surface mobility of molecular adsorbates. The adsorbate system comprises a series of gold clusters that are prepared on silicon (111) with a native oxide layer. The gold system has been chosen because the fluorescence emission spectra of the various clusters (e.g. 8, 13, 21, 32 atoms) have been measured. Gold clusters are distinguished through band-pass filter spectroscopy and tracked by fluorescence. This allows measurement of surface mobility enhancement by SAWs as a function of cluster size (i.e. binding energy). The SAW source is a pulsed UV (355nm) laser operating at a repetition rate of 100Hz where the laser fluence is set below the damage threshold of silicon. The experiment measures the emitted light for a particular cluster through a high magnification (100X) imaging microscope that is integrated with a water cooled EMCCD camera. The enhanced mobility induced by SAWs is derived by comparing a set of images before and after repeated SAW excitation pulses produced by the “tapping” laser. Centroid method or other algorithms are used to track the light emission. Initial results show that the cluster Au_8 moves approximately 0.2-0.3 Angstroms/laser shot (when the excitation source is approximately 2 cm away). We will present data that tracks the displacement of various gold clusters and provide information on the applied SAWs as measured by an in situ CW laser heterodyne technique. These results lay the foundation for “growing”/ synthesizing thin films via surface aggregation of cluster compounds.

8969-8, Session 2

Characterization of two-photon polymerization process using Raman microspectroscopy

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We investigated the quantitative relationships between the TPP laser conditions and the cross-linking of an acrylic-based IP-L photoresist via systematical Raman characterization. By probing the excitation of carbon-carbon double bond vibrations, the differences in the Raman spectra between the non-polymerized and the polymerized IP-L photoresists were observed. A simple mathematic model of the degree of polymerization with respective to the TPP conditions including laser average power and writing speed was established. The established model will contribute to the advanced 3D TPP micro/nanofabrication with improved controls of laser energy, voxel sizes, and the mechanical strength of polymers.

8969-9, Session 2

Stability of Rh-Pd-Pt alloy nanoparticles produced by femtosecond laser irradiation of aqueous solution with surfactant

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Effect of surfactant on Rh-Pd-Pt alloy nanoparticles (NPs) produced by femtosecond laser irradiation of aqueous solution was studied. It was found that the addition of surfactant (PVP) significantly contributed to reduce the mean particles size to 3 nm, which was much smaller than that of particles fabricated without any surfactants (~20 nm), and to improve the stability of the colloidal solution. The surfactants covered the particle surface during particle formation resulting in the improved size uniformity as well as stability of the fabricated NPs. Structure of fabricated NPs was characterized by X-ray diffraction. The XRD peaks for (111) and (200) planes were typical ones for fcc-structured crystal and in the range of those of pure Rh, Pd and Pt, strongly indicating the formation of solid-solution alloy. Crystalline nature of the alloy NPs was also confirmed by high-resolution transmission electron microscopy (HR-TEM). On the other hand, the elemental composition of individual NPs evaluated by energy dispersive X-ray spectrometry (EDS) analysis was different from the initial feeding ratio of mixed metal ion solution. The fabricated NPs were Pt rich Rh-Pd-Pt alloy for all the samples. This might be due to the difference of the reduction potentials of metallic ions by the formation of “polymer-metal ion complex”. Based on the result, we will be able to control the size and composition of NPs by the addition of surfactant and the feeding ratio of sample solution. The effect of different surfactant will be also reported in the presentation.

8969-10, Session 2

Preparation of submicron-sized gold particles using laser-induced agglomeration-fusion process

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Very recent studies have shown that laser irradiation (LI) for colloidal nanoparticles (NPs) using a non-focused laser beam at moderate fluence transforms the NPs to submicron-sized spherical particles (SMPs). For this study, we applied this technique to prepare gold SMPs from source gold NPs prepared by laser ablation of a gold plate in an aqueous solution. Results show that SMPs were obtained from NPs in pure water, but a considerably large amount of the source NPs were sedimented without LI. On the other hand, SMPs were not obtained from NPs stabilized by 1 mM citrate. These findings indicate that the agglomeration of the source NPs prior to the laser-induced melting is important to obtain SMPs, although the sedimentation of the source NPs caused by considerable agglomeration should be reduced to obtain SMPs efficiently. A proper condition of the agglomeration tendency of the source NPs to prepare SMPs reducing the sedimentation of the source NPs was obtainable by simply adjusting the citrate solution concentration. Moreover, investigation of the temporal dynamics of the formation process of SMPs suggested that the agglomeration of the source NPs not only is controlled by citrate but also is induced by LI. LI brings about the decomposition and removal of citrate molecules on the surface of the source NPs, and cause the agglomeration of the source NPs dynamically; then it brings about the fusion of the agglomerated NPs. In addition, similar protocol was applied for the source NPs stabilized other ligands such as acetone and sodium chloride.

8969-11, Session 2

Compositional analysis of silicon fibrous nanostructures synthesized using femtosecond laser pulses under ambient condition

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Surface processing of crystalline silicon samples using femtosecond laser pulses at megahertz pulse repetition rate under ambient condition lead to the generation weblike fibrous nanostructures. Electron Microscopy analysis revealed that the fibrous nanostructures are formed with silicon nanoparticles of size about 40 nm. In addition Micro-Raman analysis shows that the nanofibrous structures are a mixture of amorphous and polycrystalline siliconas compared to bulk. X-ray photoelectron spectroscopy analysis reveals the oxidized and unoxidised elemental states of silicon in the fibrous nanostructures. Moreover weblike nanostructures formation is essentially due to nucleation and condensation of super saturated vapour in the plasma plume generated during the irradiation process.

8969-12, Session 3

Fluorescence and second-harmonic generation correlative microscopy to probe space charge separation during femtosecond direct laser writing

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Femtosecond (fs) direct laser writing (DLW) in homogeneous dielectrics provides three-dimensional (3D) material modifications at the micro-nanoscale, at the root of chemical [1], mechanical [2] as well as optical [3] contrasts. Such approach has already demonstrated an extremely broadband range of fundamental mechanisms and original applications [4,5]. The different time scales; during laser processing; lead to material modifications. The fast processes such as multiphoton excitation and pulse-to-pulse accumulation have already been have already been pointed out to the understanding of DLW.

In this article, we report on, real time correlative microscopy studies of both fluorescence and effective second-order nonlinear responses during 3D fs laser irradiation in glass.

Fluorescence contrast is perfectly adapted to probe material modification and colored centers growth [6] after the material modification or during laser processing. On the other hand, nonlinear optical contrast has also been reported, such as effective second-harmonic generation (SHG), even in an initially centro-symmetric material, thanks to local space charge separation. Such buried electric field that induced second-harmonic generation (EFISHG) has largely been reported under

thermal poling [7–9]. SHG microscopy while processing the dielectric material through EFISHG process, leads to measurement of spatial and temporal dynamics of photo-generated electrons. In cumulative regime, remanent electric field amplitude build up could also be investigated [10]. However, to our knowledge, no correlative studies of both fluorescence and nonlinear laser-induced responses originating from fs DLW during laser processing were conducted in detail, in order to improve the understanding of the dynamics in the processes of these written optical responses.

8969-28, Session 3

Excimer laser-induced nanoablation of amorphous and nanocrystalline diamond films

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Possibility of ultra-precision laser-induced etching of diamond materials has been demonstrated. Nanocrystalline diamond & amorphous diamond-like films were irradiated in air and low vacuum with excimer laser (?=248 & 193 nm, ?=20 ns) at fluencies 0.01÷20 J/cm2. It is found that depending on material, laser fluence and wavelength physical (vaporization) and physical-chemical (oxidation) regimes of such materials ablation are realized. It is shown that in chemical etching regime the ablation rates as low as 10-3-10-4 nm/pulse for multi-pulsed irradiation can be obtained. The process was called nanoablation and applied to surface nanostructuring. Specific features of short pulsed surface chemical reaction will be discussed. Particular attention will be paid to water adsorption in atmospheric air.

8969-13, Session 4

The liquid phase assembly of metallic nanoparticle arrays using nanolithography and pulsed laser melting *(Invited Paper)*

Jason D. Fowlkes, The Univ. of Tennessee (United States)

An integrated approach using nanolithography coupled with pulsed laser melting made it possible to assemble particle arrays with precisely defined size and spacing. Specifically, liquid–phase, pulsed laser induced dewetting was used to transform solid metallic thin film strips into particle arrays, a form of directed assembly. A fluid instability akin to the Rayleigh – Plateau instability, which describes the destabilization of a fluid jet in response to surface perturbations, ultimately drives the particle formation reported here with a key role played by the supporting substrate surface. The resulting arrays exhibit an unnaturally low deviation in particle size and particle spacing. Nanoparticles were also realized following instability development and were size-selected for surface display by implementing a subsequent ion milling step. Further, we demonstrate the ability to direct the assembly of particles and wires simultaneously, from a common initial thin film strip geometry, which advances our current directed assembly paradigm to facilitate both directed and parallel assembly. Key to realizing this accomplishment was (1) the control of the liquid lifetime on the order of the nanosecond time scale and (2) the ability to define nanoscale perturbations on the initial thin film strip structure using nanolithography. Hydrodynamic simulations have played a key role in both understanding and designing particle array formation; uses of the linear stability analysis (LSA) approach for design purposes as well as results from non-linear hydrodynamic simulations of instability development will be reported.

8969-14, Session 4

Laser-induced periodic nanoparticle patterns

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Creating the conditions so that matter naturally self-arranges at the nanoscale under a homogeneous excitation is an exciting challenge for the development of efficient and cost-effective processes. Sub-micrometer periodic templates can be formed spontaneously on materials by low-energy ion sputtering or with lasers. In the latter case, the formation of self-organized grating-like structures requires a high temperature rise and generally results from interactions with ultrashort laser pulses. Recently, a few studies have dealt with self-formed periodic patterns of metal nanoparticle assemblies, but they only reported changes in the spatial and size distributions of metal nanoparticles deposited on surfaces prior to interaction with femtosecond lasers.

Here, we show that metal nanoparticles can grow in a self-organized manner within a waveguide illuminated from free-space by a continuous wave visible laser. We explain the mechanisms involved in the formation of such nanostructures on the basis of interference phenomena between the incident wave and guided modes. The discussion is based on characterizations by electron microscopy techniques and on the comparison of experimental and simulated transmission spectra of few samples, which clearly evidence the coexistence of plasmon and waveguides resonances in the structure. The influence of different parameters linked to the illumination conditions or to the opto-geometrical parameters of the waveguide is studied. We also demonstrate that it is even possible to extend the grating without stitching errors by successive illuminations partially overlapping, which is a serious asset to make nanoparticle gratings with locally tuning parameters on large areas.

8969-15, Session 5

Optical and electronic properties of transition metal dichalogenides at monolayer thickness *(Invited Paper)*

Tony F. Heinz, Columbia Univ. (United States)

MoS_2 is a prototype of a family of atomically thin metal dichalcogenides. Although the structure of the monolayer is similar to that of graphene, the A and B sublattice are occupied either by Mo atoms or by a pair of S atoms, rather than by C atoms. This difference in symmetry allows $MoS_2$to be a semiconductor with a significant band gap. Through characterization of the optical properties of the material as a function of thickness, we show that quantum confinement effects lead to a crossover in MoS_2 from a dark, indirect-gap semiconductor in the bulk to a bright, direct-gap semiconductor at monolayer thickness [1]. As is common for lower-dimensional materials, excitonic effects are also very strong in MoS_2 as we demonstrate through the spectroscopic identification of charged excitons (trions) [2]. Another distinctive feature of this material is the possibility of producing long-lived valley polarization by excitation with circularly polarized light [3], as we show through photoluminescence measurements [3].

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8969-16, Session 5

Near-infrared emission from freestanding single- and few-layer graphene

Tu Hong, Yunhao Cao, Da Ying, Yaqiong Xu, Vanderbilt Univ. (United States)

We investigate the near-infrared emission from freestanding single- and few-layer graphene. In contrast to monolayer graphene, folded few-layer graphene displays much stronger thermal radiation under high laser power, with temperatures exceeding 700 K before structure breakdown. By analyzing the thermal emission and Raman spectra, we obtain a coefficient relating Raman G' mode shift to temperature for few-layer graphene. This coefficient is higher than the previously-reported value for supported single-layer graphene, possibly due to the elimination of energy dissipation into the substrate. However, the thermal emission from graphene drops dramatically in an aqueous medium as a result of the high thermal conductivity of water. When thermal radiation becomes negligible, a gate voltage can be applied to tune the near-infrared emission of graphene by changing its Fermi energy. The emission intensity is related to the thickness of graphene, with monolayer graphene displaying the weakest intensity, and successive layer numbers showing higher intensity. Moreover, a gate-dependent Raman spectroscopy study reveals that the one-phonon Raman signal of suspended single- and few-layer graphene increases with increasing Fermi energy, whereas the two-phonon Raman mode diminishes. Hot-electron luminescence is also observed for both single- and few-layer graphene at a high Fermi level. These results are similar to previously-reported results of supported graphene.

8969-17, Session 5

Nanophotonics for light-management in thin-film photovoltaics and optical nanopatterning for their fabrication *(Invited Paper)*

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Photovoltaic devices with ultra-thin absorbers allow for high charge-transport and carrier-collection efficiencies.[1] Furthermore, such devices could be cost-effectively manufactured by scalable technologies.[2] However, ultra-thin layers are intrinsically poor absorbers of incident photons. We have recently developed methodologies for designing 2D and 3D nanophotonic structures to efficiently couple incident light into guided modes resonances (GMRs) within an ultra-thin photovoltaic device.[3,4] As a result, light absorption may be increased beyond the 4n2 (ergodic) limit and the efficiency of ultra-thin photovoltaic devices can be boosted significantly. I will review the photonic principles of these novel devices.

Another challenge in these and related applications is the accurate patterning of these nanostructures in a cost-effective manner that can be scaled to large areas. We are developing two approaches that overcome the far-field diffraction barrier in optical nanopatterning,5,6 and allow near-UV and visible photons to pattern sub-50nm structures. Since optical patterning can be considerably faster than alternatives such as scanning-electron-beam lithography, these techniques have the potential to address the challenge of scalable nanomanufacturing. I will also review these approaches.

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8969-18, Session 6

Multifunctional materials for electronics and photonics *(Invited Paper)*

Riad Nechache, Federico Rosei, INRS, Univ. du Québec (Canada)

The bottom–up approach is considered a potential alternative for low cost manufacturing of nanostructured materials [1]. It is based on the concept of self–assembly of nanostructures on a substrate, and is emerging as an alternative paradigm for traditional top down fabrication used in the semiconductor industry. We demonstrate various strategies to control nanostructure assembly (both organic and inorganic) at the nanoscale. Depending on the specific material system under investigation, we developed various approaches, which include, in particular: (i) control of size and luminescence properties of semiconductor nanostructures, synthesized by reactive laser ablation [2]; (ii) we developed new experimental tools and comparison with simulations are presented to gain atomic scale insight into the surface processes that govern nucleation, growth and assembly [3-7]; (iii) we devised new strategies for synthesizing multifunctional nanoscale materials to be used for electronics and photovoltaics [8-24].

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8969-19, Session 6

Optical-only methods for measuring charge carrier diffusion in colloidal quantum dot films *(Invited Paper)*

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Colloidal quantum dots (CQDs) are an attractive low-cost material for various electronic devices. Transport properties of CQD films are of particular importance for device performance. Present day CQD photovoltaics rely increasingly on the carrier diffusion in the quasi-neutral region, however, the techniques for measuring the diffusion length under device operation conditions, i.e. low injection levels, are limited.

We propose a new optical-only method, similar to a contactless time-of-flight measurement, utilizing the bandgap tunability of CQDs and low-bandgap CQDs as an optical reporter. A variation of the method, mixing high- and low-bandgap material, allows for decomposition of the diffusion length into mobility and recombination centers density components. Surprisingly, we find that diffusion lengths are insensitive to changes in mobility and are currently limited by rare recombination centers in the films, calling for further improvements in surface passivation.

Complementary techniques, such as ultrafast photoluminescence decay and transient IR absorption measurements of intraband transitions allowed peering deeper into the process of transport-assisted recombination. These findings elucidated the origin of detrimental traps and suggested the means to eliminate them.

8969-20, Session 6

Polarization-dependent switching in gold-vanadium dioxide heterodimers

Kannatassen Appavoo, Richard F. Haglund Jr., Vanderbilt Univ. (United States)

Metallic nanostructures have plasmonic resonances that can spatially concentrate light field on the nanometer length scale, strongly focusing electromagnetic energy in a nanometer-scale volume. By positioning a phase-transforming nano-object with variable dielectric properties in the optical near-field zone of a plasmonic nanoantenna, the localized surface plasmon resonance (LSPR) can be modulated. We used a three-stage lithographic process to fabricate arrays of heterodimers with varying intra-dimer spacing, each comprising a phase-changing nanoparticle (NP) of vanadium dioxide (VO_2) and a gold plasmonic nanoantenna with a size-dependent surface-plasmon resonance. The VO_2 undergoes a reversible solid-solid phase transformation combining an insulator-to-metal transition (IMT) with a structural reconstruction from monoclinic M1 to rutile R phase at 68°C.

The effects of coupling between the Au nanoantenna and the VO_2 NP were monitored by white-light transmission spectroscopy. Near-field, polarization-dependent switching of the SPR wavelength due to the IMT is observed when the distance between the gold and VO_2 NPs is of order 30 nm, with a sharp increase in the wavelength shift beginning at 20 nm spacing and an SPR shift of 10 nm at 14 nm spacing (the closest spacing achieved lithographically). This is consistent with what is known about the length scale of the plasmon field. The experimentally measured distance dependence of the change in LSPR wavelength is reproduced by finite-difference, time-domain simulations. Since the IMT can be triggered optically or electrically, this nanoswitch can be operated in several different modes, including bistability, optical limiting and ultrafast operation.

8969-21, Session 6

Resonant-cavity effects on plasmon-enhanced photoluminescence in zinc-oxide core-shell nanowires

Daniel C. Mayo, Claire Marvinney, Ephraim Bililign, Vanderbilt Univ. (United States); Richard Mu, Fisk Univ. (United States); Richard F. Haglund Jr., Vanderbilt Univ. (United States)

Zinc oxide (ZnO), a II-VI semiconductor with a direct bandgap of 3.37 eV and exciton binding energy of 60 meV, has emerged as one of the most promising optoelectronic materials for a wide variety of applications. Room temperature photoluminescence (PL) spectra for ZnO exhibit a band-edge exciton-recombination peak at 3.37 eV and a broad visible emission peak centered near 2.3 eV that is usually described as superposition of donor-acceptor-pair (DAP) recombination lines. By carefully tuning emission of ZnO nanowires, a wide range of optoelectronic devices have been developed, including LEDS, lasers and sensors. Although different growth, annealing, and doping conditions have been used to control the ZnO emission, one of the most effective methods for PL enhancement is the Purcell mechanism, mediated by coupling localized surface plasmons to the luminescent centers.

We have demonstrated significantly enhanced band-edge PL in core-shell ZnO/MgO nanowires coated variously with Ag, Al, Au and Cu nanoparticles. The enhancement peaks at specific MgO shell thicknesses that correspond to Fabry-Perot cavity resonances in the core-shell nanowire. This enhancement is much larger than can be accounted for from surface passivation of shallow ZnO defects; indeed, the defect PL intensity is unaffected by the core-shell geometry. The hypothesis of PL enhancement via the Purcell mechanism is further supported by the variation in band-edge PL for the various nanoparticle species, with Al nanoparticles exhibiting both the strongest plasmonic coupling to the band-edge exciton and largest PL enhancement. These results establish the core-shell nanowire structure, decorated with plasmonic nanostructures, as an interesting tunable ultraviolet light source.

8969-22, Session 6

Femtosecond pump-probe spectroscopy of Au/TiO2 nanocomposites: the evolution of localized plasmon resonance and its connection to charge transfer effects

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Gold nanoparticles (AuNP) embedded in mesoporous films of wide band gap semiconductors such as TiO_2 are used for promising applications in solar cells, visible light-sensitive photocatalysts, and biosensors developed on the basis of localized plasmon resonance (LPR) properties of metal nanoparticles. Femtosecond laser sources have made it possible to temporally resolve electron–electron and electron–phonon dynamics under a variety of excitation conditions in colloids and dielectric glasses. Contact between AuNP and TiO_2 could be a reason of the additional mechanism of electron relaxation in plasmonic NPs related to the charge transfer that manifests itself as specific features of femtosecond transient absorption spectra of the system. In this work, femtosecond transient absorption spectra of AuNPs embedded in mesoporous TiO_2 matrix were studied by a laser photolysis pump – probe technique using 25 fs pulses at 740 nm (1.68 eV). The shift of the bleaching peak in transient spectra of order of 100 meV is detected in the AuNP/TiO_2 system, whereas the bleaching peak shift of the same AuNPs in aqueous colloids does not exceed 5 meV. Moreover, the observed LPR shift is the same for the broad range of pump pulse energies: from 30nJ to 300nJ. Such a behavior can be explained in frame of electron transfer model from AuNPs to TiO_2 which takes into account LPR position of charged AuNPs

(calculated by TD-DFT) as well as electron relaxation into TiO2 traps. Additionally, measured photoinduced reduction of the methyl viologen (MV+2 to MV+1) on the surface of Au/TiO2 proves possible electron transfer in such nano-composites.

8969-23, Session PTue

Interpreting strong two-photon absorption of PE3 platinum acetylide complex: double resonance and excited state absorption

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Herein, we report on the strong two-photon absorption (2PA) of PE3 platinum acetylide complex dissolved in dichloromethane. PE3 present ground-state absorption with high molar absorptivity at the near-UV region (<420 nm), providing a wide transparence window in the visible region ideal for applications in photonic devices. The 2PA spectrum was measured though the open-aperture Z-scan technique using an amplified femtosecond laser system (150 fs) operating at low repetition rate (1 kHz). Since PEs present short intersystem crossing time (ps) and long phosphorescence time (microseconds), the 2PA cross-section obtained from the Z-scan technique may have contribution from the triplet states. However, we shown through the rate equations model and pump-probe experiments that the rate of the population transferred to the triplet state via 2PA, employing femtosecond laser and low repetition, is completely negligible (< 1%). Consequently, 2PA cross-section between tens to thousands of GM units observed along the nonlinear spectrum is due only to pure singlet-singlet transitions. Our results show that the 2PA spectrum of PE3 in dichloromethane solution exhibit two 2PA allowed bands centered at 760 nm (120 GM) and 610 nm (680 GM) and a very intense 2PA for wavelengths below of 500 nm (>1000 GM). The 2PA bands were attributed to the 11Ag-like?11Bu-like and 11Ag-like?21Bu-like transitions, which are possible due to violation of selection rules of PE3 that, in solution, present centrosymmetric and noncentrosymmetric conformers. 2PA region with prodigious cross-section observed between 460 and 500 nm was ascribed the double resonance effect and high singlet excited state absorption (S0?Sn).

8969-24, Session PTue

Structure-property relationships for two-photon absorbing triarylamine chromophores containing trifluoromethyl

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Herein, we report on the influence of the Electron Withdrawing Groups (EWG) strength on the one- and two-photon absorption properties of six novel push-pull triarylamine molecules containing trifluoromethyl (CF3). The molecules present octupolar structures with a core based in triarylamine (strong donor group) containing two trifluoromethyl-phenyl arms (acceptor group) and another with distinct EWG strength (H < CN < CHO < NO2 < Cyet < Vin). For the two-photon absorption measurements we used the open-aperture Z-scan technique with femtosecond pulses operating at low repetition rate (1 KHz). Our results point out that the 2PA cross-section is enhanced and redistributed more homogeneously along the nonlinear spectrum as a function of increase of the EWG strength. More specifically, the 2PA cross-section is enhanced of 40 up to 125 GM for the lowest energy band and 95 up to 265 GM for the high energy band. These results were elucidate from the large changes observed in transition and permanent dipole moment as consequence of increase of the EWG strength, improvement in electronic coupling among the arms and higher planarization of triarylamine core. We apply two and three-energy level approximation to establish a quantitative relation between the 2PA and the molecular properties of the chromophores in solution. In addition, we found that the 2PA cross-section normalized by the molecular weight for these compounds are considerably higher than to others triarylamine derivatives with similar molecular structures. We attributed this result to presence of the CF3 group that provides new charge transfer excited states from the amino core towards the biphenyl groups.

8969-25, Session PTue

Correlation between the morphology of the DEA-Mn compounds and the photoinduced absorption

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In this work, we report photoinduced optical absorption and nonlinear – optical second harmonic generation (SHG) of different ferroic nanocomposites in a form of films and bulks. As a basic we have chosen the DEA:Mn [(NH(CH3)3]2MnCl4 nanocrystallites possessing incommensurate phase embedded into the polymer matrices. The corresponding nanoparticles (NP) were embedded into polymer matrices with content of NP varying from 1 up to 5 % in weight unitns. In order to study the physical origin of the effects observed in the ferroic nanocomposites, in the present work we studied the photoinduced changes of the optical spectra in the vicinity of the visible absorption edge energy gap versus treatment time as well as their kinetics after switching off the laser. We have found substantial changes of the absorption under influence of the continuous wave lasers. The changes of the photoinduced optical second harmonic generation were stimulated by the two bicolour laser coherent beams. To clarify the role of the photoinduced changes of these surfaces, the corresponding AFM investigated of the surfaces performed before and after illumination we presented. We have found that there exists some optimal sizes at which the photoinduced changes of the absorption are maximal. These features correlate well with the photoinduced enhancement of the linear electrootpics effect and SHG. Substantial dependence on temperature near the phase transformation temperature was found. Moreover, it was found substantial influence of the polymer matrix on the photoinduded optical and nonlinear optical parameters. Principal role of the nanointerfaces on the border polymer-nanocrystals is shown.

8969-26, Session PTue

Raman gas sensing of modified Ag nanoparticle SERS

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Recent progress in modified Surface Enhanced Raman Scattering (SERS) using Ag nanoparticles makes them promising optical technique for direct gas sensing of interest. However, SERS has been shown to provide sub ppb level detection of the compounds in the vapor phase. The major problem with the sensitivity scaling-up was in the development of fabrication technology for stability and reproducibility of SERS substrates. We report an optimization of 1-propanethiol coated Ag nanoparticle layers on SiO2 substrate as well as new records of real-time, simultaneous vapor phase detection of toluene and 1-2 dichlorobenzene by the radiation of fiber optic coupled 785nm diode

laser and spectrograph. Multiple depositions of Ag NPs were loaded on SiO_2 and soaked in 1-propanethiol solution for 24 hours to modify the surface into hydrophobic due to the vapor phase of our interests. Raman peaks at 1003 cm^{-1} and 1130 cm^{-1} for toluene and 1-2 dichlorobenzene, respectively were compared to 1089cm^{-1} and each gas concentration in 1000ml cylindrical flask were calculated as a function of each vapor phase ratio. The saturation of toluene and 1-2 dichlorobenzene were limited only by 800ppm and the detectable range was 0.6-800 ppm. The results were simultaneously compared to commercially available gas sensor.

8969-27, Session PTue

Variation of cell spreading on TiO_2 film modified by 775 nm and 388 nm femtosecond laser irradiation

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Titanium (Ti) is one of the most used biomaterials in metals. However, Ti is typically artificial materials and has no biofunction. Thus, it is necessary for improving the bioactivity of Ti. Recently, coating of the titanium dioxides (TiO_2) film on Ti plate has been proposed to improve biocompatibility of Ti. We have developed coating method of the film on Ti plate with an aerosol beam. Then, interaction of biomaterial surface and cells was very important for biocompatibility. Periodic structures formation on biomaterials was also useful method for improving the biocompatibility. Direction of cell spreading might be controlled along the grooves of periodic microstructures. In our previous study, the film was formed by using the aerosol beam. Periodic nanostructures were formed on the film by femtosecond laser irradiation at fundamental wave (775 nm). Period of the periodic nanostructures was about 230 nm. In cell test, cell spreading along the grooves of the periodic nanostructures was observed although it was not done for the film without the periodic nanostructures. Then, influence of the period of the periodic nanostructures on cell spreading has not been investigated yet. Period of periodic nanostructures might be changed by changing the laser wavelength. In this study, we created the periodic nanostructures on the film with femtosecond laser at 775nm and 388 nm, respectively. Then, cell test was conducted to examine cell spreading on the film with periodic nanostructures. Osteoblast (MG-63) was used for cell test.

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8970-1, Session 1

A synopsis of DARPA investment in additive manufacture and what challenges remain *(Invited Paper)*

Michael C. Maher, Defense Advanced Research Projects Agency (United States)

DARPA's interest in additive manufacture dates back to 1990 with the Solid Freeform Fabrication program. The drivers for this program included reducing development times by enabling "tool-less" manufacturing as well as integration of design and fabrication tools. DARPA consistently pushed the boundaries of additive manufacture with follow-on programs that expanded the material suite available for 3-D printing as well as new processes that expanded the technology's capability base. Programs such as the Mesoscopic Integrated Conformal Electronics program incorporated functionality at the manufacturing processes through direct write of electronics.

DARPA's investment in the additive manufacture continues to this day but the focus has changed. DARPA's early investments were focused on developing and demonstrating the technology's capabilities. Today's investment addresses the systematic barriers to implementation rather than the technology itself. The Open Manufacturing program is enabling rapid qualification of new technologies for the manufacturing environment through the development of new modeling and informatics tools.

While the technology is becoming more mainstream, there are plenty of challenges that need to be addressed. And as the technology continue s to mature, the agency will continue to look for those "DARPA-hard" challenges that enable revolutionary changes in capability an performance for the Department of Defense.

8970-2, Session 1

Laser additive manufacturing: where it has been, where it needs to go *(Invited Paper)*

Khershed P. Cooper, National Science Foundation (United States) and U.S. Naval Research Lab. (United States)

It is no secret that the laser was the driver for additive manufacturing (AM) of 3D objects since such objects were first demonstrated in the mid-1980s. A myriad of techniques utilizing the directed energy of lasers were invented. Lasers are used to selectively sinter or fuse incremental layers in powder-beds, melt and deposit streaming powder following a programmed path, and polymerize photopolymers in a liquid vat layer-by-layer. The laser is an energy source of choice for repair of damaged components, for manufacture of new or replacement parts, and for rapid prototyping of concept designs. Lasers enable microstructure gradients and heterogeneous structures designed to exhibit unique properties. Laser additive manufacturing (LAM) has been successful in producing relatively simple near net-shape metallic parts with material and cost savings, but requiring significant finishing. LAM has been successfully applied in repair and refurbishment of worn components. It has been routinely used to produce polymer parts. These capabilities have been widely recognized as evidenced by the explosion in interest in AM. These successes are, however, tempered by challenges facing practitioners such as process and part qualification and verification, which are needed to bring AM to the path of true manufacturing. ONR, NSF, DARPA and other government agencies have invested in basic R&D in AM since the early 1990s. Currently our focus is on developing cyber-enabled manufacturing systems for AM. It is believed that such computation, communication and control approaches will help in validating AM and moving it to the factory floor along side CNC machines.

8970-3, Session 1

Laser embedding electronics on 3D printed objects

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Additive manufacturing techniques such as 3D printing are able to generate reproductions of a part in free space without the use of molds; however, the objects produced lack electrical functionality from an applications perspective. At the same time, techniques such as inkjet and laser direct-write (LDW) can be used to print electronic components and connections onto already existing objects, but are not capable of generating a full object on their own. The approach missing to date is the combination of 3D printing processes with direct-write of electronic circuits. Among the numerous direct write techniques available, LDW offers unique advantages and capabilities given its compatibility with a wide range of materials, surface chemistries and surface morphologies. The Naval Research Laboratory (NRL) has developed various LDW processes ranging from the non-phase transformative direct printing of complex suspensions or inks to "lase-and-place" for embedding entire semiconductor devices. These processes have been demonstrated in digital manufacturing of a wide variety of microelectronic elements ranging from circuit components such as electrical interconnects and passives to antennas, sensors, actuators and power sources. At NRL we are investigating the combination of lase-and-place with 3D printing to demonstrate the digital fabrication of functional parts, such as 3D circuits. Merging these techniques will make possible the development of a new generation of structures capable of detecting, processing, communicating and interacting with their surroundings in ways never imagined before. This presentation will show the latest results achieved at NRL in this area, describe several applications being pursued and explore their impact in additive manufacturing.

8970-4, Session 1

Fabricating specialised orthopaedic implants using additive manufacturing *(Invited Paper)*

Paul Unwin, Stanmore Implants Worldwide Ltd. (United Kingdom)

It has been hypothesised that AM is ideal for patient specific orthopaedic implants such as those used in bone cancer treatment, that can rapidly build structures such as lattices for bone and tissues to in-grow, that would be impossible using current conventional subtractive manufacturing techniques.

This aim of this study was to describe the adoption of AM (direct metal laser sintering and electron beam melting) into the design manufacturing and post-manufacturing processes and the early clinical use.

Prior to the clinical use of AM implants, extensive metallurgical and mechanical testing of both laser and electron beam fabrications were undertaken. Concurrently, post-manufacturing processes evaluated included hipping, cleaning and coating treatments.

The first clinical application of a titanium alloy mega-implant was undertaken in November 2010. A 3D model of the pelvic wing implant was designed from CT scans. Novel key features included extensive lattice structures at the bone interfaces and integral flanges to fix the implant to the bone. The pelvic device was implanted with the aid of navigation and to date the patient remains active. A further 18 patent specific mega-implants have now been implanted.

The early use of this advanced manufacturing route for patient specific implants been very encouraging enabling the engineer to produce more advanced and anatomical conforming implants. However, there are a new set of design, manufacturing and regulatory challenges that require addressing to permit this technique to be used more widely. This technology is changing the design and manufacturing paradigm for the fabrication of specilaised orthopaedic implants.

8970-5, Session 2

3D two-photon lithography: an enabling technology for photonic wire bonding and multi-chip integration *(Invited Paper)*

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Photonic integration is characterized by the coexistence of various material platforms, each having specific strengths and weaknesses. However, combining the strengths of these material platforms within a compact multi-chip photonic system remains challenging since there is currently no solution for reliable chip-to-chip interfaces that can be efficiently be fabricated in large numbers. Current photonic interconnect techniques are mainly based on highly precise positioning of chips or fibers with respect to each other, and fabrication usually requires intricate active alignment techniques.

As an alternative approach to connect nanophotonic circuits on different chips, we have introduced the concept of photonic wire bonding. The technique is based on in-situ fabrication of three-dimensional (3D) freeform waveguides between coarsely prepositioned chips. The shape of the photonic wire-bond waveguides is adapted to the exact positions of the chips such that high-precision alignment of optical devices becomes obsolete. By using dedicated waveguide design techniques and writing techniques, we have demonstrated that photonic wire bonds enable broadband low-loss transmission with average insertion losses of less than 2 dB within the infrared telecommunication bands. Moreover, the structures can handle terabit/s data streams without introducing any signal impairments. Photonic wire bonding offers the potential to assemble photonic multi-chip systems from known-good dies of different materials, thereby exploiting the strengths of specialized fabrication processes that are not subject to technology-related compatibility constraints.

8970-6, Session 2

Nano-confined polymer structures for protein adhesion *(Invited Paper)*

Moritz Wiesbauer, Johannes Kepler Univ. Linz (Austria) and Upper Austria Univ. of Applied Physics (Austria); Richard Wollhofen, Johannes Kepler Univ. Linz (Austria); Kurt Schilcher, Upper Austria Univ. of Applied Physics (Austria); Jaroslaw Jacak, Thomas A. Klar, Johannes Kepler Univ. Linz (Austria)

The ability to place individual proteins onto nano-confined structures plays a constantly growing role in bioscience, from basic studies in biology to the development of nanosensors. One possibility to generate sub-micrometer sized structures in three dimensions is two photon polymerization lithography (2PPL) [1]. The resolution of 2PPL can be enhanced by stimulated emission depletion (STED) [2]. Using a pulsed 780nm laser for 2PPL and a 532nm laser for STED, we were able to obtain structure sizes of 55 nm and manufacture two clearly separated lines with 120 nm distance [3]. We now apply these nanostructures as nanoanchors for the attachment of a controlled number of proteins, down to the level of single proteins per nanoanchor. Acrylate nanostructures with various sizes are fabricated on a poly(ethylene) glycol (PEG) functionalized glass surface. Controlling the size, geometry and the chemical properties of the nanostructures allows for tuning the protein adhesion and binding capacity, from bulk coverage down to single protein presentation. Direct stochastic optical reconstruction microscopy (dSTORM) and statistical fluorescence analysis methods are used to quantify the protein density. Moreover we compare the densities of proteins on nanostructures obtained from STED-2PPL and standard 2PPL. We find, that 2PPL written structures of minimal size carry at least 8 IgG antibodies, while single IgG presentation is possible using STED-2PPL written structures.

1. S. Maruo, et al. Opt Lett, 22, 132 (1997).

2. J. Fischer, et al. Advanced Materials, 22, 3578 (2010).

3. Wollhofen R. et al. Opt. Express, 21, 10831 (2013).

8970-7, Session 2

3D porous structures fabricated by 2PP induce liquid crystal bistability

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The interaction of the liquid crystals with the confining surfaces, through the topological defects, is essential for the onset of bistability and memory. Nematic liquid crystals confined in porous media with controlled geometry exhibit large memory effects, as they retain the alignment induced by electric fields even after the field removal. Two-photon polymerization is an ideal technique to create 3D microscaffolds, with tunable size and geometry, which can be directly written in nematic liquid crystal cells, acting as individual pixels with bistability. Micrometer-scale 3D scaffold structures were fabricated in a sandwich of two electrically conductive ITO-coated glass substrates, separated by 25-?m thick mylar spacers. The structures were formed by direct laser writing in a hybrid organic-inorganic photoresist (SZ2080), which offers high optical quality and good mechanical stability. The electric field alignment of the liquid crystals inside the porous medium is maintained when the applied field is above a threshold (approximately 2 V per micrometer of cell thickness). The onset of the memory is an on/off type process for each individual pore of the scaffold, and the memory typically starts emerging in one region of the structure and then propagates. The global memory effects in porous structures with controlled geometry are enhanced with respect to the case of random porous structures. Optimizing the geometry of the scaffolds is expected to further improve the performance of these bistable devices. Future work will also seek to form a larger-scale device composed of many pixels, for use as ultralow energy bistable displays.

8970-8, Session 2

Three-dimensional dilational mechanical metamaterials: a 3D printing challenge *(Invited Paper)*

Tiemo K. Bückmann, Robert Schittny, Karlsruher Institut für Technologie (Germany); Michael Thiel, Nanoscribe GmbH (Germany); Muamer Kadic, Karlsruher Institut für Technologie (Germany); Graeme W. Milton, The Univ. of Utah (United States); Martin Wegener, Karlsruher Institut für Technologie (Germany)

Mechanical metamaterials are artificial materials allowing for obtaining tailored and/or extreme effective elastic properties. Following a recent theoretical suggestion by Graeme Milton, we design fabricate, and characterize an extreme elastic solid with a shear modulus much larger

than its bulk modulus. In contrast, in liquids, the bulk modulus is much larger than the shear modulus. Our structure can thus be seen as a crystalline “anti-liquid”. In macroscopic form, the complex corresponding 3D microstructure can only be fabricated by 3D printing; in microscopic form by direct laser writing. We measure a record-low Poisson’s ratio for crystalline materials of -0.79.

In more detail, we have extended a recent two-dimensional blueprint by Graeme Milton for a structure with isotropic Poisson’s ratio of -1 towards three dimensions and modified it to allow for fabrication out of only a single constituent material (a polymer) and air voids. Our numerical calculations using COMSOL Multiphysics show that it is crucial to make the size of the connections mimicking ideal joints a small as possible in comparison to the lattice constant of the crystal. We achieve ratios below 1%. Similar structures are fabricated in macroscopic form with a commercial 3D printer (Objet 30) and in microscopic form by dip-in galvo-controlled 3D direct laser writing (Nanoscribe Photonic Professional GT). Poisson’s ratios are measured by pushing onto the samples, analyzing the optical images taken from the side by an autocorrelation approach, and by comparison with numerical calculations for a fictitious infinite periodic structure.

8970-9, Session 2

Creation of high efficiency light extractors of LED structures by means of laser nanolithography

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In lithography photosensitization of polymer materials are used for the efficient manufacturing of microdevices. Polymerization employing ultrafast lasers enables fabrication of high quality three-dimensional structures within micro/nano-scale [1]. Even though the concentration of the photoinitiators is relatively low (commonly 0.2 - 2%), yet it introduces strong light absorption in UV range and it limits their applicability for blue and shorter wavelengths LED’s. Additionally, it lowers the optical damage threshold in comparison to non-photosensitized materials. Finally, they are toxic compounds. Recently it was shown that employing ultrafast lasers one can nanostructure pure polymers via controlled avalanche and thermal conditions [2]. In this report we present study on the influence of laser pulse repetition rate to structuring in the sense of dominating photo-polymerization mechanism, fabrication window, obtainable feature resolution and their rigidity. The experiments were carried out tuning 300 fs pulse duration laser’s repetition rate from 1 kHz to 200 kHz. The applied material was hybrid organic-inorganic ORMOSIL class material. Parameters important for optical applications were determined - the influence of photoinitiator and its concentration to laser induced optical damage threshold, refractive index, and transmission. A difference of photosensitized and pure materials optical damage was found even for VIS light (~ 2 times for 515 nm) and dramatic for UV. Absorbance at 400 nm widely used in blue LED’s was found negligible in pure material while it was significant in the photosensitized sample. The proposed nanostructuring via avalanche ionization was successfully implemented for the fabrication of light extracting square shaped microoptical (300 x 300 μm2, f = 250 μm) elements on LED sapphire substrate. Noticeable increase of light extraction coefficient was demonstrated. In brief, we show two approaches for light extraction and enhanced LED performance: (i) polymerization of optical elements and (ii) creation of micro-pits in sapphire substrate for lateral overgrowth of GaN. Shim copies of polymerized optical elements and textured surfaces of sapphire into Ni were used for structural characterization and can be used for mass replication of the patterns.

[1] M. Malinauskas et al., Ultrafast-laser micro/nano-structuring of photopolymers: a decade of advances, Phys. Rep., accepted (2013).

[2] R. Buividas et al., Nano-structuring of materials by controlled avalanche using femtosecond laser pulses, Opt. Mat. Express, accepted (2013).

8970-10, Session 3

3D micro-printing for photonics and biology *(Invited Paper)*

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3D micro-printing is a fast and versatile technique for the fabrication of three-dimensional nano- and microstructures and has become recently commercially available [1]. Applications range from cell-biology and microfluidics to three-dimensional nanophotonic structures [2]. For the latter one lateral feature sizes down to 100 nm or even below are desirable. This can be achieved via two-photon absorption and the threshold behaviour of the photoresist. However, the finite numerical aperture (typically NA 1.4, oil immersion) of the objective lens results in features which are axially elongated by more than a factor of 2.6 for conventional photoresists. To reduce the elongation, we employ a spatial light modulator to modify amplitude and phase distribution on the back focal plane of the objective lens, also allowing to correct remaining aberrations in the setup [3]. Spherical aberrations induced by focusing deep into the volume of photoresists usually counteract this correction already for small writing depths. To circumvent this, we use an index matched photoresist as immersion system in a so-called dip-in configuration, allowing for photonic crystals with several hundred layers without any observable degradation in feature size.

Writing times in serial writing processes are easily prohibitive for industrial applications. We reach a reduction by at least two orders of magnitude following two strategies: (i) Writing with several voxels in parallel reduces writing times by about one order of magnitude. (ii) Scanning the beam instead of the sample reduces the writing time by another two orders of magnitude.

[1] see http://www.nanoscribe.de

[2] G. von Freymann et al., Advanced Functional Materials 20, 1038 (2010)

[3]E. Waller et al., Optics Express 20, 24949 (2012)

8970-11, Session 3

Towards larger printing volumes in multi-photon polymerization

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The technique of direct laser writing (DLW) based on multi-photon polymerization allows for the fabrication of microstructures with sub-micrometer spatial resolution. In recent years, considerable efforts have been made to improve the resolution to smaller values, e.g., for metamaterial applications. Far less effort has been expended on bridging the gap in achievable printing volume between DLW and conventional 3D printing techniques like stereolithography.

Here, we present our efforts to standardize 3D manufacturing based on multi-photon polymerization from nanometer to millimeter scale. To achieve larger volumes and diffraction-limited spot size of oil immersion objectives we use a set of high-speed pivoted galvomirrors insuring highest spatial resolution. Low-magnification objectives allow for large scanning fields of more than 0.5 ? 0.5 mm?. To further enlarge the patterning volume, we employ stage stitching enabling the fabrication of highly complex structures with volumes of more than 1mm? and on arbitrary substrates. In order to handle the increasing amount of data we had to develop new software solutions. We introduce our standardized workflow for the prototyping of 3D objects in the millimeter range using typical CAD data of 3D printers.

Additionally, we present our recent results on a newly developed DLW photoresist that shows ultra-low shrinkage and smooth surfaces. We compare the resist with other commercial available resists in terms of shrinkage behavior and achievable feature sizes. The applicability of the resist for the fabrication of high-quality micro-optical elements like microspheres and diffractive optical elements is investigated.

8970-12, Session 3

Laser fabrication of polymeric microstructures with SWCNT

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Singled-walled-carbon nanotubes (SWCNT) have unique and versatile electrical and mechanical properties. They have been used in polymer composites to change its electrical characteristics (1) and to increase materials hardness (2).

Here we present the fabrication of microstructures doped with SWCNT by means of two-photon polymerization (TPP). For this purpose, the SWCNT are mixed to the uncured resin in ethanol. The sample is heated to 40 °C in order to reduce resin viscosity, making the mixing procedure more efficient. To avoid agglomeration of the carbon nanotubes in the resin, the sample is sonicated prior to the TPP fabrication process. This resin is placed between a glass substrate and a cover slip for the microfabrication process. The laser source used is a Ti: Sapphire oscillator operating at a repetition rate of 86 MHz delivering 100 fs pulses, centered at 790 nm. The apparatus comprises a pair of movable mirrors, a motorized stage, a red LED as illumination source and a CCD camera for real time monitoring of the process. The laser beam is focused through a microscope objective into the liquid resin.

We have produced 10 ?m microcubes with good spatial resolution, evidenced by SEM images. Raman microscopy confirms the presence of the nanotubes in the microstructures. Despite some CNT agglomeration on the surface of the cubes, this method represents a simple and effective way to produce polymeric microstructures with enhanced properties due to the presence of the SWCNT, paving the way towards new microdevices with enhanced mechanical and electrical properties.

8970-13, Session 3

Direct writing of shape-controlled nanodot array by two-photon nanolithography using an elliptical beam

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Two-dimensional (2D) periodic array has been studied in optical waveguide, photonic crystal laser, plasmonic lens and sensors. Two-photon nanolithography (TPNL) is an economical and flexible means for high resolution fabrication-which can be used to fabricate diverse microstructures owing to its unique 3D processing capability, arbitrary designability and high fabricating accuracy. Up to now, only dot arrays with an element diameter of less than 300 nm has been produced by TPNL. However, the adjustment of ellipticity and the orientation of the nanodot have not been thoroughly investigated. TPNL of 2D arrays with shape-controlled structural units has emerged as a challenge.

In this study, we present and demonstrate a method to direct write shape-controlled nano-pattern array by TPNL. With a slit to achieve the elliptical beam, elliptical nano pattern with minor axis diameter of 50 nm, about one-sixteenth of laser wavelength at 780 nm, was realized by using AR-N 4340 photoresist. Theoretical simulations based on the elliptical beam were carried out to estimate the feature size of nanostructures. The adjustment of the ellipticity and direction of nano pattern were investigated. Furthermore, we fabricated large area elliptical and rectangular nano-pattern arrays. This study would provide an evidence for fabricating shape varied nano-pattern arrays in the fields of plasmonics and photonics by using femtosecond direct writing technique.

8970-14, Session 3

Three-dimensional ceramic molding process based on microstereolithography for the production of piezoelectric energy harvesters

Shoji Maruo, Kenji Sugiyama, Yokohama National Univ. (Japan); Yuya Daicho, Yokohama National Univ. (Japan) and CMET Inc. (Japan); Kensaku Monri, Yokohama National University (Japan)

We have developed a three-dimensional (3-D) ceramic molding process based on microstereolithography to produce functional 3-D ceramic microstructures. In this method, high concentration slurry of ceramic micro/nano particles was filled in a 3-D polymer mold fabricated by microstereolithography. The polymer mold was thermally decomposed by an optimal heating profile to reduce harmful crack of a green body. The green body was finally sintered to produce 3-D ceramic microstructures. We have already demonstrated that transparent silica microchannels [1] and bioceramic scaffold [2] could be produced by this method.

In this study, we used a water-based slurry containing barium titanate submicron particles to produce vibrational energy harvesters [3]. To make finer piezoelectric elements with high production yield, we have developed a new photopolymer suitable for thermal decomposition at low temperature. The photopolymer enables to reduce harmful cracks during thermal decomposition process. A prototype of the spiral-shaped piezoelectric element was fabricated by the ceramic molding process. The electric power generation using the spiral-shaped element was demonstrated in 3-D vibration experiments. The piezoelectric effect of the spiral-shaped element was also analyzed by COMSOL multiphysics. As a result, we found that the electric power could be drastically improved by optimizing electrode pattern according to charge distribution. The spiral-shaped piezoelectric elements will be applied for high-performance vibrational energy harvesters.

Reference

[1] Jpn. J. Appl. Phys. Vol. 48, no. 6, 06FK01 (2009).

[2] Jpn. J. Appl. Phys. Vol. 50, no. 6, 06GL15 (2011).

[3] Sensors and Actuators A (in press).

8970-15, Session 4

Simple technique for high rate and highly conductive metal (Al) deposition on silicon by laser selective metallization

Armel Bahouka, Frédéric Mermet II, IREPA LASER (France); Pablo M. Romero, Nerea Otero, Ivette Coto, Cristina Leira, Alejandro González, Asociación de Investigación Metalúrgica del Noroeste (Spain); Thomas Schutz-Kuchly, Karim Derbouz Draoua, Abdelilah Slaoui, ICube (France)

In this experimental work we present the results of direct laser printing of Al electrically conductive free patterns on thin mono and poly-crystalline silicon wafers (140 and 200 µm thick). The patterns created are lines, crosses and squares. We measured and compared the electrical performances (Rsheet, Conductivity, Resistivity, Mobility…) and mechanical properties (adhesion forces and volumes deposited) of this technique considering that we used different power densities, and different scan speeds. Scanning Electron Microscopy (SEM) pictures are taken for each case and it was demonstrated that the vicinities of the deposited metal are not thermally affected nor damaged. Combined with the Alicona 3D InfiniteFocus ® images, they revealed that the deposited areas dimensions can be: thick from 300 nm up to 15µm, large from 100 µm up to 2x2 cm?. The SEM's EDX module confirmed that the sheet deposited are over 93 % in weight composed by aluminium: there is neither alloy nor oxide formed during the process. Standard scotch adhesion tests are successful. The first basic electrical tests, conductivities and Rsheet measurements, showed that the pattern can be used to conduct current: Rsheet are from 0.05 ?/? to 0.15 ?/? on all substrates (mono and poly crystalline silicon). Since this technique is maskless, operative in Normal Temperature and Pressure Conditions (NTPC) and cost effective, it can stand for a good alternative to classical metallization techniques.

8970-16, Session 4

The shape of nanospheres propelled by femtosecond laser-excited enhanced near field

Takuya Shinohara, Mitsuhiro Terakawa, Keio Univ. (Japan)

Laser-based additive manufacturing has receiving growing interest. Several methods such as stereolithography, selective layer sintering and laser engineered net shaping have been reported. To extend the laser additive manufacturing into nanoscale, the methods for manipulation and arraying nanospheres are necessary. There are many methods for nanosphere propulsion such as laser induced forward transfer and inkjet system. We have been investigating nanosphere propulsion by using femtosecond laser-excited enhanced near field by controlling the optical intensity distribution in the vicinity of a nanosphere. In our method, gold nanospheres on silicon substrate are irradiated by femtosecond laser which leads to a small region of silicon substrate ablation. The nanospheres are propelled by the plasma expansion and by the collision with ablated plume. In this study, we investigated the shape of gold nanospheres. The diameter of a gold nanosphere was 200 nm. The receiver substrate was placed 2 mm under the laser irradiated spot vertically to the irradiated substrate. Gold nanospheres on the irradiated substrate were propelled with the irradiation of a single 280 mJ/cm2, 80 fs, 800 nm laser pulse. In specific experimental conditions, the nanosphere showed no change in shape which was observed by SEM.

8970-17, Session 4

Laser-induced forward transfer as an immobilization tool for biosensor applications

Marianneza Chatzipetrou, National Technical Univ. of Athens (Greece); Christos Boutopoulos, Ecole Polytechnique de Montréal (Canada); Athanasios Papathanassiou, National Technical Univ. of Athens (Greece); Eleftherios Touloupakis, Univ. of Crete (Greece); Ioanna Zergioti, National Technical Univ. of Athens (Greece)

Laser Induced Forward Transfer (LIFT) enables the direct immobilization of biomaterials, on rough substrates, without the need for functionalization layer, due to the high printing velocity of the liquid biomaterial. A laser pump-probe setup was used so as to observe the printing mechanisms and measure the speed of the ejected liquid jet.

The LIFT technique was applied for the fabrication of an enzymatic biosensor, by immobilizing Laccase enzyme, on Screen Printed Electrodes. The biosensor was characterized towards a polyphenol compound, catechol, as its detection is very important for the food industry.

8970-18, Session 5

Multifunctional 3D printing *(Invited Paper)*

Ricky Wildman, The Univ. of Nottingham (United Kingdom)

Additive Manufacturing, or 3D Printing as it is often termed, is now beginning to gain traction in both the public's imagination as well as becoming a seriously considered and implemented manufacturing tool by leading industry. The presentation will explore why additive manufacturing has the potential to disrupt current thinking in the context of:

- Its role as the enabler for low volume production and the democratization of manufacturing
- the dramatic increases in design complexity & flexibility that are afforded by taking an additive approach
- the cost effective product personalisation and customization possibilities
- the reduction of the environmental burden of manufactured goods
- he potential for new business models and supply chain realignment
- increased part functionality today, and multifunctionality in the coming years.

The presentation will particularly explore "next generation" Additive Manufacturing where the concept of multifunctional AM is currently being researched.

8970-19, Session 5

Creation of multimaterial micro- and nanostructures through aqueous-based fabrication, manipulation, and immobilization *(Invited Paper)*

John T. Fourkas, Farah Dawood, Sijia Qin, Linjie Li, Sanghee Nah, Chad Ropp, Zachary Cummins, Edo Waks, Benjamin Shapiro, Univ. of Maryland, College Park (United States)

Despite the rapid growth of microfabrication technologies over the past decades, many desirable microstructures remain difficult or even impossible to create, especially when the structures are composed of multiple components that feature different materials that must be

arranged in a highly specific, 3-D pattern. We have developed aqueous photoresists that can be used in combination with different techniques for nanomanipulation to create such structures. Multiphoton absorption polymerization (MAP) can be used to create unsupported polymeric microstructures that can be nanomanipulated to place them in any desired position and orientation. Nanomanipulation techniques can also be used to place micro- or nanoscale components in desired locations in three dimensions, after which they can be immobilized in place using MAP. This toolbox of techniques offers the capability of creating a broad range of new structures and devices featuring polymeric, inorganic, metallic and biomolecular components.

8970-20, Session 5

The design and production of 3D structures using bitstreams of light *(Invited Paper)*

Suman Das, Georgia Institute of Technology (United States)

This talk provides an overview of additive manufacturing research efforts involving various lasers and light sources in the Direct Digital Manufacturing Laboratory at Georgia Tech over the past 7 years. The presentation will cover additive manufacturing of 3D structures spanning the nano to the macro length scales in diverse materials including hydrogels, polymers, metals, semiconductors, ceramics and nanocomposites. The production of diverse 3D structures by taking advantage of light-matter interactions at various wavelengths spanning 266nm to 10600nm, pulse widths spanning 130fs to continuous wave, and various physico-chemical mechanisms involving photopolymerization, melting, crystallization and ablation will be described through representative examples.

8970-21, Session 5

Gas-mediated charged particle beam processing of nanostructured materials *(Invited Paper)*

Milos Toth, Aiden Martin, Charlene J. Lobo, Igor Aharonovich, Univ. of Technology, Sydney (Australia)

Focused electron and ion beam processing in reactive gaseous environments enable mask-free deposition, etching and restructuring of solids with nano to micro scale spatial resolution. This technology facilitates fabrication and editing of photonic crystals, plasmonic nanostructures, optical resonators and related structures designed for controlled investigation of light-matter interactions. Such applications will be reviewed with an emphasis on damage-free chemical etching of optoelectronic materials, localized surface functionalization, deposition of high purity materials, and fabrication of high aspect ratio and self-supporting, undercut structures. We will also discuss novel bottom-up growth processes which offer potential pathways for scalability of serial, beam-directed fabrication methods.

Localized, gas-mediated processing is achieved by beam-induced decomposition of surface-adsorbed precursor molecules into reactive fragments which react with a solid substrate in the vicinity of a charged particle beam. The decomposition mechanisms are typically athermal, enabling the use of cryogenic, room and elevated temperatures for manipulation of precursor molecule adsorption pathways, etch kinetics and deposit composition. Resolution, proximity effects and structure aspect ratios are controlled by tuning the flux profiles of the beam and electrons emitted from the substrate, and the replenishment kinetics of adsorbates consumed during processing. Defects generated by the beam compromise the functional properties of some materials, but can also enable processes such as electron beam etching of ultra nano-crystalline diamond, and ion beam etching of III-V nitrides. Material quality, process resolution and throughput can be optimized using strategies that will be demonstrated using photonic devices and materials such as diamond, GaN, SiC, Si, SiO_2 and Pt.

8970-22, Session 6

High performance laser additive manufacturing of metal components *(Invited Paper)*

Weidong Huang, Xin Lin, Northwestern Polytechnical Univ. (China)

Laser Additive Manufacturing (LAM) has been used to produce high performance metal components for aviation and aerospace applications. The LAMed metal parts have excellent mechanical properties usually in the class of those of forging parts. Fully dense materials, fine microstructures and even composition distribution without macrosegregation are responsible for the excellent mechanical properties. A LAMed metal part usually has much larger crystal grain size and finer microstructure features inside a crystal grain compared with a forging part. In most cases, the crystal grains are columnar instead of equiaxed because of extension growth behavior during laser cladding. Temperature of the molten pool and the cladding geometry are in-situ monitored to guarantee steady processing conditions. Heat treatment is applied to release stresses and to obtain optimized microstructures and mechanical properties. Very high consistency of mechanical properties has been obtained for LAMed Ti64 alloy parts. The consistency of both tensile strength and elongation are in the range of 1~3%. The fatigue properties are also very high and consistent. As large as 3m Ti64 parts have been LAMed for the C919 airplane under development. The final parts after machining satisfy the designed geometry, showing a good control of stresses and deformation during LAM and machining. High performance repair and hybrid manufacturing applications are presented, too.

8970-23, Session 6

Real-time laser cladding control with variable spot size

Jorge L. Arias, M. Angeles Montealegre, Felix Vidal, Jorge Rodríguez, Asociación de Investigación Metalúrgica del Noroeste (Spain); Stefan Mann, Peter Abels, Fraunhofer-Institut für Lasertechnik (Germany); Filip Motmans, VITO NV (Belgium)

Laser cladding processing has been used in different industries to improve the surface properties or to reconstruct damaged pieces. In order to cover areas considerably larger than the diameter of the laser beam, successive partially overlapping tracks are deposited. With no control over the process variables this conduces to an increase of the temperature, which could decrease mechanical properties of the laser cladded material. Commonly, the process is monitored and controlled by a PC using cameras, but this control suffers from a lack of speed caused by the image processing step.

The aim of this work is to design and develop an FPGA-based laser cladding control system. This system is intended to modify the laser beam power according to the melt pool width, which is measured using a CMOS camera. All the control and monitoring tasks are carried out by a FPGA, taking advantage of its abundance of resources and speed of operation. The robustness of the image processing algorithm is assessed, as well as the control system performance. Laser power is decreased as substrate temperature increases, thus maintaining a constant clad width.

This FPGA-based control system is integrated in an adaptive laser cladding system, which also includes an adaptive optical system that will control the laser focus distance on the fly. The whole system will constitute an efficient instrument for part repair with complex geometries and coating selective surfaces. This will be a significant step forward into the total industrial implementation of an automated industrial laser cladding process.

8970-24, Session 6

Post-processing of 3D-printed parts using femtosecond and picosecond laser radiation

Ilya Mingareev, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); Nils Gehlich, Tobias Bonhoff, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States) and Fraunhofer-Institut für Lasertechnik (Germany); Wilhelm Meiners, Ingomar Kelbassa, Fraunhofer-Institut für Lasertechnik (Germany); Tim Biermann, Joining Technologies, Inc. (United States); Martin C. Richardson, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

Additive manufacturing, also known as 3D-printing, is a near-net shape manufacturing approach, meaning that the resulting part geometry can be considerably affected by various process conditions, heat-induced distortions, solidified melt droplets, partially fused powders, and surface modifications induced by the manufacturing tool motion and processing strategy. High-repetition rate femtosecond and picosecond laser radiation was utilized to improve surface quality of metal parts manufactured by laser additive techniques. Different laser scanning approaches were utilized to increase the ablation efficiency and to reduce the surface roughness while preserving the initial part geometry.

We studied post-processing of 3D-shaped parts made of Nickel- and Titanium-base alloys by utilizing Selective Laser Melting (SLM) and Laser Metal Deposition (LMD) as additive manufacturing techniques. Process parameters such as the pulse energy, the number of and the distance between layers were varied. Surface processing in several layers was necessary to remove the excessive material, such as individual powder particles, and to reduce the average surface roughness from as-deposited 20-45 ?m to a few microns.

Due to the ultrafast laser-processing regime and the small heat-affected zone induced in materials, this novel integrated manufacturing approach can be used to post-process parts made of thermally and mechanically sensitive materials, and to attain complex designed shapes with micrometer precision.

8970-25, Session 7

Femtosecond laser micromachining for 3D optofluidic devices *(Invited Paper)*

Roberto Osellame, Istituto di Fotonica e Nanotecnologie (Italy)

Femtosecond laser micromachining of transparent materials is a very powerful tool to produce advanced optofluidic devices. In particular, its unique 3D capabilities enable the implementation of novel device layouts. Direct laser waveguide writing, microfluidic channel fabrication and two-photon polymerization compose a well-assorted portfolio of microfabrication techniques that can be combined for integrating advanced functionalities in microfluidic devices. Examples of monolithic integrated devices for on-chip sensing and single-cell manipulation will be provided.

8970-26, Session 7

Rapid manufacture of freeform micro-optics for high power applications

Matthew O. Currie, Roy McBride, PowerPhotonic, Ltd. (United Kingdom)

We report a new route to obtaining custom freeform micro-optical components that is free from symmetry restrictions, offering drastically lower cost and delivery times than what is required by other freeform manufacturing methods.

Using optical design software such as Zemax, complex freeform surfaces with no axes of symmetry can be created. However, fabricating such structures has proven both expensive and time-consuming; limiting their use to niche applications. PowerPhotonic's LightForge service offers optical designers the ability to realise these complex surfaces at a fraction of the cost and time commitment necessary with processes such as lithography and single point diamond turning. The optical surfaces produced using LightForge are rendered in fused silica, enabling the integration of custom freeform structures in very high power applications.

Presented here is the full LightForge sequence, from optical design to analysis of the fabricated part. We describe how this process can be used to realise a complex custom optic using data generated directly from a design in Zemax. This surface is then extracted from Zemax and fabricated using the LightForge service before being measured. A quantitative analysis of the real optic is carried out both numerically and with the design source in Zemax, and we present a comparison between design and fabricated part performance.

8970-27, Session 7

Flexible and robust beam shaping concepts with aspheres

U. Fuchs, asphericon GmbH (Germany)

Employing aspherical lenses to reduce aberrations to improve focusing qualities is a well-known concept. But the potpourri of aspherical surfaces offers way more possibilities, even the chance for flexible beam shaping setups. Since these are refractive optical elements the beam shaping is robust with respect to wavelength changes. Basic requirement for optimal and flexible usage of all beam shaping elements is a flexible beam expanding approach, which will be introduce as well.

Being able to generate ring shaped light distributions is interesting for various applications. Here the most uncommon aspherical surface – an axicon – is utilized. Axicons are rotational symmetric prisms, which convert the incoming light into Bessel beams. Those are characterized by their concentrical ring structure and long depth of focus, which makes them very interesting for material processing. Above that, combining such an axicon with a focusing lens leads to a ring focus. Its size is not only determined by the choice of the axicon angle and the lens properties, but also through the diameter of the incoming beam. Thus, for optimal usage a flexible beam expander, which leaves the beam quality unaltered is mandatory. The remarkable properties of these beamshaping set-ups are shown in theory and experimentally.

8970-28, Session 7

Forming of 3D complex shapes of AISI 304 stainless steel by high power diode laser

Massimiliano Barletta, Univ. degli Studi di Roma Tor Vergata (Italy); Annamaria Gisario, Simone Venettacci, Francesco Veniali, Univ. degli Studi di Roma La Sapienza (Italy)

High power diode laser is potentially attractive in several manufacturing domains. Transfer efficiency by far higher than competitors, long lasting source, easy setting-up and automation, lack of maintenance as well as moderate investment and running costs make diode laser extremely promising in forming process. Nevertheless, the achievement of complex shape by forming with diode laser is still poorly investigated. The nearly unpredictable influence of the material properties and initial geometries on the final shapes and the need for composite forming strategy has hitherto discouraged the accomplishment of systematic investigations. In order to bridge the gap, 3d forming strategies of flat stainless steel substrates with variable shapes by high power diode laser is herein investigated making use of Design of Experiment (DoE). The experimental investigation was two-fold: (i) forming on substrates with simplified geometries was studied through a full factorial experimental plan of the three laser operational parameters (i.e., laser power, scan speed and number of passes); (ii) based on the previous experimental findings, the second analysis focused on the scaling-up of forming on substrates with unabridged shapes. Scanning electron microscopy, contact gauge profilometry and coordinate measurement machine were used to monitor the process, allowing the evaluation of the morphology and visual appearance of the shaped materials, their microstructural features and, above all, the achieved shapes. Bending angle was then modeled by the definition of fitting empirical and analytical models, thus providing an useful tool to scientists and practitioners on how to best deal with the setting of laser operational parameters.

8971-1, Session 1

Investigation of profiled beam propagation through a turbulent layer and temporal statistics of diffracted output for a modified von Karman phase screen

Monish R. Chatterjee, Fathi H. A. Mohamed, Univ. of Dayton (United States)

In this paper, profiled beam propagation through a turbulent layer is examined using a split-step methodology established recently (see Whitfield et. al, Proc. SPIE 8517, 85170P, October 24, 2012). Accordingly, the beam is alternately propagated (i) through a thin Fresnel layer, and hence subjected to diffraction; and (ii) across a thin modified von Karman (mVKS) phase screen which is generated using the power spectral density (PSD) of the random phase obtained via the corresponding PSD of the medium refractive index for mVKS turbulence. The random phase screen in the transverse plane is generated from the phase PSD by incorporating (Gaussian) random numbers representing phase noise. Using this method, the scintillation indices and fringe visibilities of the propagating beam are evaluated for different turbulence layer thicknesses, and other parameters. More significantly in this research, the temporal statistics (such as the mean and variance) of the amplitude and phase of the propagated field are derived using successive simulations of the output data. The output beam characteristics will fluctuate with time due to the inherent randomness of the mVKS phase (even though it is fundamentally modeled in the spatial domain). Finally, we examine the effect of the same turbulence on the amplitude and phase of a chaotic laser beam generated from an acousto-optic Bragg cell with feedback. The intent in the long run is to determine if information encrypted in a chaotic (instead of deterministic) carrier wave experiences some degree of immunity when propagating through atmospheric turbulence.

8971-2, Session 1

Optical beam spreading in the presence of both atmospheric turbulence and quartic aberration

Nelofar Mosavi, Johns Hopkins Univ. Applied Physics Lab. (United States) and Univ. of Maryland, Baltimore County (United States); Brian S. Marks, Johns Hopkins Univ. Applied Physics Lab. (United States); Curtis R. Menyuk, Univ. of Maryland, Baltimore County (United States); Bradley Boone, Johns Hopkins University Applied Physics laboratory (United States)

We study optical beam spreading in the presence of both atmospheric turbulence and quartic aberration. We obtain exact analytical expressions for the beam radius squared and the beam quality that apply at all distances. We show that the contribution of the turbulence to the beam radius squared and the beam quality is strictly additive at all distances.

We have verified these results using Monte Carlo simulations for both aberrated and unaberrated beams, and we will present these results.

For an unaberrated Gaussian beam, we have compared our exact analytical expression for beam radius squared to approximate expressions that were obtained by Fante [Proc. IEEE, vol. 69, pp. 1669-1692 (1975)] and later reproduced by Andrews and Phillips [Laser Beam Propagation Through Random Media, SPIE (2005)]. Our result agrees with Fante.s at long distances, but disagrees at short distances. We have determined the reason for the discrepancy, which we will describe. His approach was to find a good approximation for the mutual coherence function and then to calculate the mean square beam radius from that. Our approach was to use the moments method to avoid calculating the mutual coherence function and to find the mean square beam radius directly.

Our results illustrate the power of the moments method and may make possible the calculation of higher-order moments that are needed to determine the beam wander. These results also illustrate the usefulness and importance of Monte Carlo verification.

8971-3, Session 1

Transmitter diversity verification on Artemis geostationary satellite

Ramon Mata Calvo, Peter Becker, Dirk Giggenbach, Florian Moll, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); Malte Schwarzer, Martin Hinz, Cassidian Optronics GmbH (Germany); Zoran Sodnik, European Space Research and Technology Ctr. (Netherlands)

Optical feeder links will become the extension of the terrestrial fiber communications towards space, increasing data throughput in satellite communications by overcoming the spectrum limitations of classical RF-links. The geostationary telecommunication satellite Alphasat and the satellites forming the EDRS-system will become the next generation for high-speed data-relay services. The ESA satellite ARTEMIS, precursor for geostationary orbit (GEO) optical terminals, is still a privileged experiment platform to characterize the turbulent channel and investigate the challenges of free-space optical communication to GEO. In this framework, two measurement campaigns were conducted with the scope of verifying the benefits of transmitter diversity in the uplink. To evaluate such mitigation techniques, intensity measurements were carried out at both ends of the link. The scintillation parameter is calculated and compared to theory and, additionally, the Fried Parameter is estimated by using a focus camera to monitor the turbulence strength.

8971-4, Session 1

Simultaneous scintillation measurements of coherent and partially coherent beams in an open atmosphere experiment *(Invited Paper)*

Anatoly Efimov, Kirill Velizhanin, Los Alamos National Lab. (United States); Grigory Gelikonov, Institute of Applied Physics (Russian Federation)

Partially spatially coherent beams (PCB) are predicted to outperform other single-beam FSO systems in terms of scintillations and fade statistics. Existing methods to produce PCBs rely on diffusers or dynamic phase masks. These are clearly not suitable for practical high data-rate communication. We use a superluminescent diode and a multimode fiber (MMF) to generate a PCB suitable for future Gbps FSO systems. Spatial coherence function at the output of the MMF was experimentally measured using interferometry. A simple optical arrangement was used to adjust the spatial coherence radius of the beam in the range of a few to a few tens of coherent spots on the beam aperture. The Performance of our PCB was directly compared to a quasi-spherical beam in an open-atmosphere experiment in New Mexico, USA. We measured the scintillation index, the probability distribution function (PDF) and the temporal spectra of the two beams propagating through the same atmosphere in an experiment involving a transmitter and a receiver operating in the 1550nm telecom band. The coherent beam and the

PCB were overlapped and co-propagating so their parameters could be directly compared at the receiver. The analysis of the data obtained support the existing theories for the fourth-order statistics, which account for the finite apertures of the transmitter and receiver at shorter distances. At a longer distance of 6.5 km the experiment indicated somewhat better than expected performance of the PCB.

8971-5, Session 1

Evaluation of performance of ground to satellite free space optical link under turbulence conditions for different intensity modulation schemes

Anjitha Viswanath, Indian Institute of Technology Delhi (India); Hemani Kaushal, Institute of Technology and Management (India); Virander K. Jain, Subrat Kar, Indian Institute of Technology Delhi (India)

We evaluated the performance of a ground to satellite free space optical (FSO) link in which the atmospheric conditions play a very crucial role. Due to non-uniform temperature and pressure conditions, the index of refraction is different along the path of propagation causing a variation in the intensity of the light falling on the detector both in space and time. This in turn causes the degradation in the performance of the FSO link manifesting in an increased bit error rate.

In our experiment, atmospheric conditions were artificially recreated within the optical turbulence generator chamber (OTG) by varying the temperature conditions. The 1550 nm laser source was internally modulated using the laser driver with the intensity modulation schemes (64 and 256-ary pulse position and differential pulse position modulation schemes) being implemented in VHDL on a FPGA. Modulated laser beam was then made to pass through the OTG chamber. The wavefront (with aberrations) emerging out of the OTG chamber was captured by the beam profiler placed after a neutral density filter, which prevented the beam profiler from getting saturated, and thus the spatial parameters of the incident beam were obtained. Here the spatial parameter of interest is the beam variance which is the measure of the displacement of the point of maximum intensity of the beam (the hot spot). From the beam variance value the bit error rate was determined by using the log normal irradiance model corresponding to the weak turbulence regime.

8971-6, Session 1

High altitude clouds impacts on the design of optical feeder link and optical ground station network for future broadband satellite services

Sylvain Poulenard, Mathieu Ruellan, Bernard Roy, Infoterra France (France); Jérôme Riedi, Frederic Parol, Univ. des Sciences et Technologies de Lille (France); Angélique Rissons, Institut Supérieur de l'Aéronautique et de l'Espace (France)

Optical links at 1.55µm are envisaged to cope with the increasing capacity demand from satellite operators. Due to clouds blockages, site diversity techniques based on a network of Optical Ground Stations (OGS) are necessary to approach the link availability requirement (e.g.99.9% over the year).

In [1], we presented a method to find OGS localizations maximizing the availability of the network while minimizing the number of sites. It is based on conditional opposite weather conditions between OGSs and uses SAF-NWC Cloud Masks (CM). In [1], we considered a site available only if it was clear sky however low attenuation of high altitude clouds (i.e. cirrus) can be incorporated to the budget link. Cirrus attenuation is not provided by CM so we co-localized our CM databank with LIDAR data from CALIOP instrument and derived their attenuations. It resulted in a second optimized Optical Ground Station Network (OGSN).

OGSN1 and OGSN2, respectively the network with a link budget not including and including thin cirrus, were compared over a full year in terms of system parameters like availability, number of handover (i.e. switch between OGS); time duration distribution of handover, time duration distribution between consecutive handovers. These parameters are essential to design an operational network of interconnection between OGS and the associated mechanisms/protocols to handle seamless handover. Eventually, the impacts on the optical feeder link system for OGSN1 and OGSN2 conclude the paper.

[1] S.Poulenard, B.Roy, M.Hanna, F.Lacoste, H.Le-Gléau, A.Rissons "Optical ground station network optimization and performances for high data rate geosatellite-to-ground telemetry", TTC 2013

8971-7, Session 1

Channel characterization for air-to-ground free-space optical communication links

Kevin Shortt, Dirk Giggenbach, Ramon Mata Calvo, Florian Moll, Christian Fuchs, Christopher Schmidt, Joachim Horwath, Jack Yeh, Vevek Selvaraj, Ranjoy Banerjee, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany)

The next five to ten years will see more and more free-space optical communication systems being put into practical use as technologies and techniques continue to mature, particularly in the area of mobile and satellite-to-ground communications. To meet the increasing demand of these types of systems, it is necessary to gain a deeper understanding of the various atmospheric effects at play in a free-space optical link in an effort to mitigate their impact on operational systems. In that context, the German Aerospace Center (DLR) has conducted a number of field trials between a Dornier 228 aircraft and its ground station in Oberpfaffenhofen, just south of Munich, Germany. These field trials have involved the concurrent measurement of atmospheric turbulence using three different techniques: pupil plane imaging, focus spot imaging and Shack-Hartmann wavefront sensing. To ensure the accurate synchronization of measurements between the three techniques, a concerted effort was made in the selection of computer hardware and the development of image acquisition software. Furthermore, power measurements in up- and downlink have been taken to be further correlated with the 3 primary instruments. It is envisioned that the resulting analysis of these measurements shall contribute to the implementation of new adaptive optics techniques to facilitate various air and space communication links. This paper shall describe the overall experiment design as well as some of the design decisions that led to the final experiment configuration.

8971-8, Session 1

Performance analysis of coherent tiled fiber-array beam director with near-field phase-locking and programmable control of tip/tilt and piston phases

Grigory A. Filimonov, V.E. Zuev Institute of Atmospheric Optics (Russian Federation) and Univ. of Dayton (United States); Mikhail A. Vorontsov, Univ. of Dayton (United States) and Optonicus (United States); Svetlana L. Lachinova, Optonicus (United States)

The phase-noise that is originated in the multi-channel master-oscillator power amplifier (MOPA) system of tiled fiber-array beam director may drastically impact performance of laser beam projection on a remotely located target in atmosphere. In the presented paper using wave-optics numerical simulation we analyze different techniques that can be applied for both the MOPA phase noise mitigation and programmable control

of fiber-array output beams piston and tip and tilt wavefront phase in order to optimize coherent beam combining performance for different propagation paths and turbulence conditions

8971-9, Session 1

Scintillation resistant multi-aperture phase-contrast wavefront sensor

Jeffrey R. Kraczek, Univ. of Dayton (United States); Mathieu Aubailly, Univ. of Maryland, College Park (United States) and Optonicus (United States); Mikhail A. Vorontsov, Univ. of Dayton (United States) and Optonicus (United States) and Univ. of Maryland, College Park (United States)

A multi-aperture wavefront sensor based on phase-contrast technique is introduced and analyzed. Unlike the conventional phase-contrast sensors (Zernike filter, point diffraction interferometer, etc.), the multi-aperture phase contrast sensor (MAPC) is composed of an array of phase contrast sensors operating in parallel. The spatial sub-division of the input optical field results in significant increase of wavefront phase visualization contrast even while operating in strong intensity scintillation conditions. Results of numerical analysis of phase reconstruction performance for different MAPC type sensor are presented.

8971-10, Session 2

Ongoing testing of pulsed fiber amplifiers in simulated space environment

Malcolm W. Wright, Hamid Hemmati, Jet Propulsion Lab. (United States)

JPL has a continuing program to environmentally test suitable fiber based laser transmitters as reliable sources for optical communications from space. In lieu of the availability of fully space qualified systems, commercially based pulsed fiber amplifiers either upgraded to meet the necessary environmental requirements or off –the-shelf have been tested under a variety of conditions. Three systems that support high peak powers at 1550 nm have been subjected to vibration, mechanical shock, and thermal cycling tests as well as lifetime vacuum operation. The test results point to the robustness of the commercial technology and the readiness for full space qualification.

8971-11, Session 2

High power photonic crystal fiber amplifiers for deep space uplink applications

Donald Sipes Jr., Jason Tafoya, Optical Engines, Inc. (United States)

High power fiber laser based uplink lasers require high peak powers and pulse energies that are beyond the capabilities of Yb doped step index fibers(SIF). The Air hole guiding structure of photonic crystal fibers allow for a much higher degree of index control leading to a larger mode field diameter than can be found in SIF amplifers. These large mode sizes are necessary to achieve energies higher than 1 mj at 100ns.

We report on our work toward developing a high power Yb doped PM PCF based fiber amplifier for deep space uplink applications. To avoid non-linearites the laser diode seed source was pulsed in a manner to create the widest linewidth possible. Next a variable shape pulse system with a EO modulator was used to place an exponential rise time on the input pulse to achieve near square pulses on the output. Successive mid stage amplifiers are employed to boost the signal before the power amplifier, which consists of a Etched Air Taper Pump combiner and a high power multi-fiber coupled pump. Over 500W is available for pumping the amplifiers. Results from this system and analysis of the system performance under the dynamic conditions of a PPF format will be reported.

8971-12, Session 2

1030nm Yb-fiber-MOPA based, multi-aperture high-power, high energy uplink laser beacon for deep space communication

Doruk Engin, John Burton, Ibraheem Darab, Frank Kimpel, Brian Mathason, Shantanu Gupta, Fibertek, Inc. (United States)

High average power and high energy (~4kW, 2mJ) laser beacons are needed for deep space optical communication uplinks to serve as absolute reference for precise pointing/tracking of the spacecraft during downlink laser communication. High-reliability silicon avalanche photo-detectors (Si-APD) are used on the spacecraft to detect the uplink beacon. For improved SNR in pointing/tracking, and reduced uplink laser power requirement, it is desirable to operate at shorter wavelengths near 1030nm, where near-IR Si-APDs have improved (>3X) spectral responsivity. Multiple apertures (~ 8 beams) are preferred to alleviate scintillation and improve fade characteristics due to the atmospheric turbulence. The uplink laser transmitter needs to accommodate a nested pulse position modulation (PPM) format where a slower outer modulation carrying commands, slot size ~63usec, binary PPM with 2 guard bands, PPM M-2 P-2) is simultaneously transmitted with data carrying inner modulation (slot size 128nsec, PPM M-8 P-4). Here, a Yb LMA fiber amplifier based laser transmitter capable of operating with high average power and high energy (~500W, 0.5mJ) is presented. The prototype, all-fiber, high TRL level laser transmitter is designed to meet all the single aperture requirements of an eight aperture deep space laser beacon system. The high speed FPGA controlled transmitter supports a directly modulated DFB laser and two acousto-optic modulators which are used to implement an open loop pattern dependent -pulse pre-shaping algorithm. Ultra-fast high power diode drivers are used for generating the outer nested PPM modulation and for implementing <1usec loss of signal (LOS) protection. Optical performance to be presented will include diffraction limited (M2~1.2) nested PPM optical outputs with >300W average power and 0.5mJ pulse energy with >70% o-o efficiency for the final power stage.

8971-13, Session 2

Radiation-hardened Erbium-doped optical fibers and amplifiers for future high-dose space missions

Sylvain Girard, Univ. Jean Monnet Saint-Etienne (France); Arnaud Laurent, Emmanuel Pinsard, Thierry Robin, Benoit Cadier, iIXFiber SAS (France); Mathieu Boutillier, CNES (France); Claude Marcandella, Commissariat à l'Énergie Atomique (France); Aziz Boukenter, Youcef Ouerdane, Univ. Jean Monnet Saint-Etienne (France)

Rare-earth (RE) doped fibers are needed as part of optical fibers sources, gyroscopes, inter- or intra-satellites communications links for space programs. For this, they present key advantages compared to other technologies but it is also known that they are very sensitive to space environment even if recent promising results and techniques have recently been published. To overcome the radiation-induced attenuation (RIA) limiting their integration in space systems and to enhance the efficiency of already-presented radiation hardening techniques on this phenomenon, we defined of a new Hole-Assisted Carbon-Coated (HACC) erbium-doped fiber (EDF) structure that permits to ensure a long-term H2 or D2 loading of the fiber core reducing the RIA (and then the EDFA gain degradation) compared to similar fibers without the HACC design and the H2 or D2-loading treatment. This new structure has been applied

together with an appropriate choice of core codopants ensuring, at the same time, optimal optical performances and lowest radiation-sensitivity. Using this new RE-doped HACC optical fiber, a 31 dB EDFA exhibits a gain decrease lower than 0.7 dB after irradiation up to a dose of ~315 krad (0.19 rad/s). The dose dependence coefficient of the gain change is of -2.2?10-3 dB/krad (compared to -24?10-3 dB/krad for a fiber of the same composition without the HACC structure) authorizing the use of HACC doped fibers for various space applications as they are insensitive to the radiations associated to today missions (up to 50 krad) and only slowly affected for future JUICE missions with the highest radiation constraints.

8971-14, Session 3

A reconsideration of the current best wavelengths for FSO *(Invited Paper)*

Colin Reinhardt, SPAWAR Systems Ctr. (United States); Stephen Hammel, Space and Naval Warfare Systems Command (United States); John deGrassie, SPAWARSYSCEN Pacific: San Diego (United States)

The selection of the “optimal” operating wavelength for Free Space Optical (FSO) communications systems has been a subject of some controversy over the past several decades. Practical FSO systems have been found to suffer severe performance degradation in adverse atmospheric visibility (high extinction/low-transmission) conditions such as fog, haze, and other atmospheric particulates (smoke, dust). Claims have been made that certain wavelengths offer superior performance. Another important practical factor in wavelength selection is the availability and cost of transmitter and receiver components at the desired operating wavelength.

We will revisit the problem of optical propagation through atmospheric particulates, and will show that the specific selection of the particulate distribution function (PDF), which specifies the particulates’ number density distribution by radius and the corresponding wavelength-dependent complex refractive indices, can significantly influence the total extinction behavior of various wavelengths and hence the choice of “optimal” wavelength. We will use a variety of realistic atmospheric PDFs to highlight the sensitivity of the “optimal” wavelength on the PDF. A primary result will be a matrix comparison chart illustrating extinction performance across the spectrum of visible to LWIR wavelengths for a variety of realistic atmospheric PDF scenarios: fogs, hazes, smoke, and dust.

We will also temper the results of the theoretical extinction analysis by practical considerations of what devices are currently available at wavelengths in the visible to LWIR bands. We will briefly discuss recent and near-horizon technologies holding promise in these areas, and also factors (commercial, technical) which may be limiting near-term progress in various wavebands.

8971-16, Session 3

Orthogonal Multi-Phase Shift Keying (OMPSK) modulation for free-space laser communications

Saleh Faruque, The Univ. of North Dakota (United States)

Orthogonal MPSK is a coded Multi Phase Shift Keying (OMPSK) modulation technique, where the input digital signal is mapped into a block of orthogonal codes. The encoded data, which is in orthogonal space, modulates the carrier frequency by means of MPSK modulation. At the receive side, the data is recovered by means of code correlation. This modulation technique offers channel coding and modulation, and synchronization without any additional circuits. These techniques are especially beneficial in high bandwidth and secure laser communication applications, such as for use in Unmanned Aerial Vehicles.

8971-17, Session 3

Pointing, acquisition, and tracking architecture tools for deep-space optical communications

Swati Mohan, Jet Propulsion Lab. (United States)

Deep-Space Optical Communications is a key emerging technology that would allow high data-rate communications, about 10x more than the current Ka-band technology. Increasing the frequency of communication, from Ka-band to optical, allows for a higher data rate transfers. However, as the frequency of communication increases, the beam divergence decreases. Less beam divergence requires more accurate pointing to make contact with the receiver. This would require roughly a 1000x improvement from Ka-Band (~ 1 mrad) to optical (~ 1 urad) in the required pointing. Finding an architecture that can provide the necessary pointing capability is driven by many factors, such as allocated signal loss due to pointing, range to Earth, spacecraft disturbance profile, spacecraft base pointing capability, isolation scheme, and detector characteristics. We have developed a suite of tools to 1) flow down a set of pointing requirements (Error Budget Tool), 2) determine a set of architectures capable of meeting the requirements (Pointing Architecture Tool), and 3) assess the performance of possible architecture over the mission trajectory (Systems Engineering Tool). This paper will describe the three tools developed and detail their use through two case study missions, Europa Clipper cruise mission and Asteroid Retrieval Mission. Results will be presented on possible architectures for the two case study missions. Finally, the paper will detail of what aspects of the pointing, acquisition, and tracking subsystem still require technology infusion, and the future steps needed to implement these pointing architectures.

8971-18, Session 3

Improving the efficiency of undersea laser communications

Hamid Hemmati, Abhijit Biswas, Jet Propulsion Lab. (United States)

We will discuss various methods to improve the efficiency of underwater laser communications, and will compare the merits of optical communications with RF and acoustic wave communiactions.

8971-20, Session 4

The Lunar Laser OCTL Terminal (LLOT) receiver assembly

Kevin Birnbaum, Matthew D. Shaw, Michael K. Cheng, Meera Srinivasan, Kevin J. Quirk, Abhijit Biswas, Jet Propulsion Lab. (United States)

The Optical Communication Telescope Laboratory (OCTL) will be used to receive downlink communications as part of the Lunar Laser OCTL Terminal (LLOT). The LLOT will be a backup ground terminal for the Lunar Laser Communications Demonstration (LLCD). Here we will describe the communications receiver assembly of the LLOT. This assembly includes an array of photon-counting detectors based on WSi superconducting nanowires, signal-combining electronics, a data-recorder, and software tools for concurrent- and post-processing of the recorded data.

8971-21, Session 4

Ground receiver unit for optical communication between LADEE spacecraft and ESA ground station

Felix Arnold, Martin Mosberger, Johannes Widmer, Fabio Gambarara, RUAG Space AG (Switzerland)

NASA's Lunar Laser Communication Demonstration (LLCD) demonstrates optical communication between ground stations on Earth and NASA's LADEE spacecraft orbiting the Moon. As a contribution to the LLCD experiment, the European Space Agency (ESA) prepares its existing optical ground station to serve as a complementary ground communication terminal. A ground receiver unit was developed for this purpose. It comprises optical detectors and electronics to recover the frames, decode the data and store them in a large data buffer.

The overall ground receiver unit design is presented and explained together with ground test activities. Different optical detectors had been evaluated and two detector types were chosen for implementation. A multimode fibre is used to couple the optical signal from the existing telescope into the detectors. The 16ary-Pulse Position Modulation (PPM) signal is then processed in the electronics. Clock recovery and frame synchronisation could be shown to work reliably at low power and under severe power fluctuations. For error correction, a powerful ?-rate Serially Concatenated PPM (SC-PPM) decoder is applied. The user data is decoded at a throughput of 39Mbps with up to 20 turbo iterations. With the developed ground receiver unit an average signal power of only a few hundred pico watts is required to yield a frame error rate smaller than 10e-5.

The ground receiver unit was tested for compatibility with NASA's ground support equipment and installed in ESA's Optical Ground Station on Tenerife. It is used in actual optical downlinks in October 2013. LLCD downlink results are presented and analysed.

8971-22, Session 4

Monolithic telescopes for free-space optical communications

William T. Roberts, Jet Propulsion Lab. (United States)

Free-space optical communications terminals generally rely on optical telescopes to enhance the transmitted and received efficiency of the communication system. We have designed and patented a suite of monolithic optical telescope systems, fabricated from a single piece of glass. In small sizes (5-15 cm apertures) these designs hold promise for reducing flight terminal mass and volume, reducing risks associated with telescope alignment, and reducing costs of flight optical terminals when produced in volume. This paper presents variations of optical designs and compares their characteristics, fabrication tolerances for these systems, and comparisons with conventional telescopes.

8971-23, Session 4

Recent developments in the production of spin-cast epoxy mirrors

Lisa Brodhacker, Lander Univ. (United States); Joe Ritter, Univ. of Hawai'i (United States); Andrew D. La Croix, Lander Univ. (United States); Bruce Holenstein, Gravic, Inc (United States); Russell M. Genet, California Polytechnic State Unviversity (United States)

The spin-casting method has been utilized without any polishing or figuring to produce a finished epoxy optical surface. The epoxy mirror has been measured to have a 6-8 micron RMS surface figure deviation and approximately 1 nm microroughness. Since the properties of a polymer are critical for achieving sufficient image formation, the chemistry of the system has been studied and tuned accordingly. Recent advances include the synthesis and co-polymerization of spiro orthocarbonate compounds (SOCs) to reduce chemical shrinkage and the engineering of a stiff mold to hold the curing epoxy as it spins. A report of the epoxy system will be given including characteristics of an ideal system, chemical modifications of the starting materials, and ways to reduce shrinkage and stress during the polymerization time.

8971-24, Session 4

Infrared Risley prism beam pointer

Steve Harford, Homero Gutierrez, Michael Newman, Robert Pierce, Tim Quakenbush, John Wallace, Michael A. Bornstein, Ball Aerospace & Technologies Corp. (United States)

Ball Aerospace & Technologies Corp. (BATC) has developed a Risley Beam Pointer (RBP) mechanism capable of agile slewing, accurate pointing and high bandwidth. The RBP is comprised of two wedged prisms that offer a wide Field of Regard (FOR) and may be manufactured and operated with diffraction limited optical quality. The tightly packaged mechanism is capable of steering a 4 inch beam over a 60° half angle cone with better than 60 µrad precision. Absolute accuracy of the beam steering is better than 1 mrad. The conformal nature of the RBP makes it an ideal mechanism for use on low altitude aircraft and unmanned aerial vehicles. Unique aspects of the opto-mechanical design include i) thermal compliance to maintain bearing preload and optical figure over a wide temperature range; and ii) packaging of a remote infrared sensor that periodically reports the temperature of both prisms for accurate determination of the index of refraction. The pointing control system operates each prism independently and employs an inner rate loop nested within an outer position loop. Mathematics for the transformation between line-of-sight coordinates and prism rotation are hosted on a 200 MHz microcontroller with just 516 KB of RAM.

8971-26, Session 4

Liquid crystal optical phased array multiple-beam forming methods

Feng Xiao, Lingjiang Kong, Univ. of Electronic Science and Technology of China (China)

Numerous studies have introduced the phased array technology into the optical band by manufacturing the optical phased array devices, and liquid crystal optical phased array (LCOPA) is the most promising one. In this paper, we used the self-made LCOPA with 1920 elements to generate multiple-beams steering to prove this technology has the potential to be applied in FSO system to realize multiple targets detection recognition and tracing. Four control methods that we used in our experiment, sub-aperture method, array division multiplexing (ADM) method, phase retrieval method and polarization division multiplexing (PDM) method, was introduced in this paper. The sub-aperture method is borrowed from the microwave phased array radar. Take double-beam forming for instance, it divides the aperture into two parts, and each part works independently. ADM method is a variant of the sub-aperture method. It separates the array by odevity. The odd elements and the even elements work independently (for double-beam forming). This method allows each beam occupies the whole aperture size. The phase retrieval method is a kind of image processing method. We firstly designed the far-field radiation pattern, after that utilized some retrieval algorithms like GS algorithm to generate the near-field phase distribution that should be applied in the LCOPA, then the multiple-beam was formed. Finally, a method called polarization division multiplexing was proposed. The PDM method makes use of the birefringence property of nematic liquid crystal, and it can steer a circular polarization light to two different directions independently by combining two LCOPAs and a half-wave plate. The control principle and process of each method were described. The pattern functions of the sub-aperture and ADM were derived, and the differences between the two functions were analyzed in detail. Simulation

and experiment of each method were done to certify these four methods are applicable to be applied in LCOPA to realize multiple-beam steering.

8971-36, Session 4

A multi-rate DPSK modem for free-space laser communications

Neal W. Spellmeyer, C. A. Browne, David O. Caplan, John J. Carney, M. L. Chavez, Andrew S. Fletcher, J. J. Fitzgerald, R. D. Kaminsky, G. Lund, Scott A. Hamilton, Richard J. Magliocco, O. V. Mikulina, Robert J. Murphy, Hemonth G. Rao, M. S. Scheinbart, M. M. Seaver, Jade P. Wang, MIT Lincoln Lab. (United States)

The multi-rate DPSK format, which enables efficient free-space laser communications over a wide range of data rates, is finding applications in NASA's Laser Communications Relay Demonstration. We discuss the design and testing of an efficient and robust multi-rate DPSK modem, including aspects of the electrical, mechanical, thermal, and optical design. The modem includes an optically preamplified receiver, an 0.5 W average power transmitter, a LEON3 rad-hard microcontroller that provides the command and telemetry interface and supervisory control, and a Xilinx Virtex-5 rad-hard reprogrammable FPGA that both supports the high-speed data flow to and from the modem and controls the modem's analog and digital subsystems. For additional flexibility, the transmitter and receiver can be configured to support operation with multi-rate PPM waveforms.

8971-37, Session 4

Multi-rate DPSK optical transceivers for free-space applications

David O. Caplan, John J. Carney, J. Fitzgerald, I. Gaschits, D. Geisler, R. Kaminsky, G. Lund, Scott A. Hamilton, Richard J. Magliocco, Robert J. Murphy, Hemonth G. Rao, Neal W. Spellmeyer, Jade P. Wang, MIT Lincoln Lab. (United States)

Flexible high-sensitivity laser communications can significantly benefit performance and cost of NASA's satellite-based Laser Communications Relay Demonstration (LCRD). Optical communications using Differential phase shift keying (DPSK), widely deployed for use in long-haul fiber-optic networks, is well known for its superior sensitivity and link performance over on-off keying while maintaining a relatively straightforward design. However, unlike fiber-optic links, free-space applications often require operation over a wide dynamic range of power due to variations in link distance and channel conditions, which can include rapid kHz-class fading when operating through the turbulent atmosphere. Here we discuss the implementation of a robust, near-quantum-limited multi-rate DPSK transceiver, co-located transmitter (TX) and receiver (RX) subsystems that can operate efficiently over the highly-variable free-space channel. Key performance features will be presented on the master oscillator power amplifier (MOPA) based TX, including a wavelength-stabilized master laser, high-extinction-ratio burst-mode modulator, and 0.5 W single polarization power amplifier, as well as low-noise optically preamplified DSPK receiver and built-in test capabilities.

8971-28, Session 5

Introduction of a terrestrial free-space optical communications network facility: IN-orbit and Networked Optical ground stations experimental Verification Advanced testbed (INNOVA) *(Invited Paper)*

Morio Toyoshima, Yasushi Munemasa, Hideki Takenaka, Yoshihisa Takayama, Yoshisada Koyama, Hiroo Kunimori, Toshihiro Kubooka, Kenji Suzuki, Shinichi Yamamoto, Shinichi Taira, Hiroyuki Tsuji, Isao Nakazawa, Maki Akioka, National Institute of Information and Communications Technology (Japan)

This paper describes Terrestrial Free-Space Optical Communications Network Facility called IN-orbit and Networked Optical ground stations experimental Verification Advanced testbed (INNOVA). Many demonstrations have been conducted to verify the usability of sophisticated optical communications equipment in orbit. However, the influence of terrestrial weather conditions remains as an issue to be solved. One potential solution is site diversity, where several ground stations are used. The National Institute of Information and Communications Technology (NICT) is developing a terrestrial free-space optical communications network facility for future airborne and satellite-based optical communications projects called INNOVA. Several ground stations and environmental monitoring stations around Japan are being used to explore the site diversity concept.

8971-29, Session 5

Overview and results of the Lunar Laser Communication Demonstration *(Invited Paper)*

Don M. Boroson, Bryan S. Robinson, Daniel V. Murphy, Dennis A. Burianek, Farzana Khatri, MIT Lincoln Lab. (United States); Joseph M. Kovalik, Jet Propulsion Lab. (United States); Zoran Sodnik, European Space Research and Technology Ctr. (Netherlands)

No Abstract Available

8971-30, Session 5

Inter-Island Optical Link Demonstration using High Data-Rate Pulse-Position Modulation

Michael Bacher, Felix Arnold, Björn Thieme, RUAG Space AG (Switzerland)

The growing data-rate demands on satellite communication systems has led to the increased interest in optical space communication solutions for uplinks and downlinks between satellites and ground stations. As one example for applications that benefit from higher data-rates offered by optical links, RUAG Space studied an uplink scenario from an Unmanned Aerial Vehicle (UAV) to a Geostationary Orbit (GEO), under the European Space Agency project formally known as "Optical Communications Transceiver for Atmospheric Links".

Particularly suitable for optical links through turbulent atmospheres are robust Pulse Position Modulation (PPM) schemes. Communication electronics using a Multi-Pulse PPM (MPPM) scheme have been developed, increasing the data-rate compared to traditional PPM at a constant peak-to-average ratio while allowing a widely configurable data-rate range. The communication system was tested together with a newly developed receiver and transmitter at a wavelength of 1055nm in a field test campaign on the Canary Islands, where the transmitter telescope was located on La Palma while the receiver was installed within the ESA Optical Ground Station on Tenerife. The nearly horizontal link between the

two islands with a link distance of 143km allowed validation of relevant system performances under stringent atmospheric conditions. A data-rate of 370Mbps could be demonstrated using MPPM, while 250Mbps could be achieved with traditional PPM, well exceeding the targeted data-rate of the studied UAV-to-GEO scenario.

Following an introduction on the applied MPPM schemes, the architecture of the test setup is described, different modulation schemes are compared and the test results of this Inter-Island Test Campaign performed in October 2012 are presented.

8971-31, Session 5

Design and validation testing of the optical link of the Optical Payload for Lasercom Science (OPALS) system

Bogdan V. Oaida, Jet Propulsion Lab. (United States) and California Institute of Technology (United States); William Wu, Quantitative Engineering Design Inc. (United States); Baris I. Erkmen, Google (United States); Abhijit Biswas, Jet Propulsion Lab. (United States) and California Institute of Technology (United States); Kenneth Andrews, Michael Kokorowski, Marcus Wilkerson, Jet Propulsion Lab. (United States)

The Optical Payload for Lasercom Science (OPALS) system developed by the Jet Propulsion Laboratory, California Institute of Technology will be used for link experiments from the International Space Station (ISS) to a ground telescope located at Table Mountain, CA. The launch of the flight terminal is scheduled for late 2013/early 2014 with an initially planned 90-day operations period, following deployment on the exterior of the ISS. The simple, low-cost OPALS system will be used to downlink a pre-encoded video file, on a 1550 nm laser carrier using on-off key (OOK) modulation. A 976 nm multi-beam laser beacon transmitted from the ground to the ISS will initiate the downlink. Link analysis along with pre-flight ground test results of the OPALS system will be presented. Flight demonstration data, if available at the time of the presentation, will be included in the presentation.

8971-32, Session 5

LLCD operations using the Lunar Lasercom Ground Terminal

Daniel V. Murphy, Robert E. Lafon, Jan E. Kansky, Matthew E. Grein, Robert T. Schulein, Matthew M. Willis, MIT Lincoln Lab. (United States)

No Abstract Available

8971-33, Session 5

LLCD operations using the Lunar Lasercom OGS Terminal *(Invited Paper)*

Zoran Sodnik, European Space Research and Technology Ctr. (Netherlands); Igor Zayer, European Space Operations Ctr. (Germany)

No Abstract Available

8971-34, Session 5

The Lunar Laser OCTL Terminal (LLOT)

Abhijit Biswas, Joseph M. Kovalik, Malcolm W. Wright, William T. Roberts, Kevin Birnbaum, Matthew D. Shaw, Michael K. Cheng, Meera Srinivasan, Kevin J. Quirk, Jet Propulsion Lab. (United States)

The Optical Communications Telescope Laboratory (OCTL) located near Wrightwood, CA has been integrated with optics, lasers, actuators, sensors, detectors, signal processing hardware and software to form the Lunar Laser OCTL Terminal (LLOT) that will serve as one of two backup terminals for the Lunar Laser Communications Demonstration (LLCD). The second backup terminal will be implemented by the European Space Agency and located in Tenerife, Spain. The Lincoln Laboratory, Massachusetts Institute of Technology (LL-MIT) developed Lunar Lasercomm Space Terminal (LLST) and Lunar Lasercomm Ground Terminal (LLGT) located at NASA's White Sands Complex near Las Cruces, NM, will constitute the primary LLCD assets for demonstrating data-rates up to 622 Mb/s from lunar distances for the first time. The LLST will fly aboard the Lunar Atmosphere and Dust Environment Explorer (LADEE) spacecraft scheduled to launch in September 2013 with lunar orbit insertion in early October 2013. LLOT will support LLST downlink at 39 and 78 Mb/s and be capable of operating in coordination with the Lunar Lasercomm Operations Center (LLOC) located at LL-MIT. In this paper the LLOT system and its interfaces will be described and the results of verification and operations tests will be reported.

8971-38, Session 5

Electronics design of a multi-rate DPSK modem for free-space optical communications

Hemonth G. Rao, C. A. Browne, David O. Caplan, John J. Carney, M. L. Chavez, Andrew S. Fletcher, J. J. Fitzgerald, R. D. Kaminsky, G. Lund, Scott A. Hamilton, Richard J. Magliocco, O. V. Mikulina, Robert J. Murphy, M. M. Seaver, M. S. Scheinbart, Neal W. Spellmeyer, Jade P. Wang, MIT Lincoln Lab. (United States)

We have designed and experimentally demonstrated a radiation-hardened modem suitable for NASA's Laser Communications Relay Demonstration. The modem supports free-space DPSK communication over a wide range of channel rates, from 72 Mb/s up to 2.88 Gb/s. The modem transmitter electronics generate a burst-DPSK waveform, such that only one optical modulator is required. The receiver clock recovery is capable of operating over all channel rates at average optical signal levels below -70 dBm, while accommodating signal outages of tens of milliseconds. The modem incorporates a radiation-hardened Xilinx Virtex 5 FPGA and a radiation-hardened Aeroflex UT699 CPU. The design leverages unique capabilities of each device, such as the FPGA's multi-gigabit transceivers. The modem scrubs itself against radiation events, but does not require pervasive triple-mode redundant logic. The modem electronics include automatic stabilization functions for its optical components, and software to control its initialization and operation. The design allows the modem to be put into a low-power standby mode.

8971-39, Session 5

Performance and qualification of a multi-rate DPSK modem

Jade P. Wang, C. Browne, David O. Caplan, John J. Carney, M. L. Chavez, J. Fitzgerald, I. Gaschits, D. Geisler, Scott A. Hamilton, Scott R. Henion, G. Lund, Richard J. Magliocco, O. V. Mikulina, Robert J. Murphy, Hemonth G. Rao, M. M. Seaver, Neal W. Spellmeyer, MIT Lincoln Lab. (United States)

No Abstract Available

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8972-1, Session 1

Plasmonic cell transfection using micropyramids

Nabiha Saklayen, Harvard Univ. (United States); Sébastien Courvoisier, Univ. of Geneva (Switzerland); Jun Chen, Nanjing Univ. of Science and Technology (China); Jean-Pierre Wolf, Univ. of Geneva (Switzerland); Eric Mazur, Harvard School of Engineering and Applied Sciences (United States)

We present a new cell transfection method that uses femtosecond laser-excited surface plasmons on a nanostructured micropyramid array. High local electric field enhancements are produced to temporarily perforate mammalian cell (HeLa S3) membranes and allow genetic vectors to diffuse through the membrane gaps. Our gold-layered pyramids have nano-apertures at the apex to enhance the formation of “hot spots.” We also perform poration experiments with cells to optimize our laser parameters for transfection. FDTD simulation results and two-photon fluorescence microscopy on the micropyramids are used to determine the most desirable parameters for substrate fabrication. Our nontoxic, efficient, and scalable technique offers an innovative approach to the advancement of regenerative medicine and the study of photon-cell interaction.

8972-2, Session 1

Single cell transfection by laser-induced breakdown of an optically trapped gold nanoparticle

Yoshihiko Arita, Martin Ploschner, Maciej K. Antkowiak, Frank J. Gunn-Moore, Kishan Dholakia, Univ. of St. Andrews (United Kingdom)

Cell selective introduction of therapeutic agents remains a challenging problem. Cavitation-based therapies including ultrasound-induced sonoporation and laser-induced optoporation have led the way for novel approaches to provide the potential of sterility and cell selectivity compared with viral or biochemical counterparts. Acoustic streaming, shockwaves and liquid microjets associated with the cavitation dynamics are implicated in gene and drug delivery. These approaches, however, often lead to non-uniform and sporadic molecular uptake that lacks refined spatial control and suffers from a significant loss of cell viability. Here we demonstrate spatially controlled cavitation instigated by laser-induced breakdown of an optically trapped single gold nanoparticle. Our unique approach employs optical tweezers to trap a single nanoparticle, which when irradiated by a nanosecond laser pulse is subject to laser-induced breakdown followed by cavitation. Using this method for laser-induced cavitation, we can gain additional degrees of freedom for the cavitation process - the particle material, its size, and its position relative to cells or tissues. We show the energy breakdown threshold of gold nanoparticles of 100nm with a single nanosecond laser pulse at 532nm is three orders of magnitude lower than that for water, which leads to ‘gentle’ nanocavitation enabling single cell transfection. We optimize the shear stress to the cells from the expanding bubble to be in the range of 1-10kPa for transfection by precisely positioning a trapped gold nanoparticle, and thus nanobubble, relative to a cell of interest. The method shows transfection of plasmid-DNA into individual mammalian cells with an efficiency of 75%.

8972-3, Session 1

Enhanced cell transfection using subwavelength focused optical eigenmode beams

Michael Mazilu, Xanthi Tsampoula, Tom Vettenburg, Frank J. Gunn-Moore, Kishan Dholakia, Univ. of St. Andrews (United Kingdom)

For more than 100 years, it has been generally accepted that the resolution of optical microscopy is fundamentally limited by the optics and the wavelength of light. The last two decades have shown that this limit may be broken leading to advanced light microscopy techniques with resolution at the nanometer scale. The ability to explore the nanoscale at optical wavelengths is not, however, restricted solely to imaging. A myriad of other topics in nanobiophotonics would benefit from light structuring beyond the diffraction limit.

Multiphoton processes are at the heart of numerous powerful biophysics methodologies including ablation, and nanosurgery. To date, researchers have observed cutting of cellular structures using superresolved multiphoton light field. Excitingly, the use of a high repetition rate ultrashort pulsed femtosecond lasers generates a low-density free-electron plasma that creates a transient pore within the lipid bilayer. This can aid the controlled introduction of therapeutic agents into cells, and is termed optical cell transfection. Naturally this process is dependent upon the focal spot used in the experiment. In this paper we shape light in the far field using the technique of optical eigenmodes (OEi), permitting us to tune the focal spot size down to 0.36 ?/NA, smaller than the size of the diffraction limited spot. We compare cell transfection efficiencies for various spot sizes, and thus numerical apertures (NA) of our optical system. In addition to enhancing transfection efficiency, the higher effective numerical aperture allows us to use objectives of lower numerical aperture and with large working distances. This offers extended flexibility for nanoscale biomedical cell and tissue transfection.

8972-4, Session 1

Biodegradable microsphere-mediated perforation using low-intensity femtosecond laser pulses for microfluidic perforation system

Tatsuki Mitsuhashi, Mitsuhiro Terakawa, Keio Univ. (Japan)

In this study, we demonstrate the cell membrane perforation using transparent biodegradable microspheres excited by a low-intensity femtosecond laser pulses. Applications of microfluidic system to the microfluidic analysis, sorting, purification and on-chip cell culture study have been attracting increasing attention. A laser drug delivery system within a flow channel in a microfluidic system can simplify the process and improve the throughput of delivering efficiency by irradiating the flowing cells in the flow channel. We have been studying cell-selective perforation using an enhanced optical field around biodegradable microspheres conjugated to the cell membrane excited by a near-infrared femtosecond laser. In the method of using a microfluidic system, the high-peak intensity of femtosecond laser irradiation possibly leads to self-focusing, multiphoton absorption and optical breakdown in the transparent material which cause damage to a flow channel. Therefore, high delivering efficiency at low-peak intensity is desirable for developing the microfluidic perforation system. In this study, we delivered FITC-dextran into A431 cells by using low-peak intensity femtosecond laser pulses. As a result, FITC-dextran was able to be delivered by multi

femtosecond laser pulses at the irradiated peak intensity of 8.8 ? 10^11 W/cm2, where an external molecule was not able to be delivered with a single shot of femtosecond laser pulse. The results of applying our method to the microfluidic perforation system will also be presented.

8972-6, Session 2

Mechanistic investigations and molecular medicine applications of gold nanoparticle mediated (GNOME) laser transfection

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Alternative high throughput transfection methods are required to understand the molecular network of the cell which is linked to the evaluation of target genes as therapeutic agents. Besides diagnostic purposes, the transfection of primary- and stem cells is of high interest for therapeutic use. Here the cell release of trans- or exogene proteins is used to develop immune cancer therapies. The basic requirement to accomplish manipulation of cells is an efficient and gentle transfection method. Therefore we developed an automatized cell manipulation platform providing a high throughput by using GNOME lasertransfection. Herein, plasmon resonances evoked by the interaction of moderately focused laser pulses with gold nanoparticles in close vicinity to the cell membrane mediate transient membrane permeabilization. The exact nature of the involved permeabilization effects strongly depends on the particles and laser parameters applied. Herein, we describe investigations considering the parameter regime, the permeabilization mechanism and the safety profile of GNOME laser transfection. The experimental and calculated results imply a combined permeabilization mechanism consisting of both photochemical and photothermal effects.Furthermore, paramount spatial control achieved either by laser illumination with micrometer precision or targeted gold nanoparticle binding to the cells was demonstrated, allowing selective cell manipulation. An efficient gene knockdown in cancer cells and the possibility to manipulate hard to transfect primary cells (neurons) is shown. These results give insights in the basic mechanisms involved in GNOME laser transfection and serve as a strong basis to deliver different molecules for therapeutic (e.g. proteins) and diagnostic (siRNA) use.

8972-7, Session 2

Dynamic imaging of transient bubbles generated by femtosecond irradiation of plasmonic nanoparticles in cell environment

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Femtosecond (fs) laser generation of submicron bubbles in aqueous solutions plays a key role in advanced laser nanosurgery applications such as cell transfection. In particular, the ability to control bubble dynamics (i.e. size, life time) in close proximity to a cell membrane, could lead to high efficiency in introducing exogenous molecules into the cytoplasm without decreasing cell viability. In this context, we have developed a pump-probe shadowgraphy ultrafast imaging technique capable of tracking transient bubbles generated by fs irradiation (? =800 nm, ? = 50 fs) of: (a) plasmonic NPs in cell medium and (b) plasmonic NPs attached to cells. The technique allows for tracking successive bubbles generated by a single NP and clusters of NPs with nanosecond (ns) temporal resolution and submicron spatial resolution at a repetition rate of 10 Hz. The laser fluence was systematically varied from 50 mJ/cm2 to 400 mJ/cm2 to study the effect on the bubble dynamics generated around 100 nm Au NPs. The maximum bubble size and life time were found to be 1.2 ± 0.1 ?m and 45 ± 5 ns, respectively. For the entire laser fluence range, the 100 nm Au plasmonic NPs showed a notable ability to generate up to 1000 successive bubbles (i.e. exceeding the maximum achievable tracking time) without any indication of fragmentation. The dynamics of bubbles generated in close proximity to the membrane of cancer cells were correlated with their perforation efficiencies to provide an insight to the perforation mechanism.

8972-8, Session 2

New methods to study fluence threshold in nanoparticle mediated laser-induced bubble formation

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Focused ultra-fast laser pulses with high peak intensities result in photo-ionization and plasma formation within the laser focal volume when above a certain threshold fluence. This high pressure plasma expands to form transient bubbles that grow and collapse. Close to threshold energies and at the region of low density plasma formation, these bubbles can be smaller than the diffraction limited focal spot size and are detected using scattering techniques like the pump-probe method. However, for nanoparticle–enhanced laser ablation, the uncertainty of particle position within the laser focal volume renders the pump probe technique ineffective in relating bubble radius to their corresponding breakdown fluences. Here, we present two new approaches to determine nanoparticle mediated bubble formation enhancements in liquid media. The first method uses kinetic theory to provide spatial information on where the smallest bubbles are formed within the laser focal volume. The radial information is calculated from the collision frequency of the nanoparticles in solution. The second method compares observed probability distributions for bubbles formed at nanoparticle sites with a theoretical distribution for particle location within the ultrafast laser focal volume to establish a relationship between bubble radii and associated laser intensity. Applying these methods to data from solutions of 50 nm gold spheres exposed to near infrared femtosecond pulses yields expected bubble energy threshold reduction when compared to pure water.

8972-9, Session 2

Nanoplasma formation around plasmonic nanostructures in ultrafast laser-induced nanocavitation

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Irradiating plasmonic nanostructures in water, such as gold nanorods (NRs) or gold nanoparticles (NPs), with an ultrafast laser leads to various phenomena, including the formation of a nanoplasma and nanobubbles. Those nanobubbles could be used namely to perform optoporation of cell membranes and gene transfection. We found that when NRs are irradiated in-resonance with ultrafast laser pulses, the formation of a nanoplasma around the particles shields the plasmonic resonance, thus leading to smaller nanobubbles than expected [1]. The NRs are also heavily damaged, thus limiting multi-pulses applications and raising some toxicity concerns. In comparison, when NPs are irradiated off-resonance

with the ultrafast laser pulses, the creation of a nanoplasma directly in the water around the NPs can be the dominant physical mechanism leading to cavitation [2]. Because of the limited energy absorption in the particle, this mechanism has the advantage to let the NPs undamaged. This work presents the recent observation of a polarization dependence on the nanobubble size. This technique is used to probe which of the thermal or the plasma mechanism is the dominant physical mechanism leading to nanobubble formation. In particular, we observed that, when the laser pulse duration is shorter than 1ps, bubbles generated with linear polarization are larger than those generated with circular polarization, which is a clear signature of plasma-mediated nanocavitation.

[1] E. Boulais et al., Journal of Physical Chemistry C, 117, 9386-9396 (2013)

[2] E. Boulais et al., Nano Letters, 12, 4763-4769 (2012)

8972-11, Session 2

Plasmonic nanobubbles for target cell-specific gene and drug delivery and multifunctional processing of heterogeneous cell systems *(Invited Paper)*

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Cell and gene cancer therapies require ex vivo cell processing of human grafts. Such processing requires at least three steps – cell enrichment, cell separation (destruction), and gene transfer – each of which requires the use of a separate technology. While these technologies may be satisfactory for research use, they are of limited usefulness in the clinical treatment setting because they have a low processing rate, as well as a low transfection and separation efficacy and specificity in heterogeneous human grafts. Most problematic, because current technologies are administered in multiple steps – rather than in a single, multifunctional, and simultaneous procedure – they lengthen treatment process and introduce an unnecessary level of complexity, labor, and resources into clinical treatment; all these limitations result in high losses of valuable cells.

We report a universal, high-throughput, and multifunctional technology that simultaneously (1) transfects target cells, (2) destroys unwanted cells, and (3) preserve valuable non-target cells in heterogeneous grafts. Each of these functions has single target cell specificity in heterogeneous cell system, processing rate > 45 mln cell/min, injection efficacy 90% under 96% viability of the injected cells, target cell destruction efficacy > 99%, viability of not-target cells >99%

The developed technology employs novel cellular agents, called plasmonic nanobubbles (PNBs). PNBs are not particles, but transient, intracellular events, a vapor nanobubbles that expand and collapse in mere nanoseconds under optical excitation of gold nanoparticles with short picosecond laser pulses. PNBs of different, cell-specific, size (1) inject free external plasmid with small PNBs, (2) Destroy other target cells mechanically with large PNBs and (3) Preserve non-target cells.

The multi-functionality, precision, and high throughput of all-in-one PNB technology will tremendously impact cell and gene therapies and other clinical applications that depend on ex vivo processing of heterogeneous cell systems.

8972-10, Session 3

Specific manipulations of cancer cells using gold nanoparticles and femtosecond pulses *(Invited Paper)*

Dvir Yelin, Daniella Yeheskely-Hayon, Limor Minai, Technion-Israel Institute of Technology (Israel)

Optical manipulation of cells on subcellular scales is a key challenge in numerous biomedical applications, allowing minimally invasive interference in important cellular processes. Yet, a tightly focused laser beam is rarely used for such purpose, most often since it does not allow adequate efficiency or specificity; it is too large for the smallest organelles, too small for handling large cell populations, and lacks specific affinity to most molecules, organelles or cells. To improve specificity and efficiency of light-tissue interactions, we employ gold nanoparticles coated by specific antibodies for specific cell targeting, followed by intense widefield femtosecond-pulse illumination of the targeted cells, resulting in widespread formation of localized cavitation bubbles around the nanoparticles. The exact effect (or combination of different effects) of the laser irradiation on the cells depends on numerous experimental parameters, including pulse irradiance, duration and repetition rate, nanoparticle concentration, affinity and size, as well as cell type, density and viability. The talk presents our ongoing efforts to study and control the different effects and to utilize them for various applications. Specifically, we present laser-induced formation of viable hybrid myeloma-splenic B cells, and induction of specific cell death through membrane rupture, release of drug from the nanoparticles, and formation of intracellular reactive oxygen species. The main advantages of the presented approach include low toxicity of the nanoparticles and the laser light, high targeting specificity, nanometric interaction volumes on large scales, and a diverse experimental parameter range that allows optimization for achieving a desirable task.

8972-12, Session 3

Femtosecond optical injection of intact plant cells using a reconfigurable platform

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By tightly focusing a femtosecond laser beam onto a cell membrane, the membrane permeability can be transiently increased, allowing membraneimpermeable yet biologically relevant molecules to enter the cell. Although this non-invasive and highly selective technique has been used in mammalian cell studies for the past decade it has rarely been used in plant cells where the presence of the cell wall and high interior turgor pressure increases the difficulty of molecule delivery.

Photoporation has previously been shown to be sensitive to many optical parameters including laser intensity, beam geometry and pulse duration. In this study an optical system was built on a commercial microscope to quickly switch between different laser configurations to directly compare these optical parameters.

Varying the spatial geometry of the laser beam from a Gaussian beam to a “nondiffracting” Bessel beam has been shown in mammalian cells to dramatically reduce the requirement for accurate membrane targeting. By redirecting the laser path we can choose between an axicon-generated Bessel beam or a Gaussian beam at the focal plane.

Previous mammalian cell studies have demonstrated that high photoporation efficiencies are achievable when using very short pulses, owing to the high peak power. We switch between a high-powered, 140 fs laser and a pulse dispersion compensated system, capable of providing <20 fs pulses at the sample plane, and compare the effect of pulse duration on plant cells for both Gaussian and Bessel beams. Crucially, this is the first time that these parameter regimes have been explored in plant cell photoporation.

8972-13, Session 3

Evaluation of pulsed laser ablation in liquids generated gold nanoparticles as novel transfection tools - efficiency and cytotoxicity

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Varying transfection efficiencies and cytotoxicity are crucial aspects in cell manipulation. The addition of gold nanoparticles (AuNP) has lately attracted special interest to enhance transfection efficiency. Conventional AuNP are usually produced by chemical reactions or gas pyrolysis requiring cell-toxic stabilizers or coatings to conserve their characteristics. Alternatively, stabilizer- and coating-free, highly pure, colloidal AuNP can be generated by pulsed laser ablation in liquids (PLAL). Mammalian cells were transfected efficiently by addition of PLAL-AuNP, but data evaluating the cell-toxic potential are lacking.

Herein, the transfection efficiency and cytotoxicity of PLAL AuNP was evaluated by transfection of a mammalian cell line with a recombinant HMGB1/GFP DNA expression vector. Different methods were compared using two sizes of PLAL AuNP, commercialized AuNP, two magnetic NP-based protocols and a conventional transfection reagent (FuGENE®HD; FHD). PLAL-AuNP were generated using a Spitfire Pro femtosecond laser system delivering 120 fs laser pulses at a wavelength of 800 nm focussing the fs-laser beam on a 99.99% pure gold target placed in ddH2O.

Transfection efficiencies were analysed after 24h using fluorescence microscopy and flow cytometry. Toxicity was assessed measuring cell proliferation and percentage of necrotic, propidium iodide positive cells (PI%).

The addition of PLAL-AuNP significantly enhanced transfection efficiencies (FHD: 31%; PLAL-AuNP_size-1: 46%; size-2: 50%) with increased PI% but no reduced cell proliferation. Commercial AuNP-transfection showed significantly lower efficiency (23%), slightly increased PI% and reduced cell proliferation. Magnetic NP based methods were less effective but showing also lowest cytotoxicity.

In conclusion, addition of PLAL-AuNP provides a novel tool for transfection efficiency enhancement with acceptable cytotoxic side-effects.

8972-14, Session 4

Extreme ultra violet optical coherence tomography with high harmonic generation sources

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We present a novel method for cross sectional imaging with nanometer resolution which is referred to as XUV coherence tomography (XCT). XCT uses extreme ultra violet light (XUV), e.g., from high harmonic generation (HHG). In XCT, the coherence length of a few nanometers of broadband XUV sources is exploited. Thus, XCT extends optical coherence tomography (OCT) by improving the axial resolution from micrometers to nanometers. In a first step, we demonstrated XCT at synchrotron sources. Three dimensional images of nano-structured samples based on silicon and carbon were recorded. We reached an axial resolution of 12nm in the silicon transmission window (30-99eV) and 3 nm in the water-window (270-530eV) – solely limited by the spectral transmission windows of the materials used. XCT can be regarded as a perfect application for laser-driven HHG sources due to their intrinsic broad bandwidths which would have disadvantages for other imaging methods such as confocal microscopy or non diffractive imaging. In addition, HHG enables XCT to become a table top nanometer imaging technique. We present first results of an adaption of XCT using few-cycle laser driven HHG.

8972-15, Session 4

Label-free high-throughput imaging flow cytometry

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Flow cytometry is an optical method for studying cells based on their individual physical and chemical characteristics. It is widely used in clinical diagnosis, medical research, and biotechnology for analysis of haematocytes and other cells in suspension. Conventional flow cytometers aim a laser beam at a stream of labeled cells and measure the elastic scattering at forward and side angles. They also perform single-point measurement of fluorescent emission from labeled cells. However, many reagents used in cell labeling reduce cellular viability or change the behavior of the target cells by activating undesired cellular processes or inhibiting normal activity of the cells. Therefore, labeled cells are not completely representative of their intact form and fully reliable for downstream studies. To remove the requirement of cell labeling in flow cytometry, while still meeting the classification sensitivity and specificity goals, measurement of other biophysical parameters in addition to elastic scattering is essential. Here, we introduce an interferometric imaging flow cytometer based on world's fastest continuous-time camera. Our system simultaneously measures size and protein concentration of the cells as supplementary biophysical parameters for label-free classification. It exploits wide bandwidth of ultrafast laser pulses to perform blur-free quantitative phase imaging at flow speeds as high as 10 meters per second and achieves sub-nanometer optical path length resolution for precise measurement of cell protein concentration. We experimentally demonstrate the utility of our imaging flow cytometer in label-free classification of multiple cell types.

8972-16, Session 4

Smart surgical tool

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In this paper, a LIBS guided smart surgical tool using a femtosecond (fs) fiber laser is investigated. This functional system includes a high energy fs fiber laser system (PolarOnyx Laser, Inc. - Uranus Series), a scanning system, a handheld processing head allowing for free hand preparations and a LIBS signal collection and feedback system. The laser source employed emits pulses with pulse duration of 700 fs at a repetition rate tunable from 1 Hz to 1 MHz. The centre wavelength is at 1030 nm and the average output power can be tuned up to 50 W. The whole functional system is compact in size and moveable. General characteristics like optical losses and ablation rate are determined at first. Furthermore the LIBS signal collection and feedback system is used for material characterization and surgery control. It comprises a spectrum collection fiber and a focal lens to collect plasma spectrum signal for material

characterization in real time, a detector, a spectrometer for spectrum analysis and a system control module. Comparison methods to identify the different materials emissions are developed and algorithms are implemented into a real-time control system. This system allows real time processing of different tissue types (hard and soft tissues) with possibility to real-time tailor the laser parameters (pulse energy and repetition rate) and system operation (scanning speed) and provides a “proof-of-principle” LIBS guided smart surgical tool with fs fiber laser.

8972-17, Session 5

Femtosecond-laser induced nanostructuring for surface enhanced Raman spectroscopy

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The formation of laser-induced periodic nanostructures (LIPNS) by the excitation and interference of surface plasmon-polaritons (SPPs) can be applied to create highly efficient substrates for surface-enhanced Raman spectroscopy (SERS). There exist two different approaches, both utilizing intense ultrashort laser pulses: (a) direct top-down processing of a metallic substrate in a simple and cost-effective, single-step procedure, or (b) a two-step process comprising an initial structuring of highly transparent or absorbing non-metallic (i.e. dielectric or semiconducting) materials followed by the deposition of a thin metal layer. Here we report about the more easy and less time consuming fabrication of type-(a) LIPNS on Ag-substrates and their application to the sensitive detection of selected biomolecules. In our experiments, the SERS of DNA and protein molecules was studied. Maximum enhancement factors were found on Ag-substrates structured with the second harmonic of a Ti:sapphire laser and for LIPNS periods near the corresponding wavelength of 400 nm. The LIPNS were characterized by scanning electron microscopy and found to be mostly regular gratings with a slight contribution of randomness. The structure quality was analyzed by extracting the spatial frequency spectra with the Fast Fourier Transform of the imaged patterns. Nanostructured areas in the range of 1.25 mm2 were obtained during a processing time of 10 s. Beside the SERS, metallic LIPNS are interesting for many other applications like adhesion control, photoelectron generation, discharge confinement, harmonics enhancement or as targets for relativistic laser physics.

8972-18, Session 5

High fidelity fiber-based optical parametric oscillator for coherent anti-stokes Raman (CARS) microscopy

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High fidelity CARS imaging relays on powerful, synchronized picosecond pulses with defined frequency differences and narrow bandwidths. A new type of CARS laser source based on four-wave-mixing has been developed in the last couple of years, making all-fiber CARS sources a reality. In order to enhance the spectral resolution, these sources can be seeded by an external laser. This increases the contrast of the CARS signals allowing distinguishing between closely spaced resonances. Now, a FWM based fiber optical parametric oscillator (FOPO) has been developed to avoid external seeding while maintaining an excellent bandwidth for all wavelengths. The FOPO consists of an endlessly single-mode fiber for light conversion and a 275 m long polarization maintaining feedback fiber. Chromatic dispersion in the feedback fiber (33 ps/nm) leads to a temporal broadening of the initial FWM signal which exceeds the pulse duration of the pump light by a factor three. Only part of the spectral components of the signal pulse is overlapping with one of the following pump pulses, consequently, decreasing the bandwidth of the generated pulses. At 4 MHz an output power of 150 mW for the CARS pump and 200 mW for the Stokes signal with a bandwidth of <4 cm-1 has been achieved. At pulse durations of 30 ps for the Stokes and <30 ps for the CARS Pump a peak power of 1500 W and >800 W is obtained. The potential of the source has been demonstrated by imaging different Raman resonances to distinguish between multiple types of tissue.

8972-19, Session 5

A novel compact femtosecond Ti:sapphire laser with inherently synchronized high-power fiber amplifier for nonlinear microscopy

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For many biomedical imaging applications the light source is the key component that determines the performance and value of diagnosis. We present a multimodal nonlinear imaging platform based on a novel compact and cost effective high power single tapered diode laser pumped femtosecond Ti:sapphire laser with inherently synchronized high power Yb fiber amplification system. This device is capable of simultaneously acquiring nonlinear microscopy, such as multi-photon absorption fluorescence (2P, 3P), SHG and THG and CARS measurements based on the same microscope and simple laser with high spatial resolution at depths down to 400µm. Depth resolved morphological and molecular information based on intrinsic fluorophores, such as elastin, melanin, flavins and reduced nicotinamide denine dinucleotide in combination with SHG is significantly enhanced as compared to the performance of each individual technique alone. Additional labelfree functional, metabolic and molecular information can be achieved with a CARS add-on. Fast Fourier Transform (FT) CARS based on the Ti:sapphire laser allows for imaging of multiple Raman lines with complex structures in the fingerprint region with high resolution. In combination with an Yb fiber amplifier the system can be extended to a multiplex CARS system based on the same platform to achieve supplementary information in the lipid region to investigate simultaneously multiple Raman bands between 500 and 3500 cm-1 with the potential to identify subtle molecular changes in biological samples with ultrahigh spatial resolution. For additional large area screening and morphologic information our approach can easily be combined with OCT.

8972-20, Session 5

Synchronization of fiber laser with Ti:sapphire laser for multimodal nonlinear imaging

Mathieu Laliberté, Institut National de la Recherche Scientifique (Canada); Youngjae Kim, André Archambault, Alain Villeneuve, Genia Photonics Inc. (Canada); Charles Doillon, Univ. Laval (Canada); François Légaré, Institut National de la Recherche Scientifique (Canada)

Coherent anti-Stokes Raman Scattering (CARS) microscopy is a label-free imaging technique that is capable of real-time, non-pertubative examination of biological samples based on molecular vibrational spectroscopy with a sub-micron spatial resolution. CARS microscopy is often used with other nonlinear imaging techniques, such as 2-photon fluorescence (2PF) and second harmonic generation (SHG). These techniques are generally using a femtosecond laser to generate the images, in contrast with the picosecond optical parametric oscillator (OPO) used for CARS microscopy. Having both setups turns out to be expensive and hard to handle for non-experts. Considering that multimodality is the key to tissue imaging, we have in collaboration with Genia Photonics built a laser system for multimodal nonlinear microscopy, consisting of a femtosecond laser synchronized electronically with a picosecond fiber laser.

We developed two synchronization schemes: the Common Reference mode and the Clock Recovery mode. In the Common Reference mode, a highly stable primary clock reference source is fed to both the femtosecond laser and the fiber laser for synchronized operation. In the Clock Recovery mode, a fraction of the femtosecond laser output is fed into a clock recovery system that regenerates a low-jitter reference clock for the fiber laser which becomes 'slaved' to the femtosecond laser, thus achieving synchronization. In both cases, the phase difference between the two pulse trains is electronically adjustable.

Recent results show that this system offers superior stability to the system using two synchronized picosecond Ti-Sa oscillators, and equivalent to using picosecond parametric oscillator, in a user-friendly system for a fraction of the cost.

8972-21, Session 6

Compact, high-repetition rate OPCPA system for high harmonic generation

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A compact, high-repetition rate OPCPA system for the generation of CEP-stable few cycle pulses with 10 µJ of pulse energy is presented. The system is seeded from a commercially CEP-stabilized Ti:sapphire oscillator (VENTEON PULSE : ONE OPCPA SEED) delivering without any external spectral broadening an octave-spanning spectrum from 600-1200 nm. The spectrum serves on the one hand as broadband signal for the parametric amplification process and on the other hand as narrowband seed for an Ytterbium-based fiber preamplifier with subsequent main amplifier and frequency doubling. Broadband parametric amplification up to 17 µJ at 200 kHz repetition rate was achieved in two 5mm BBO crystals using non-collinear phase matching in the Poynting-vector-walk-off geometry with 27 µJ (first stage) and 44 µJ (second stage) of pump energy. Efficient pulse compression down to 6.3 fs using chirped mirrors leading to a peak power exceeding 800 MW. We observed after warm-up time a stability of < 0.5 % rms over 100 min. Drifts of the CE-phase in the parametric amplifier part could be compensated by a slow feedback to the set point of the oscillator phase lock. The CEP stability was measured to be smaller than < 80 mrad over 15 min (3 ms integration time). Furthermore the output spectra and energies could be well reproduced with the help of 2+1 dimensional nonlinear propagation simulations which give important insight for future repetition scaling of OPCPA systems.

The system is well-suited for high harmonic generation and first results for HHG in Argon will be presented.

8972-22, Session 6

UV-VIS enhanced supercontinuum source based on higher-order mode excitation for hyperspectral (fluorescence lifetime) imaging

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We report on a new source able to provide pulsed ps probe in the visible - UV range and the demonstration of applications to hyperspectral (fluorescence lifetime) imaging measurements. The source is able to generate UV and blue light exploiting high-order mode propagation in a microstructured fiber pumped by a Ti:Sapphire laser. We observed efficient visible-UV light generation when the pump wavelength is close to the zero-dispersion wavelength of the fiber first high-order mode and offset axial pumping is used. By tuning the pump wavelength and power level we were able to generate mW-power levels in the visible wavelength interval and of about hundreds of microwatt in the UV wavelength interval down to 300 nm. The pump alignment was very simple and very stable. We believe that further optimization of pump wavelength, fiber length and fiber zero-dispersion wavelength could generate light well below 300 nm using a simple and stable set-up and become a useful tool for biomedical imaging. This source can substitute and complement arrays of semiconductor laser and extend the applications of continuum sources to the UV range. We demonstrated its versatility using the source for hyperspectral FRET-FLIM measurements. The paper will first describe the source and afterward the mentioned application.

8972-23, Session 6

Powerful 67 fs Kerr-lens mode-locked Yb: KGW oscillator

Haitao Zhao, Arkady Major, Univ. of Manitoba (Canada)

In recent years Yb-ion doped gain media have been recognized as promising and cost-effective candidates to generate high power ultrashort pulses. As a pulse shaping mechanism, the semiconductor saturable absorber mirror (SESAM) based mode-locking (ML) has been routinely employed to deliver ultrashort pulses with high average output powers. However, the saturation and slow bleaching recovery dynamics of the SESAMs causes the onset of ML instabilities at high output powers due to the decreased discrimination against the continuum background. Introduction of a large amount of negative dispersion can prevent the instabilities at the expense of increased pulse duration. Hence there is a dilemma of obtaining both high average output power and keeping the pulse duration short. In contrast, the fast-saturable-absorber like action of Kerr-lens mode-locking (KLM) can offer larger modulation depths without introduction of additional losses, resulting in a dramatic reduction of pulse duration.

In this work we report on a powerful Kerr-lens mode-locked Yb:KGW oscillator. Unlike the traditional KLM oscillators, the loosely focused pump beam in the gain medium (~300 ?m) and a high output coupler transmittance (T=10%) ensured the generation of high average output power. With a careful optimization of the dispersion compensation, the laser delivered pulses with 67 fs duration at a repetition rate of 77 MHz.

The average output power reached 3 W which is, to the best of our knowledge, the highest power produced from the Yb-ion lasers at this level of pulse duration.

8972-24, Session 6

Industrial 300-fs, 300-µJ thin disk amplifier with >30W average power and efficient frequency conversion to green and UV

Martin Delaigue, Julien Pouysegur, Clemens Hönninger, Eric P. Mottay, Amplitude Systèmes (France)

Ultrashort pulse lasers with pulse duration around 300 fs can be advantageously applied in a variety of applications that rely on multiphoton processes, as e.g. glass cutting or other laser-matter interactions involving transparent media. Typically, rather complex chirped pulse amplification (CPA) schemes are applied to achieve femtosecond pulses at high energy. We have developed an innovative laser architecture that allows the generation of significantly shorter pulses then state-of-the-art CPA amplifiers and moreover can be realized in a robust and simple setup avoiding important temporal stretching and compression ratios. Moreover, we have demonstrated efficient frequency conversion of the laser output to the green and UV spectral region. These achievements will facilitate the penetration of such laser sources into large scale industrial environments.

The generation of the ultra-short pulse duration is enabled by an optimized management and exploitation of dispersive and nonlinear effects during the amplification process inside the regenerative amplifier cavity (Figure 1). Excellent spatial and temporal quality of the laser beam and the pulses are maintained.

Applying this amplification method to an Yb:YAG thin disk regenerative amplifier enabled the generation of pulses as short as 300-fs at high pulse energies of 300 µJ (Figure 2) and high average power exceeding 30 W. Frequency conversion of the amplifier output lead to 17.5W average output power at a wavelength of 515nm, and 8.5W at 343nm, respectively.

8972-25, Session 6

Industry-grade high average power femtosecond light source

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Ultrashort pulses are capable of processing practically any material with negligible heat affected zone. Typical pulse durations for industrial applications are situated in the low picosecond-regime. Pulse durations of 5 ps or below are a well established compromise between the electron-phonon interaction time of most materials and the need for pulses long enough to suppress detrimental effects such as nonlinear interaction with the ablated plasma plume. However, sub-picosecond pulses can further increase the ablation efficiency for certain materials, depending on the available average power, pulse energy and peak fluence.

Based on the well established TruMicro 5000 platform (first release in 2007, third generation in 2011) an Yb:YAG disk amplifier in combination with a broadband seed laser was used to scale the output power for industrial femtosecond-light sources: We report on a sub-picosecond amplifier that delivers a maximum of 160 W of average output power at pulse durations of 750 fs. Optimizing the system for maximum peak power allowed for pulse energies of 850 µJ at pulse durations of 650 fs. A further increase in peak power is straight forward by increasing the chirp of our seed pulses.

Based on this study and the approved design of the TruMicro 5000 product-series, industry-grade, high average power femtosecond-light sources are now available for 24/7 operation.

8972-26, Session 6

Femtosecond burst laser based on 100mJ Yb:CaF2 regenerative amplifier

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Several applications require bursts of pulses in the femtosecond regime, from micromachining applications to emission of electrons after interaction with a photocathode. Solutions already exist to produce multiple replicas from a single high energy pulse. Such solutions require additional alignment and sometimes additional active elements. Specific adjustments are also required when timing jitter is an issue.

We report a diode-pumped laser architecture that allows to produce bursts of up to 500ns macropulse duration, in the femtosecond regime. The lases source is based on a long-cavity regenerative amplifier based on Yb:CaF2 crystal, able to produce up to 100mJ pulse energy at 10Hz repetition rate.

When used in CPA architecture, the regenerative amplifier is seeded by a 43MHz femtosecond oscillator, with an additionnal pulse picker in order to adjust the number of pulses injected in the cavity. When injecting the maximum of pulses, the system allows to produce bursts of 19 pulses with 20mJ total compressed pulse energy with 550fs pulse duration. Reducing the number of pulses allows to improve the energy per pulse, and allows to provide a single pulse of 17mJ with 450fs, at a wavelength of 1047nm.

Interestingly, the delay between each pulse of the burst corresponds to the period of the seeding oscillator, which avoids additional adjustment when this consideration is of importance, as for photocathode applications.

8972-27, Session 7

The coherent artifact in modern pulse measurements *(Invited Paper)*

Michelle Rhodes, Georgia Institute of Technology (United States); Madhuri Mukhopadhyay, University of Arkansas (United States); Jonathan Birge, Lincoln Laboratory, Massachusetts Institute pf Technology (United States); Günter Steinmeyer, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany); Rick Trebino, Georgia Institute of Technology (United States)

All pulse-characterization techniques necessarily fail in multi-shot measurements of trains with pulse-shape instabilities. The measurement averages over different events and must provide a single result, despite the presence of many different events. Consequently, it is inherently impossible for an ultrashort-laser-pulse measurement technique to accurately describe a train of varying pulses in a multi-shot measurement. Therefore, in addition to yielding a reasonable representation of the typical pulse intensity and phase vs. time, a measurement technique should also provide an indication of the stability of the pulse train or otherwise indicate the reliability of its measurement.

The warning signs of instability are unknown for many pulse-measurement techniques currently in use. We therefore study the behavior of several interferometric pulse measurement techniques to understand their response to a train of varying pulses. The most common interferometric, self-referenced technique, spectral phase interferometry for direct electric-field reconstruction (SPIDER), has already been shown to measure only the coherent component of a train of pulses of varying shape. We perform similar analysis for a relative of SPIDER, two-dimensional spectral shearing interferometry (2DSI), and for self-referenced spectral interferometry (SRSI). Both of these techniques only measure the coherent artifact, similarly to SPIDER. 2DSI and SRSI also have background in their average measurements of unstable pulse trains, which could be an indicator of instability, but background caused by other effects remains to be analyzed. This result is consistent with the fact that information about phase variations is generally lost in interferometry.

8972-28, Session 7

Spatio-temporal characterization techniques of high-power femtosecond laser chains

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In many applications of high-power femtosecond lasers (particle acceleration, attosecond pulse generation…), one of the most important issues is to obtain the maximum intensity possible at focus. In such laser chains, because of misaligned or chromatic optics, the spatial and temporal pulse properties might be interlinked leading to a potential significant reduction of the laser peak power.

To diagnose the presence of these spatiotemporal couplings in femtosecond pulses, we first improved an already-existing technique called SEA TADPOLE which is based on spectrally-resolved spatial interferometry. In this setup, light is locally collected by two optical fibers, one of which scans the beam, while the other remains fixed. Unfortunately, because of phase fluctuations, the measurement of some spatiotemporal coupling such as pulse front tilt is impossible to achieve. To solve this problem, a second light source, so-called reference source, is used and allows measuring very precisely spatiotemporal couplings present in pulses delivered by a 100-TW laser chain.

However, a complete measurement with SEA TADPOLE is not immediate since the pulse needs to be scanned in 2D, which assumes a very good stability of the laser. This is why we implemented a new technique called MUFFIN, for MUltiple Fibers Frequency-resolved INterferomer, which allows measuring a pulse in a single shot. In this technique, many fibers (typically sixteen) are used instead of only two in SEA TADPOLE. Finally, we obtain a N-sources interferogram which can be analyzed by 2D Fourier transform to retrieve the phase and the amplitude of the pulse.

8972-29, Session 7

Plasma generation by ultrashort multi-chromatic pulses during nonlinear propagation

Jeremy R. Gulley, Jiexi Liao, Thomas E. Lanier, Kennesaw State Univ. (United States)

The use of femtosecond lasers in industrial, biomedical, and defense related applications during the last 15 years has necessitated a detailed understanding of pulse propagation coupled with ultrafast laser-material interactions. Current models of ultrashort pulse propagation in solids describe the pulse evolution of fields with broad spectra and are typically coupled to models of ionization and laser-plasma interaction that assume monochromatic laser fields. In this work we address some of the errors introduced by combining these inconsistent descriptions. In particular, we show that recently published experiments and simulations demonstrate how this contradiction can produce order-of-magnitude errors in calculating the ionization yield, and that this effect leads to altered dimensions and severity of optical breakdown and laser-induced modifications to dielectric solids. We introduce a comprehensive treatment of multi-chromatic non-equilibrium laser-material interaction in condensed matter and successfully couple this model to a unidirectional (frequency-resolved) pulse propagation equation for the field evolution. This approach, while more computationally intensive than the traditional single rate equation for the free electron density, reduces the number of adjustable phenomenological parameters typically used in current models. Our simulations results suggest that intentionally multi-chromatic fields (i.e. strongly chirped pulses or co-propagating pulses of different frequencies) can be arranged to control ionization yields and hence ultrafast laser induced material modifications.

8972-30, Session 7

Nonlinear shaping of ultrashort pulses in optical fibers under steady-state propagation conditions: triangular waveforms

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Ultrashort optical pulses of special waveforms are very important in a number of all-optical signal processing applications. For example, triangular pulses have found various applications in add-drop multiplexing, wavelength conversion, optical signal doubling, time-to-frequency mapping of multiplexed signals. In order to fulfill requirements of telecommunications, the compact fiber-based techniques for producing of special pulse waveforms from Gaussian or secant pulses delivered by modern ultrafast lasers are required. Recently it was shown that a combined action of self-phase modulation and normal dispersion in optical fiber could provide pulse reshaping towards triangular pulses from chirped Gaussian pulse. However, triangular pulse shape is achieved only within the narrow range of the fiber lengths, and during subsequent pulse propagation in a fiber the triangular pulse shape is destroyed. Here we propose another approach allowing preserve triangular waveform, and present analysis of nonlinear pulse reshaping in single-mode optical fibers depending on pulse and fiber features applying normalized parameters: soliton number, pulse chirp, normalized propagation distance. Simulations are made by solving nonlinear Schrödinger equation with addition of third-order dispersion using a split-step Fourier method. It was found that proper combination of initial parameters provides formation of stable triangular pulse in the fiber, which conserves its shape during subsequent propagation in fiber. It was found also that not only pulse is triangular, but also a spectral profile is nearly triangular due to the spectronic nature of the pulses formed in the steady-state regime.

8972-31, Session 8

Arbitrary integrated multimode interferometers for the elaboration of photonic qubits

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Roberto Osellame, Istituto di Fotonica e Nanotecnologie (Italy) and Politecnico di Milano (Italy)

Integrated photonic circuits with many input and output modes are essential in applications ranging from conventional optical telecommunication networks, to the elaboration of photonic qubits in the integrated quantum information framework. In particular, the latter field has been object in the recent years of an increasing interest: the compactness and phase stability of integrated waveguide circuits are enabling experiments unconceivable with bulk-optics set-ups.

Linear photonic devices for quantum information are based on quantum and classical interference effects: the desired circuit operation can be achieved only with tight fabrication control on both power repartition in splitting elements and phase retardance in the various paths.

Here we report on a novel three-dimensional circuit architecture, made possible by the unique capabilities of femtosecond laser waveguide writing, which enables us to realize integrated multimode devices implementing arbitrary linear transformations. Networks of cascaded directional couplers can be built with independent control on the splitting ratios and the phase shifts in each branch. In detail, we show an arbitrarily designed 5x5 integrated interferometer: characterization with one- and two-photon experiments confirms the accuracy of our fabrication technique. We exploit the fabricated circuit to implement a small instance of the boson-sampling experiments with up to three photons, which is one of the most promising approaches to realize phenomena hard to simulate with classical computers. We will further show how, by studying classical and quantum interference in many random multi-mode circuits, we may gain deeper insight into the bosonic coalescence phenomenon.

8972-32, Session 8

Writing polarization dependent and independent directional couplers in optical fiber with femtosecond lasers

Jason R. Grenier, Luis A. Fernandes, Peter R. Herman, Univ. of Toronto (Canada)

Femtosecond lasers offer the opportunity to develop new 3D integrated photonic devices in the core and cladding of single mode fibers, thereby extending the range of possible functions available on this compact and highly utilized platform. The present work extends the femtosecond laser writing technique to high numerical aperture lens focusing with oil immersion thereby eliminating the optical aberrations at the glass-air interface and confining the laser interaction more tightly for strongly confined waveguide modes with high birefringence. Low loss waveguides (0.65 dB/cm) formed with the second harmonic (522 nm) of a high repetition rate (500 kHz) femtosecond laser writing system were applied to form S-bend, cross, and directional couplers for connecting the light in the core waveguide with optical circuits written into the fiber cladding. Couplers with up to 97% coupling efficiency and broadband (70 nm) 3 dB splitters are presented at 1550 nm wavelength. Real-time monitoring of directional coupler splitting ratio as a function of the coupling length revealed a periodic beating of the polarization dependent coupling ratio, resulting from the laser-induced waveguide birefringence. This birefringent coupling was harnessed to develop in-fiber polarization splitters, polarization selective taps with 3 dB bandwidth of 100 nm in SMF as well as polarization beam splitters with an extinction ratio of 13 dB in coreless fiber. This polarization dependent coupling, together with birefringence tuning (~ 4?10^{?6} to 2?10^{?3}) stress tracks, lay a solid grounding of polarization dependent analyzers for in-fiber polarimeters and polarization sensitive optical circuits for phase-shift keying in optical communication and applications in quantum optics.

8972-33, Session 8

Integrated optical waveplates fabricated by femtosecond laser micromachining

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The application of integrated photonic technologies to quantum optics has recently enabled a wealth of breakthrough experiments in several quantum information areas. In particular, femtosecond laser written optical circuits revealed to be the ideal tool for investigating the features of polarisation encoded qubits. However, the difficulty of integrating half and quarter wave plates in such circuits avoids the possibility to perform arbitrary rotations of the polarisation state of photons on chip.

Femtosecond laser written waveguides intrinsically exhibit a certain degree of birefringence and thus they could be exploited as waveplates. In practice, the direction of the birefringence axes of the waveguides is the same of the propagation direction of the writing femtosecond laser beam, namely perpendicular to the substrate surface. Its fine rotation in a controlled fashion, preserving the accuracy of the positioning of the laser focal spot required by the fabrication process, is extremely challenging. In order to achieve this goal, we combine a high NA (1.4) focusing objective partially filled with a reduced diameter writing beam. In this way, the translation of the beam with respect to the objective center produces a rotation of the focusing direction, without altering the focal spot position. With this method we are able to tilt the birefringence axes of the waveguides up to 35°, and thus to use them as integrated light polarisation rotators. In order to demonstrate the effectiveness of these components, we developed a fully integrated device capable to perform the quantum tomography of an arbitrary two-photon polarisation state.

8972-34, Session 8

Morphological evolution of nanopores and cracks as fundamental components of ultrashort pulse laser-induced nanogratings

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I would like to participate in the student competition.

Ultrashort pulse-induced nanogratings have gained significant interest in recent years. These self-organized structures appearing after several laser pulses show strong form-birefringence which allows, by combination with the three-dimensional freedom of the direct laser writing technique, to fabricate versatile functionalities.

However, the underlying structure has been the subject of intensive debate since the discovery of the nanogratings. In order to uncover the primary constituents of nanogratings typical visualisation techniques (e.g. SEM) rely on cleaving and subsequent etching of laser treated samples. Thus fine details are effectively erased by such invasive preparation methods.

Recent investigations based on exclusively cleaved samples report on hollow cracks embedded within the bulk material. However, these time-consuming imaging methods only provide two-dimensional cross sections and can hardly address the evolution of cracks depending on various laser parameters.

To overcome these limitations we performed a comprehensive study of nanopores and cracks using small-angle x-ray scattering (SAXS) in combination with focussed ion beam milling (FIB) and scanning electron microscopy (SEM).

By probing nanogratings inscribed in the bulk of fused silica reveal that nanopores with dimensions of (29x24)nm and (284x24)nm are formed. While the dimensions remain constant with ongoing laser exposure and different pulse energies the nanopore shape changes from cuboid cracks to ellipsoidal structures.

8972-35, Session 8

Direct-write diffracting tubular optical components using femtosecond lasers

Ben W. McMillen, Yves Bellouard, Technische Univ. Eindhoven (Netherlands)

Over the last decade, femtosecond lasers have been used extensively for the fabrication of optical elements via direct writing and in combination with chemical etching. These processes have been an enabling technology for manufacturing a variety components such as such as waveguides, fluidic channels, and mechanical components.

Here, we present high quality microscale optical components buried inside various glass substrates such as soda-lime glass or fused silica. These components consist of high-precision, simple patterns with tubular shapes. Typical diameters range from a few microns to one hundred microns. With the aid of high-bandwidth, high acceleration flexure stages we achieve highly symmetric pattern geometries, which are particularly important for achieving homogeneous stress distribution within the substrate.

We model the optical properties of these structures using beam propagation simulation techniques and experimentally demonstrate that such components can be used as cost-effective, low-numerical aperture lenses. Additionally, we demonstrate their capability for studying the stress-distribution induced by the laser-affected zones and possible related densification effects.

Finally, we demonstrate a polarization dependence of these lenses in fused silica and explore potential applications for low-cost polarization sensors.

8972-36, Session 8

Temperature-compensated fiber-optic 3D shape sensor based on femtosecond laser direct-written Bragg grating waveguides

Kenneth K. C. Lee, Univ. of Toronto (Canada); Adrian Mariampillai, 7D Surgical Inc. (Canada); Moez Haque, Univ. of Toronto (Canada); Beau A. Standish, Victor X. D. Yang, Ryerson Univ. (Canada); Peter R. Herman, Univ. of Toronto (Canada)

Fiber Bragg gratings (FBGs) are invaluable optical devices in optical communication, sensing, and fiber laser applications. In conventional strain gauging, Bragg gratings that are photo-inscribed into a single-mode optical fiber (SMF) must be securely bonded to or embedded in a host structure, which under flexure, will strain along the neutral axis of the optical fiber to create a measurable shift in the Bragg wavelength. In contrast, such FBGs cannot be readily applied in shape sensing and accelerometers, where strain cannot be induced along the neutral fiber core axis in a freestanding configuration. While shape sensing has been reported when Bragg gratings were formed inside multicore optical fibers (MCF), simultaneous interrogation of the multiple waveguides remains a major packaging challenge in this approach. Hence, femtosecond laser writing of 3D optical circuits directly in a standard optical fiber offers a unique solution to make freestanding fiber sensor devices.

We demonstrate temperature-compensated 3D fiber shape sensing with axially and radially distributed Bragg grating waveguides inside a single coreless optical fiber. An optical circuit with multiple optical components was precisely laser-written with an oil immersion objective lens in a single exposure step while being tuned with a real-time characterization system. A laser-written 1?3 directional coupler enabled efficient light coupling between the optical circuit and a SMF. Hence, simultaneous interrogation of nine Bragg gratings is presented through a single waveguide port at 1 kHz sampling rate, permitting real-time shape and temperature profile sensing along the fiber length. The fiber-optic shape sensor was inserted into a biomedical catheter in a pre-clinical animal trial to determine the catheter's 3D orientation in vivo in real-time with the objective to minimize X-ray dosage in minimally invasive surgical procedures.

8972-37, Session 8

On the use femtosecond laser for ultra-high accuracy alignment and positioning of optical elements: toward new concepts for optical device integration and packaging

Yves Bellouard, Technische Univ. Eindhoven (Netherlands)

Packaging and permanent alignment in particular are some of the major challenges for miniaturizing photonics devices due to commonly high accuracy requirements. In optical systems, sub-micron to tens of nanometers accuracy are usual assembly specifications for achieving high performances, even for simple systems with few elements.

On the other hand, femtosecond laser pulses below ablation threshold induce localized and confined volume variation in glass materials. As demonstrated recently, this volume expansion and its dependence on pulse energy and writing conditions can be accurately quantified (for instance using the deflection of micro-cantilevers which top surfaces is exposed to the laser beam or using optical based techniques to measure stress-induced birefringence).

Here we show that this precise laser-induced volume changes can be used to accurately distribute stress and deformations in substrates in order to achieve fine and permanent positioning of optical elements attached to it.

In particular, we demonstrate the working principle by repositioning spatially a tiny optical element along various axis, thanks to the combination of laser induced volume expansion and specific kinematics that channels displacements along dedicated and well-defined degrees-of-freedom. This concept can be extended to 'smart' substrates were components attached to it (or embedded in it) are fine positioned to compensate for intrinsic and unavoidable inaccuracy resulting from bonding or other manufacturing issues. This method can be further used to achieve increased level of integration and has the potential to achieve unprecedented level of permanent optical alignment.

8972-38, Session 9

Towards a more complete understanding of laser ablation *(Invited Paper)*

Heinz P. Huber, Matthias Domke, Regina Moser, Stephan Rapp, Juergen Sotrop, Munich Univ. of Applied Science (Germany)

Pulsed laser material processing by laser ablation is based on the electronic absorption of laser energy within a defined absorption length, heat generation in the lattice and the subsequent heat transport within a defined diffusion length. Finally phase transitions are leading to material removal.

For a deeper understanding of “direct” and “confined” laser ablation with ns-, ps-, and fs-pulsed lasers, the transient states of matter from the femtosecond to the microsecond range are explored with a combination of pump-probe microscopy and numerical simulations. With these techniques the role of shock waves is revealed, which are generated on an ultrafast time scale, leading to material removal in the nanosecond range.

Material removal by laser ablation with nanosecond pulses at the threshold is mainly taking place in the liquid phase. The ablation, however, is connected with thermal damages, such as burr and micro cracks in the dimension of the thermal diffusion length, which limits precision to a few µm.

For pulse durations in the ps- and fs-range, the optical and thermal diffusion lengths are in the order of a few of 10 nm - a steep increase of temperature and pressure is the consequence. Material removal by “direct” laser ablation at the threshold mainly takes place in the gas phase, leading to lower ablation efficiency than in the nanosecond case. For thin-film systems, however, the energy can be confined between transparent and absorbing layers. A propagating shock wave is leading to a thermo-mechanical material removal by “confined” laser ablation. In this case, the ablation efficiency is even below the thermodynamic limit for melting and ultrafast lasers are even more efficient than nanosecond lasers, while thermal damages can be completely avoided.

8972-39, Session 9

Micro-patterning of self-assembled organic monolayers by using tunable ultrafast laser pulses

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We study the application of NOPA in self- assembled organic monolayer (SAMs) micro-patterning. SAMs are ultra- thin organic monolayers which can be used in a variety of ways to assemble functionalized surface structures. In our study, we investigate the characteristics of SAMs as monomolecular resists during etching of gold. Non collinear optical parametric amplification (NOPA) is a versatile method which provides the generation of ultrafast laser pulses, with a tunable wavelength in the visible and near infrared range. Due to the non-collinear geometry, a broadened spectral range can be amplified. The NOPA delivers wavelengths in the range of 480nm to 950nm with sub- 30 femtosecond laser pulses by using a prism compressor after the nonlinear conversion. The ultrashort laser technology together with the advantages of the NOPA system guarantee high precision and allow to determine the optimum conditions of sub- wavelength patterning by studying the effects of the fluence and the wavelength. At the same time, single-pulse processing allows us to selectively remove the ultrathin organic coating, while it ensures short processing time. In our study we used thiol based SAMs as ultrathin layers on gold substrate with a thickness of 1-2nm and 40nm respectively.

8972-40, Session 9

Comparison of different processes for separation of glass and crystals using ultra short pulsed lasers

Malte Kumkar, TRUMPF Laser- und Systemtechnik GmbH (Germany); Lara Bauer, Simone Russ, TRUMPF Laser GmbH & Co. KG (Germany); Myriam Wendel, Jonas Kleiner, TRUMPF GmbH & Co. KG (Germany); Klaus Bergner, Stefan Nolte, Friedrich-Schiller-Univ. Jena (Germany)

We compare different methods for cutting brittle transparent materials applying ultra short pulsed solid state lasers. Pros and cons of these methods will be discussed for introduction.

Experiments were carried out by varying pulse duration, arrangement of pulse groups, repetition rate, focusing condition, wavelength and processing speed; examples are given for the influence on the selected processes.

We will present cross sections of laser induced ablation and modification. Additional information on the spatiotemporal absorption profiles inside the transparent material from pump probe measurements supports a fundamental understanding about relevant effects like nonlinear absorption, self focusing, incubation and accumulation. Even if it turns out that there exists a complex interplay of diverse effects, we can show that there exist some options to tailor absorption and energy deposition in space and time for different cutting applications of these transparent materials.

This allows discussing parameter windows for the individual cutting processes like ablation cutting, scribe & break and in volume modification for cleaving or selective laser etching.

Cutting results achieved by using an experimental processing station demonstrate the potential of ultra short pulsed laser processing. Especially the efficient and high quality cutting of brittle transparent materials, like strengthened and non strengthened glass for displays and sapphire, are presented in detail. The results are summarized in an updated valuation chart for the cutting processes analyzed, intended as a basis for discussion and extension.

8972-41, Session 9

Microscopic investigation on the ultrafast laser cutting of chemically strengthened glass

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Ultrafast laser cutting of chemically strengthened glass has drawn much attention from mobile display manufacturers as this approach promises innovative breakthroughs such as less chipping, arbitrarily curvy cutting lines, and reduction of post processes. The trend for mobile devices is moving fast toward ultrathin and lightweight platforms without losing robustness, thus the cover glass for those devices must be thinner and flawlessly cut. Recently the Dept. of laser and ebeam application at Korea institute of machinery and materials (KIMM) and L2K Co. Ltd. has been cooperating to develop a laser cutting technology involving ultrafast lasers. Superior quality of cut surfaces of strengthened glass was already demonstrated via femtosecond laser cutting. In this talk, we will focus on the demonstration of the physical and chemical analyses of the microstructural changes induced by femtosecond laser pulses enabling such high edge quality. We expect that there is a process window enhancing certain structural changes. These changes may not result in ablation, but cause physical phase change leading to sharp fissure at irradiated region. Microscopic analyses such as spectroscopy and X-ray diffraction has been performed to investigate the origin of the structural changes.

8972-42, Session 9

Rapid microfabrication of transparent materials using a filamented beam of the IR femtosecond laser

Simas Butkus, Domas Paipulas, Zydrunas Viburys, Aleksandr Alesenkov, Eugenijus Gaizauskas, Dalia Kaskelyte, Martynas Barkauskas, Valdas Sirutkaitis, Vilnius Univ. (Lithuania)

A great number of articles have been published on glass drilling and welding applications, however, such systems typically employ high NA focusing conditions, low repetition rate lasers and complex fast motion translation stages. Due to the sensitivity of such systems, slight instabilities in parameter values can lead to crack formations, severe fabrication rate decrement and poor quality overall results. A microfabrication system lacking the stated disadvantages was constructed and showed in this report. An f-theta lens was used in combination with a galvanometric scanner, an additional water pumping system that enables formation of water films of variable thickness in real time on the samples. Water acts as a medium for filamentation, which in turn decreases the focal spot diameter and increases fluence. This article demonstrates the application of a femtosecond (280fs) laser towards two different micromachining techniques: rapid cutting and welding of transparent materials. Filament formation in water give rise to strong ablation at the surface of the sample, moreover, the water, surrounding the ablated area, adds increased cooling and protection from cracking capabilities. The constructed microfabrication system yielded 2 mm wide, 1 mm thick holes drilled in soda-lime glass in 40 seconds, the shape of these holes can be altered by varying the thickness of the water film. Moreover, complex-shape fabrication was demonstrated. Filament formation at the interface of two glass samples was also used for welding applications. By varying repetition rate, scanning speed, focal position optimal conditions for strong glass welding via filamentation were determined.

8972-43, Session 10

Contrasting femtosecond laser-written Fabry-Perot resonators, Mach-Zehnder-type interferometers and micro-cavity arrays for lab-in-fiber (LIF) sensing

Moez Haque, Yiwen Shen, Kenneth K. C. Lee, Peter R. Herman, Univ. of Toronto (Canada)

The formation of nanogratings during femtosecond laser processing of fused silica has opened new possibilities for highly selective chemical etching that is now being exploited to form novel 2D and 3D optofluidic lab-on-chip (LOC) devices. The pure fused silica cladding found in most types of standard, multicore and photonic crystal fiber presents an ideal material platform on which to bring microfluidic, optical and structural components into even more compact size scales by wrapping components around the guiding core waveguide of such fibers and thus define new lab-in-fiber (LIF) sensors. LIFs promise to preserve favorable biocompatibility, resist chemical erosion, harness fiber flexibility, and naturally facilitate intimate optical interrogation of microfluidic and micro-reactor components with integrated sources and diagnostics.

In this paper, laser-formed waveguides and micro-optical resonators were embedded within optical fiber using femtosecond direct-laser-writing with subsequent chemical etching. Resonators fabricated within single mode fiber (SMF) provided rapid probing capabilities through the existing SMF core that readily linked to sources, filters and spectrometers, while coreless fiber fusion spliced to SMF further introduced facile 3D positioning of laser-formed waveguides and microfluidic networks. Optimized laser exposures exploited nanograting alignment with the resonator sidewalls to provide smooth 12 nm rms surface quality that yielded optical quality interfaces and near-theoretical insertion losses and fringe contrasts for an embedded inline Fabry-Perot (FP) resonator. Inline Mach-Zehnder-type interferometers (MZIs) were then shown to improve fringe contrast and refractometer sensitivity by 2? and 10?, respectively, relative to the inline FP to offer new opportunities in photonic temperature, strain, pressure and refractive index sensing. Finally, inline micro-cavity arrays (MCAs) were shown to dramatically increase fringe contrast and bandwidth relative to FPs that open new prospects for inline stop- and pass-band optical filters. Inline FP, MZI and MCA properties will be contrasted for sensing efficacy with emphasis on device insertion loss, fringe contrast and sensitivity.

8972-44, Session 10

Ultrafast laser-assisted local energy deposition in bulk silicon

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The laser-induced, 3-D structural modification of materials has been revealed to be a prominent tool for fabrication of optical components. Until present, applications may be found in the case of dielectric materials (e.g. fused silica) but not in the case of semiconductors as their intrinsic properties (low bandgap, low-order nonlinearities, aberrations etc.) prevent efficient energy deposition in the bulk.

We highlight these aspects by using a long wavelength beam (1.3 µm) to penetrate in the volume avoiding linear absorption on the surface and tight focusing to confine energy. The short pulse durations used (40 fs) ensure relatively high-intensities resulting in nonlinear absorption only in the focal region. We measure the absorption of this beam as a function of different parameters (energy, sample depth, doping) to account for the total energy deposition in the solid. No modification is observed in this case.

8972-45, Session 11

Simultaneous spatially and temporally focusing light for tailored ultrafast micro-machining

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Simultaneously spatially and temporally focussing (SSTF) of ultrashort pulses allows for an unprecedented control of the intensity distribution of light. It has therefore a great potential for widespread applications ranging from nonlinear microscopy, ophthalmology to micro-machining. SSTF also allows to overcome many bottlenecks of ultrashort pulse micro-machining, especially non-linear effects like filamentation and self-focussing. Here, we describe and demonstrate in detail how SSTF offers an additional degree of freedom for shaping the focal volume.

In order to obtain a SSTF beam, the output of an ultrafast laser is usually split by a grating into an array of copies of the original beam, which we refer to as beamlets. The ratio of the beamlet array width to the width of the invidual beamlet is the beam aspect ratio. The focal volume of the SSTF beam can now be tailored transversally by shaping the cross-section of the beamlets and axially by choosing the right beam aspect ratio.

We will discuss the requirements of the setup for a successful implementation of this approach: Firstly, the group velocity dispersion and the third order dispersion have to be compensated in order to obtain

a high axial confinement. Secondly, the beamlet size and their orientation should not vary too much spectrally. Thirdly, beamlet and SSTF focus should match. We will hence demonstrate how SSTF allows to inscribe tailored three-dimensional structures with fine control over their aspect ratio. We also show how the SSTF focus can be adapted for various glasses and crystals.

8972-46, Session 11

In situ spectral phase characterization of simultaneous spatially and temporally focused pulses

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Simultaneous spatial and temporal focusing (SSTF) of femtosecond pulses has been shown to be useful in micromachining to deliver high energy, ultrafast pulses to a focal plane without incurring nonlinear material damage or beam distortion. Though the optical components used to create these beams are common, the alignment of them (gratings and focusing optics in particular) is critically important to obtain the optimum localization of intensity. Here we present a single-pulse, in situ method to characterize residual compressor spectral phase in a relatively simple way. The technique makes use of the evolution of the second order spectral phase of the angularly spatially chirped pulse through the focus [1]. As a thin doubling crystal is translated along the optical axis, the evolution peak of the second harmonic (SH) spectrum traces out the second derivative of the spectral phase of the pulse. In principle this is similar to multiphoton intrapulse interference phase scan (MIIPS) [2], but does not require a pulse shaper and produces data that can be interpreted intuitively without deconvolution. In our experiment, a spatially chirped beam from a single pass grating compressor was focused with an off-axis parabolic mirror (f=326 mm, 30 deg) into 100?m thick KDP crystal which was scanned through the confocal parameter, producing an intensity plot of SH vs axial position (second order phase). We will also present characterization techniques to ensure optimum overlap of the Gaussian and wavelength crossing focal planes. Together these techniques allow the optimization of the SSTF focal intensity and axial localization.

1. C. G. Durfee et al, “Intuitive analysis of space-time focusing with double-ABCD calculation,” Optics Express 20, 14244 (2012).

2.Xu, Bingwei, et al. “Quantitative investigation of the multiphoton intrapulse interference phase scan method for simultaneous phase measurement and compensation of femtosecond laser pulses.” JOSA B 23, 750 (2006).

8972-47, Session 11

A brief analysis on pulse front tilt in simultaneous spatial and temporal focusing

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When focusing ultrashort pulses with simultaneous spatial and temporal focusing (SSTF), the pulse front tilt (PFT) effect appears. It could be a potentially useful effect in laser material processing, e.g., in ”quill” writing, while sometimes it is undesired. This article provides paraxial analysis of it with the help of Collins integral. First we explain the origin of PFT. Then based on Gaussian approach we analyze the pulse evolution in focus and also near focus and especially we included the influence of an initial PFT. After that, rigorous simulations are also preformed accordingly. Our aim is to find a way to shape the pulse in both spatial and temporal domain.

8972-48, Session 12

Monolithic hybrid optics for focusing ultrashort laser pulses

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Almost any application of ultrashort laser pulses involves focusing them in order to reach high intensities and/or small spot sizes as needed for micro-machining or Femto-LASIK. Hence, it is indispensable to be able to understand pulse front distortion caused by real world optics. Focusing causes pulse front distortion due to aberrations, dispersion and diffraction. Thus, the spatio-temporal profile of ultrashort laser is altered, which increases automatically the pulse duration and the focusing spot. Consequently, the main advantage of having ultrashort laser pulses – pulse durations way below 100fs - can be lost in that one last step of the experimental set-up by focusing them unfavorable. Since compensating for dispersion, aberration and diffraction effects is quite complicated and not always possible, we pursue a different approach.

We present a specially designed monolithic hybrid optics comprising refraction and diffraction effects for tight spatial and temporal focusing of ultrashort laser pulses. Both aims can be put into practice by having a high numerical aperture (NA=0.3) and low internal dispersion at the same time. We are presenting what we believe is the first experimental realization of such a monolithic hybrid focusing optics for ultrashort laser pulses. The focusing properties are very promising, due to a design, which provides diffraction limited focusing for 100nm bandwidth at 780nm center wavelength. Thus, pulses with durations as short as 10fs can be focused without pulse front distortion. The outstanding performance of this optics is shown in theory and experimentally.

8972-49, Session 13

Ultrashort pulse lasers for precise processing: overview on a current German research initiative *(Invited Paper)*

Stefan Nolte, Friedrich-Schiller-Univ. Jena (Germany)

Ultrashort laser pulses provide a powerful means of processing a wide variety of materials with highest precision and minimal damage. In order to exploit the full potential of this technology, the German Federal Ministry of Education and Research has launched a 20 Million EUR initiative about two years ago. Within 9 joint research projects, different aspects from novel concepts for robust and powerful laser sources to reliable components with high damage thresholds and dynamic beam shaping and steering are investigated. Applications include eye surgery as well as the processing of semiconductors, carbon fiber reinforced plastics and metals. The presentation will give an overview on the different projects and highlight first results.

8972-50, Session 13

Trepanning drilling of stainless steel using a high-power Ytterbium-doped fiber ultrafast laser: influence of pulse duration on hole geometry and processing quality

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Percussion drilling is a well-established technique for several applicative markets such as for aircraft and watch industries. Lamp pumped solid state lasers and more recently fiber lasers, operating in millisecond or nanosecond regimes, are classically used for these applications. Unfortunately, long and short pulses introduce some detrimental effect

such as heat affected zone, recast layer, uneven shape and sidewall roughness. Furthermore, percussion drilling is not suitable to achieve high aspect ratio (10:1) and custom-shape holes which are required for automotive industry for instance. In this context, we present some results on the influence of pulse duration on gas-assisted laser drilling of stainless steel using a trepanning head and a high power Ytterbium doped fiber ultrafast laser (20W). The influence of pulse energy (10-80µJ), repetition rate (250kHz-2MHz), beam angle and aperture, gas pressure and drilling protocol will be discussed as well.

8972-51, Session 13

High-precision micro-machining with ultraviolet wavelength picosecond lasers

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The demand to reduce the size, weight and material cost of modern electronic devices has created a requirement for high precision micromachining to aid new product development. Laser processing offers a route to achieving this, however, the thermal damage due to the laser pulse duration sets a limit on the process quality, especially in thin (<100µm), sensitive materials. The unique advantages of ten picosecond pulse duration and ultraviolet wavelength are here shown to be advantageous for machining transparent, polymer materials such as bio-absorbable tubes for medical applications and clean cutting/patterning of sensitive materials and thin films. The high repetition rate of 1MHz allows industrial throughput targets to be met. Another growing application area is picosecond laser machining of hard steel to reduce friction wear and increase fuel efficiency in automotive engines. The high repetition rate of 1MHz and excellent beam quality/pointing allow the surface quality and throughput targets to be met in industrial environments.

8972-52, Session 13

Determination of the AISI 1045 steel ablation threshold dependence on the pulse superposition using the Diagonal Scan (D-Scan) technique

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AISI 1045 carbon steel is a common engineering material that presents a well-defined temperature dependent phase transition, making it a good probe to study heating effects under laser etching. The ablation by ultrashort laser pulses can minimize thermal effects by removing material by direct sublimation, but melting will occur if the pulse energy is excessive. In order to avoid modifications of the material properties by this process, it is important to use the correct parameters when machining this steel with ultrashort pulses. The setting of these parameters (sample translating speed, laser repetition rate, pulse energy) involves knowing the material ablation threshold for different pulses superpositions. The determination of the ablation threshold by the traditional method can take a long time for a single superposition, and its repetition for many pulses overlapping conditions can take days, or even weeks. We report here the use of the Diagonal Scan (D-Scan) technique to quickly measure the 25 fs pulses ablation threshold of the AISI 1045 steel for superpositions ranging from single shot up to more than 10,000 pulses. It only took two hours of laboratory time to determine more than 20 ablation thresholds spanning 4 orders of magnitude of superpositions, and the results clearly exhibit the ablation threshold dependence on the pulses superposition and the influence of the incubation effects. The large amount of data generated shows a small deviation of the ablation threshold from the expected behavior, which can lead to the use of a model that better describes the dynamics of the ultrashort pulses ablation mechanism in metals.

8972-53, Session PTue

Optimizing plasmonic transfection using nanostructured substrates

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Gene therapy is the use of DNA as an agent to cure or slow down the progression of a disease. A crucial requirement for gene therapy is the efficient and safe introduction of genetic vectors into mammalian cells. We developed a high-efficiency, low-toxicity, spatially-selective and high-throughput transfection method using fs laser induced-plasmons on a nanostructured substrate.

We specifically compare two designs of plasmonic substrates (whole pyramid arrays and tipless pyramid arrays) using FDTD simulations and two-photon experiments. We then explore the laser parameter space to optimize large scale transfection using selected nanostrucred substrates.

8972-54, Session PTue

Surface nanostructure formation on biodegradable polymer film by femtosecond laser irradiation

Shuhei Yada, Hisashi Shimizu, Go Obara, Mitsuhiro Terakawa, Keio Univ. (Japan)

Recently, biodegradable polymers for biomedical applications have attracted considerable interest owing to its high biocompatibility, strength and processability. Some reports have shown that nanostructure formation on biodegradable polymer surfaces improves adhesive and anisotropic properties of cells. However, existing surface processing methods of biodegradable polymers such as photolithography or wet etching are complicated, unable to process after molding, and problematic if chemical components harmful to cells remain on material surfaces. We focused on laser induced periodic surface structures (LIPSS), which can be formed after molding without using chemical components. Some papers have demonstrated that LIPSS formed on metal surface improves cell adhesion. In this study, we demonstrate LIPSS formation on Poly-L-lactic Acid (PLLA) film, a typical- and widely used biodegradable polymer. LIPSS was observed under the condition of 1000 shots of 80-fs laser pulses at the laser fluence of 0.3 J/cm2. The single-shot ablation threshold of PLLA was estimated as a fluence of 3.52 J/cm2. The thermal effect may be relatively large and thus LIPSS is unlikely formed due to the thermal properties of PLLA (the melting point temperature (Tm) 180°C, the glass transition temperature (Tg) 55-60°C). The biodegradability properties of LIPSS formed on PLLA film will be discussed.

8972-55, Session PTue

Laser drilling of carbon fiber reinforced plastics (CFRP) by picosecond laser pulses: comparative study of different drilling tools

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Carbon fiber reinforced plastic (CFRP) as a lightweight material with superior properties is increasingly being used in industrial manufacturing. Thermal damage of CFRP composites is one of the major issues when these materials are laser machined. Using ultrashort laser pulses can

improve the quality in cutting or drilling applications. At high power levels, which are necessary for high throughput, it is more complicated to maintain the accuracy and precision in CFRP drilling, due to heat accumulation and as a consequence degradation of the matrix. That is why we report on the application of picosecond laser pulses and different beam delivery systems to drilling processes of CFRP. Scanner head, trepanning head and diffraktive optical elements (DOE) have been used as drilling tools in order to evaluate the laser drilling process by picoseconds pulses in terms of geometric precision and economical feasibility.

The use of scanner technology for beam deflection is surely the most flexible drilling setup. In drilling processes of millimeter thick CFRP losses caused by the beam propagation and reflection can be compensated by optimized process sequences in order to get a minimal negative taper as small as 1.5 degree. The corresponding hole geometries are analyzed in detail by microtomography scans, that reveals the 3D-shape of the bore holes, rounded laser entrance edges and minimal thermal damages inside the bulk of the CFRP material. These results are compared with laser drilling tests using a trepanning head, which usually enables the drilling of cylindrical bore holes. Finally, the use of diffrative optical elements (DOE) will be investigated to show both their ability and limitations to transform intensity distributions in order to utilize high power picoseconds lasers in CFRP drilling.

8972-56, Session PTue

Ultrafast laser micromachining of fine structures for mobile display panels

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Advanced mobile display manufacturing including TFT LCDs and AMOLEDs consists of numbers of complicated processes in order to meet the desired specifications for high-end products such as full HD resolution, defect-free, and long lifetime. However, these processes are too sophisticated thus production yields are not 100%. In this notion, appropriate post-processes should be developed to increase the overall production yield. Selective removal, drilling, cutting, and micro-patterning of multi-layers on display panels are the main tasks of the post-processing. These post-processes are all available with ultrafast laser micromachining. In addition, the trend of mobile device platforms is moving towards transparent, flexible form of electronics to provide wearable IT solution. Ultrafast laser-based micromachining is one of the candidates to provide adaptive solutions which are viable for mass production. In this talk, we will present the latest results of ultrafast laser micromachining of various display panels in rigid or flexible forms. The main task includes the selective removal of a single layer without damaging the substrate materials such as flexible polymers and glasses. The ultimate goal of the investigation is to suggest a feasible route for manufacturing via ultrafast lasers by providing an optimized micromachining process involving a state-of-the-art compact ultrafast laser and novel optical means.

8972-57, Session PTue

Surface blackening by laser texturing with high repetition rate femtosecond laser up to 1MHz

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The interaction between laser pulses and surface material can generate sub-wavelength surface structures named ripples. The used of ultrashort laser pulses avoid thermal effect in the lattice so the structures generated are well preserved and can be observed on various materials as metals, polymers or crystals. With increasing energy deposit, ripples grow to give cone-shape structures named spikes. All these structures are interesting to give special properties to the treated surface as coloration change, improvement of light absorption or modification of wettability properties.

These structures generations are well known for femtosecond Ti:Sa laser with a pulse duration below 100fs but to be relevant for industrial application, the average power of the laser is a critical parameter. The emergence of new femtosecond Yb doped fiber laser with pulse duration below 350fs permit an increase of the average power since few years. We will present our latest results obtained for LIPPS generation on various metals as stainless steel, titanium, aluminum and copper with these up to date laser source. We study the influence of the average power up to 14W and of the repetition rate from 100 to 1000 kHz on the surface texturation generated on scanned zones. We obtain light emission below 7% on stainless steel and below 5% on titanium from 200nm to 2000nm. The characterizations of the results are done with SEM imaging and with a spectrophotometer.

8972-60, Session PTue

Combination of thermal extrusion printing and ultrafast laser fabrication for the manufacturing of 3D composite scaffolds

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We present direct laser fabrication of three-dimensional (3D) microstructured scaffoldings consisting of a few polymeric materials with different biological properties. Direct laser writing in photo/thermo-sensitive materials using ultrashort (< 10 ps) light pulses of high repetition laser (> 100 kHz) provides unmatched flexibility in controllable 3D micro/nano-structuring of a variety of biocompatible materials. This is attractive for creating artificial extracellular matrix to mimic or alter natural surroundings for the cells. The manufacturing throughput empowers overall structure size of up to 1 cm3 to be produced overnight, making it an attractive method to fabricate scaffoldings for cell studies and tissue engineering applications [1]. In this paper we present successfully manufactured 3D microporous multicomponent polymer scaffoldings out of different organic-inorganic substances [2]. Such composite constructions offer several biological functionalities including biostability or biodegradation (depending on the material used) as well as the possibility to micro/nanopattern the surface with various bioactive materials such as proteins, all spatially distributed within a structure with 1 - 10 µm features. The potential of this approach is applicable for cell adhesion, migration, proliferation and differentiation mechanism study in 3D as well as suggesting the answer for best material and architecture combinations for scaffolding needed in tissue engineering and regenerative medicine applications.

[1] M. Malinauskas et al., Ultrafast-laser micro/nano-structuring of photopolymers: a decade of advances, Phys. Rep., accepted (2013).

[2] S. Rek?tyt? et al., Three-dimensional laser micro-sculpturing of silicone: towards bio-compatible scaffolds, Opt. Express, 21, 17028 (2013).

8972-61, Session PTue

Three-dimensional nano-structuring of polymer materials by controlled avalanche using femtosecond laser pulses

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We overview the basic principles and the most important developments of three-dimensional (3D) direct laser writing in polymers [1]. Challenges to reach reliable structuring with sub-100 nm resolution in all three dimensions without compromise of a high speed fabrication required for practical applications are discussed. Research into the structuring by ultrashort laser pulses has seen immense growth over the last decade due to its flexibility, easy handling and wide spectrum of applications. Here a detailed discussion regarding the mechanisms of the linear and nonlinear light absorption at tight focusing conditions is given, typical laser writing conditions and numerical examples are provided. The photochemistry of traditional and novel photopolymers together with their photosensitization and sample developing strategies are presented. We show that ultra-short sub-1 ps pulses are capable to create polymerizable species by direct absorption and bond breaking at ~TW/cm2 irradiance at the focal spot. A well-controlled local heating finishes polymerization on a longer time scales > 10 - 100 ns. With thermal and linear absorption via avalanche ionization an efficient use of light energy is used for polymerization. This is a unique feature for ultra-short laser irradiation [2]. Potential future applications are as diverse - as functional metamaterials, plasmonics, micro-optics, and microfluidic devices and cell scaffolds. Possible directions of up-scaling the fabrication throughput for industrial demands are introduced. 3D laser writing is becoming a part of wider field of additive manufacturing which is innovating number of fields in micro-machining and functional device fabrication.

[1] M. Malinauskas et al., Ultrafast-laser micro/nano-structuring of photopolymers: a decade of advances, Phys. Rep., accepted (2013).

[2] M. Malinauskas et al., Mechanisms of three-dimensional structuring of photo-polymers by tightly focussed femtosecond laser pulses, Opt. Express 18, 10209 (2010).

8972-62, Session PTue

Femtosecond laser-induced breakdown spectroscopy for understanding high-energy materials

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We present an overview of the advantages of utilizing femtosecond laser induced breakdown spectroscopic technique for understanding high energy materials. LIBS spectra of several high energy materials such as RDX, HMX, NTO, TNT, ANTA were obtianed with both nanosecond, femtosecond pulses. Time-resolved atomic (C, H, N) and molecular species (CN, C2) dynamics were retreived from the LIBS data achieved at various gate widths and delays. We attempted to correlate the dynamics observed with respect to the structure/composiiton of these compounds. For example we try to correlate the dynamics with respect to the number of C-C, C-N linkages in these molecules.

8972-63, Session PTue

Thermoelectric assessment of laser peening induced effects on a metallic biomaterial Ti6Al4V

Hector G. Carreon, Univ. Michoacana de San Nicolás de Hidalgo (Mexico); Sandra Barriuso, Ctr. Nacional de Investigaciones Metalúrgicas (Spain); Juan Antonio Porro, Univ. Politécnica de Madrid (Spain); J. L. González-Carrasco, Ctr. Nacional de Investigaciones Metalúrgicas (Spain) and CIBER-BBN (Spain); J. L. Ocañao, Ctr. de Investigación Biomédica en Red en Bioingeniería, Biomateriales y Nanomedicina (Spain)

Laser peening has recently emerged as a useful technique to overcome detrimental effects associated to another well-known surface modification processes such as shot peening or grit blasting used in the biomedical field. It is worth to notice that besides the primary residual stress effect, thermally induced effects might also cause subtle surface and subsurface microstructural changes that might influence corrosion resistance. Moreover, since maximum loads use to occur at the surface, they could also play a critical role in the fatigue strength. In this work, plates of Ti-6Al-4V alloy of 7 mm in thickness were modified by laser peening without using a sacrificial outer layer. Irradiation by a Q-switched Nd-YAG laser (10 ns) working in fundamental harmonic at 2.8 J/pulse and with water as confining medium. Laser pulses with a 1.5 mm diameter at an equivalent overlapping density (EOD) of 5000 cm-2 were applied.

Attempts to analyze the global induced effects after laser peening, were addressed by using the contacting and non-contacting thermoelectric power (TEP) techniques. It was demonstrated that the thermoelectric method is entirely insensitive to surface topography while it is uniquely sensitive to subtle variations in thermoelectric properties, which are associated with the different material effects induced by different surface modification treatments. These results indicate that the stress-dependence of the thermoelectric power in metals produces sufficient contrast to detect and quantitatively characterize regions under compressive residual stress based on their thermoelectric power contrast with respect to the surrounding intact material. However, further research is needed to better separate residual stress effects from secondary material effects, especially in the case of low-conductivity engine materials like titanium alloys.