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Contents

7578: Solid State Lasers XIX: Technology and Devices 384
7579: Laser Resonators and Beam Control XII 405
7580: Fiber Lasers VII: Technology, Systems, and Applications 415
7581: High Energy/Average Power Lasers and Intense Beam Applications V..439
7582: Nonlinear Frequency Generation and Conversion: Materials, Devices, and Applications IX.....................445
7583: High-Power Diode Laser Technology and Applications VIII.....460
7584: Laser Applications in Microelectronic and Optoelectronic Manufacturing XV.......................................472
7585: Laser-based Micro- and Nanopackaging and Assembly IV.....486
7586: Synthesis and Photonics of Nanoscale Materials VII..........494
7587: Free-Space Laser Communication Technologies XXII.........500
7588: Atmospheric and Oceanic Propagation of Electromagnetic Waves IV 506
7589: Frontiers in Ultrafast Optics: Biomedical, Scientific and Industrial Applications X (Formerly: Commercial and Biomedical Applications of Ultrafast Lasers) 512

Technical Abstract Summaries

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Conference 7578: Solid State Lasers XIX: Technology and Devices

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7578-01, Session 1

Spaceborne laser instruments for high-resolution mapping

A. W. Yu, M. Krainak, D. Harding, J. B. Abshire, X. Sun, NASA Goddard Space Flight Ctr. (United States)

A next-generation, efficient, swath mapping, space altimeter for Earth science is being developed under the Instrument Incubator Program (IIP) funded by NASA's Earth Science Technology Office (ESTO). High resolution mapping with requirements of 5-m spatial resolution and decimeter vertical precision will meet the goals of the Lidar Surface Topography (LIST) mission. Such swath mapping elevation measurements meet many Earth science needs, including (1) mapping topographic changes associated with natural hazards; (2) global surveys of vegetation height and biomass, and their response to disturbances; (3) measurements of river and lake levels for monitoring water storage and discharge changes in the global water cycle; and (4) long duration satellite observations of ice sheet and glacier mass balance from measurements of their elevation change. The approach can also be scaled and used with less laser power and smaller telescopes for mapping planetary surfaces for science and exploration. In this paper we will describe the systems requirements and technology development efforts in lasers and detectors under this IIP to fulfill the LIST mission goals and objectives.

7578-02, Session 1

High energy 2-micron solid state laser development for NASA's 3-D winds measurement from space

U. N. Singh, J. Yu, M. J. Kavaya, NASA Langley Research Ctr. (United States)

We present an overview of 2-micron laser transmitter development at NASA Langley Research Center for coherent-detection lidar profiling of winds. The novel high-energy, 2-micron, Ho:Tm:LuLiF laser technology developed at NASA Langley was employed to permit study of the laser technology currently envisioned by NASA for global coherent Doppler lidar measurement of winds in the future. The 250 mJ, 10 Hz compact transceiver was also designed for future aircraft flight. Ground-based wind profiles made with this transceiver will be presented. NASA Langley is currently funded to build complete Doppler lidar systems using this transceiver for the DC-8 and WB-57 aircraft. The WB-57 flights will present a more severe environment and will require autonomous operation of the lidar system. The DC-8 lidar system is a likely component of future NASA hurricane research. It will include real-time data processing and display, as well as full data archiving.

7578-03, Session 1

Design and environmental testing of a compact pulsed UV laser system for spaceborne applications

C. Kolleck, R. Marwah, S. Mebben, M. Ernst, T. Lang, D. Kracht, J. Neumann, Laser Zentrum Hannover e.V. (Germany)

An extremely compact UV laser system has been developed for the use in a laser-desorption mass spectrometer (LD-MS). It is designed to survive in harsh environments like planetary exploration missions. The Nd:YAG-based oscillator with a saturable absorber as passive Q-switch is longitudinally pumped and emits pulses of duration < 2 ns at 1064 nm. The frequency conversion to 266 nm with a pulse energy of > 250 µJ is accomplished by two consecutive extra-cavity SHG crystals. A subsequent stage contains photo diodes for the monitoring of the green and the UV pulses and removes the remaining IR and green light from the output signal.

In order to keep the thermal management hardware compact, a heating-only system is used to control the temperature of the nonlinear crystals, resulting in a nearly isothermal inner structure. Thermal simulations have been verified by tests in both vacuum and Martian atmosphere. The critical optical components, i.e., the nonlinear frequency conversion crystals and laser crystals, have successfully undergone proton radiation tests. Furthermore, a vibration test of the system with levels up to 20 g was successfully accomplished.

7578-04, Session 1

Quasi-CW laser diode arrays for space applications

A. Seas, E. Troupaki, A. Vasilyev, H. Conley, NASA Goddard Space Flight Ctr. (United States)

Even though LDAs have been employed in multiple space born missions and there have been significant efforts in characterizing and testing, their mechanisms of failure is not very well understood. One of the main factors has been the continuous changes made by LDA manufacturers in their efforts to improve the quality of their products. Unfortunately every change resets the space qualification process and requiring the development of new tests. Overall the quality of the LDAs has been significantly improved as compared to their quality of a decade ago.

The diode group at NASA Goddard Space Flight Center (GSFC) has been responsible for the characterization of LDAs prior to their use in space missions. The group is using multiple, state of the art experimental setups in order to fully characterize LDAs. The data collected from all procedures is then compiled and used to compare and rank all LDAs. Only LDAs that satisfy multiple criteria (usually established by mission requirements) are then selected for space use.

Recently the diode group characterized all the LDAs for the Lunar Orbiter Laser Altimeter (LOLA) instrument (aboard the Lunar Reconnaissance Orbiter) and has been preparing to do the same for the LDAs that will be used for the ICESat-2 mission. A summary of research activities will be presented where the performance of LDAs have been tested in air and vacuum for multibillion shots. Post testing characterization data, and comparison of before and after performance parameters will also be presented.

7578-06, Session 2

Extended testing of laser systems for Space applications

A. Seas, A. Yu, NASA Goddard Space Flight Ctr. (United States); A. Melak, D. Mostofi, Sigma Space Corp. (United States); E. Troupaki, A. Vasilyev, H. Conley, NASA Goddard Space Flight Ctr. (United States)

Laser systems for space applications have several special requirements that make them unique. Space borne laser systems need to be able to operate continuously for long periods of times (months or years) without any optical alignment or adjustment. Furthermore most mission have strict pointing stability requirements since the laser is aligned with a telescope with narrow field of view, and the beam has to travel hundreds of kilometers before is detected. Many missions may also require that

a laser system remains dormant for many years before it is turned on, setting special requirements for radiation hardened materials.

There are various ways to estimate how well a laser will perform in space. In some cases the reliability of space borne systems is determined by accelerated testing and qualifying the individual components. Then using the generated data together with reliability models simulations are developed to predict the system's future performance. Another method is to subject the whole laser system to extended testing at operating conditions similar to the ones in space, which is costlier and time consuming.

An extended test for a laser system identical to the lasers used onboard ICESat (Ice, Cloud, and land Elevation Satellite) has been set up in the facilities of the Lasers and Electro-Optics Branch at NASA Goddard Space Flight Center. The laser system was operated continuously for multibillion shots, while the performance of the system was closely monitored, and the values of several performance parameters were recorded. A summary of the recorded data will be presented

7578-07, Session 2

Results of the 1319 laser subsystem of a guidestar laser system

Z. Prezkuta, M. P. Jalali, I. Lee, Lockheed Martin Coherent Technologies (United States)

We have completed a >30 W laser guidestar for the Keck Observatory. The output is <1.2 M2, modelocked, and wavelength locked to the peak of the D2 sodium line within 100 MHz. A key component of this system is the 1319 master oscillator/power amplifier subsystem. We will discuss the results of this subsystem, which has consistently produced >50 W of linearly polarized output with >80% far-field power-in-the-bucket.

7578-08, Session 2

A highly reliable single mode laser for space application

S. X. Li, NASA Goddard Space Flight Ctr. (United States); A. Vasilyev, Science Systems and Applications, Inc. (United States); A. Yu, M. A. Stephen, G. Shaw, M. Krainak, NASA Goddard Space Flight Ctr. (United States); A. Rosanova, Honeywell Technology Soloutions (United States); T. Filemyr, Bastion Technologies (United States)

Since 2003, NASA Goddard space flight center has successfully designed, built and launched three laser-based instruments (ICESat, MLA and LOLA) for Earth and Planetary sciences. While these instruments provided unprecedented valuable science data, GLAS, MLA and LOLA EM had experienced some degree of optical degradation/damage during different development phases. The exact root causes of degradation are not known yet but high laser fluence along with possible contamination is the leading theory. GLAS laser had severe mode beating with 20% to 50% of the pulses. LOLA has worse mode beating due to the longer laser cavity. Mode beating increases intra-cavity fluence and it might also trigger nonlinear effects that causes laser failure. In this paper, we will discuss a simple, reliable laser design which will eliminate the harmful longitudinal mode beating.

7578-09, Session 2

Space laser transmitter development for ICESat-2 mission

A. W. Yu, M. A. Stephen, S. X. Li, G. Shaw, A. Seas, NASA Goddard Space Flight Ctr. (United States)

The Ice, Cloud and land Elevation Satellite (ICESat) was launched in January 2003 and placed into a near-polar orbit with a primary mission of global monitoring of the Earth's ice sheet mass balance. ICESat carried a single instrument, the Geoscience Laser Altimeter System (GLAS) on board. The GLAS instrument continues to provide unprecedented science data on global surface elevation of ice and land, sea ice freeboard heights, vertical cloud height distributions, and vegetation canopy heights. GLAS has accumulated over 1.8 billion data points and has exceeded the designed range accuracy of 10 cm with in-space accuracies <3 cm over a 70 meter foot point and 170 m along track separation. NASA is planning an ICESat-2 mission to continue monitoring the Earth's ice sheet mass balance with a tentative launch date of 2015. In this paper we will describe the development efforts of the laser transmitter for ICESat-2.

7578-10, Session 3

700-W intracavity-frequency doubled Yb:YAG thin-disk laser at 100 kHz repetition rate

C. Stolzenburg, W. Schüle, I. Zawischa, A. Killi, D. Sutter, TRUMPF Laser GmbH & Co. KG (Germany)

The thin-disk laser concept with its advantages high efficiency, excellent beam quality, and low depolarization losses provides a reliable platform for the generation of high power lasers in the infrared as well as the green spectral range. By employing intracavity-frequency conversion, we have obtained a maximum output power at 515 nm of 700 W at a repetition rate of 100 kHz from a Q-switched Yb:YAG thin-disk laser. An LBO crystal cut for critical phase matching of type I was mounted near one of the end mirrors inside the laser cavity. An optical efficiency (green output power with respect to incident pumping power) greater than 35% could be reached. By changing the low-loss duration at the Q-switch the pulse duration of the laser system can be adjusted between 200 ns and 750 ns with the longer pulse durations being generated with the highest efficiency. This feature can be used to maintain a constant pulse duration when varying the pumping power or repetition rate. The beam parameter product of 4 mm*mrad ($M^2 < 25$) allows for beam delivery via an optical fiber with 100 µm core diameter. To the best of our knowledge, the average power significantly exceeds all previously published results for lasers in the visible spectrum.

7578-11, Session 3

Ytterbium-based disk amplifier for an ultrashort pulse laser

J. Vetrovec, Aqwest (United States); B. Schmidt, General Atomics Aeronautical Systems, Inc. (United States); D. A. Copeland, Aqwest (United States)

We report ytterbium-based disk amplifier for USPL using edge-pumped architecture and offering excellent scalability to high-average power in kW-range. Edge-pumping [1] allows for reduced doping of crystals with laser ions, which translates to lower lasing threshold in quasi-3 level materials. The disk has a composite construction with undoped perimetral edge designed to channel pump light while efficiently outcoupling amplified spontaneous emission (ASE). Thermal management of the disk is provided by an innovative active heat sink with ultra-low thermal resistance. Uniform extraction of waste heat together with uniform pumping offers very low optical path distortion and allows for amplification of near diffraction limited beams.

This work discusses modeling of the disk amplifier performance using a time-dependent 2-dimensional model for dynamic pumping and extraction. The model tracks tempral evolution of the upper level and ground state population density maps, ASE losses, amplification by chirped seed pulses in a multi-passed extraction, and optical distortions. Use of the model for determining optimum configuration the edge pumping array is discussed. Simulations of thermal performance of the disk and the heat sink are also included. This work was in part supported by the US Army [3].

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

2. J. Vetrovec, "Active heat sink for automotive electronics, SAE paper 2009-01-0965, April 2009

3. J. Vetrovec and B. Schmidt, Ytterbium-Based Edge-Pumped Disk Amplifier for an Ultra-Short Pulse Laser (USPL), Solid-State and Diode Laser Technical Review, Newton, July 2009

7578-12, Session 3

Latest advances in high-power disk lasers

D. L. Havrilla, TRUMPF Inc. (United States); R. Brockmann, A. Killi, TRUMPF Laser GmbH & Co. KG (Germany)

While the Disk laser concept was invented in the early 90s, the first industrial products were available in the beginning of this decade. Since then, the disk laser is used in mass production and serves a large variety of application fields. The output power per disk has continually increased and reached a level of 2.5 kW per disk in 2007. As of today, the disk principle has not reached any fundamental limit regarding output power per disk or beam quality, and offers many advantages over other high power resonator architectures.

In 2009 TRUMPF released a new series of industrial disk lasers. This series is based on an output power of 4 kW per disk. Scalability of output power is achieved by serial coupling of several disks without influencing the beam quality of the system, with output powers of up to 16 kW at work piece. The new TruDisk laser series has incorporated several advancements compared to older generation disk lasers, which have allowed a considerable reduction of running cost, investment cost and footprint.

This paper will explain important details of the TruDisk laser series and process relevant features of the system, like pump diode arrangement, resonator design and integrated beam guidance. In addition, advances in applications in the thick sheet area and very cost efficient high productivity applications like remote welding, remote cutting and cutting of thin sheets will be discussed.

7578-13, Session 3

A design for a 100-kW rotary disk laser oscillator with good beam quality

S. Basu, Sparkle Optics Corp. (United States)

In this paper, we will present quantitative designs of a 25-kW and a 100-kW laser oscillator containing a number of Yb-ceramic YAG rotary disk modules. Assuming 60% efficient laser diodes will be possible in the near future, the 100-kW design will require 427 kW of electrical power to produce 65 kW of power in a far-field bucket of angular radius 1.5 /D. We will present thermal, stress and wavefront error analyses of rotary disks and compare them with the same for thin disks. We will also present the design of an unstable resonator for the 100-kW laser.

The design is modular, with identical Yb-YAG rotary disk modules stacked in series in a laser oscillator. Each module is identically pumped and cooled. The calculations for one design example shows that with a 32-module laser oscillator, 100-kW of laser power may be extracted at 44% optical efficiency and 50% slope efficiency.

References

1. S. Basu, "Nd-YAG and Yb-YAG Rotary Disk Lasers", IEEE J. Selected Topics in Quant. Electron., vol. 11(3), pp. 626-630 (2005).

7578-14, Session 3

CW laser operation of a highly-doped Tm:KLu(WO4)2/KLu(WO4)2 thin disk epitaxial laser

S. Vatnik, I. Vedin, Institute of Laser Physics (Russian Federation); M. C. Pujol, X. Mateos, J. J. Carvajal, M. Aguilo, F. Diaz, Univ. Rovira i Virgili (Spain); U. Griebner, V. Petrov, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany)

We report on the laser performance of a thin disk laser based on an epitaxially grown thin (80 µm) layer of the monoclinic KLu(WO4)2 (KLuW) doped with 15% of Tm, on a b-oriented 1.7 mm thick KLuW substrate. The epitaxial side of the sample was coated for high reflection at 0.8 µm and 1.9-2.0 µm and then bonded to a copper heat sink. The substrate side was antireflection coated for 0.8 µm and 1.9-2.0 µm with a residual reflection of <0.1%. A 805 nm laser diode bar with collimating optics was used as a pump source, delivering 20 W of power to the spot of 1 mm2. A set of RC= -40 mm output couplers, with transmission T= 0.4%, 1.6% and 2.8% were used. The cavity length was 23 mm. The laser threshold and slope efficiency for both CW and quasi-CW (18% duty cycle) regimes, were 3-4 W and 8-10%, respectively (both related to absorbed pump power). The laser emission spectra were centered at ~1850, 1915 and 1940 nm for T=2.8%, 1.6% and 0.4%, respectively. In all cases the emission spectra were "structured", consisting of a number (typically 5...10) of narrow emission lines with FWHM of ~1 nm spread irregularly over 15...30 nm, with the relative intensity and number of separate lines depending on the pump power. The structured character of the emission seems not to be related to air absorption or spectroscopic features of the active medium and further studies are in progress to explain this phenomenon.

7578-15, Session 4

Improved bond strength characterization of CADB® epoxy-free bonded solid state laser materials

N. Traggis, N. Claussen, Precision Photonics Corp. (United States)

Chemically Activated Direct Bonding (CADB®) has become widely utilized as an epoxy-free assembly process for solid state laser crystals in high fluence, or other aggressive environments. While data has been presented as to both optical and mechanical properties of these bond interfaces, previous research has hinted that sample preparation plays a large part in the final results. Surface finish of samples and any sub-surface damage present can lead to artificially low strength values and other inconclusive results. We will present shear testing data of bonded and bulk samples for common laser materials such as YAG, Phosphate glass, and fused silica.

7578-16, Session 4

Comparative performance of ASE suppressed ceramic Yb:YAG thin disks

D. J. Bossert, P. V. Avizonis, Boeing-SVS, Inc. (United States)

We report on the results of an experimental and theoretical investigation of the relevant performance attributes of Yb:YAG thin disk gain elements for use in high brightness resonators. We compare the laser operation, under extremely high pump and laser power densities, of crystalline thin disks to ceramic disks with and without undoped, amplified spontaneous emission (ASE) suppressing caps. The thin disks had between 120um and 150um thick doped regions, and the 1mm thick undoped caps were applied using chemically activated diffusion bonding. The disks were operated with impingement cooling either directly on the back (high

reflecting) surface or on heat spreaders.

Although high optical efficiency conditions were generally maintained, small differences in power and optical efficiency were observed among the disk variations, while the temperature rise and thermo-optical performance were found to depend heavily on the disk structure and mounting details. ASE was suppressed in capped disks to provide the theoretical oscillator performance without ASE. The static and active reflected wavefront error (RWE) from the disks was measured and compared to finite element modeling. Causes of OPD variations are identified and discussed.

7578-17, Session 4

6.5 kW, Yb:YAG ceramic thin disk laser

A. Lobad, Boeing LTS (United States); T. Newell, W. Latham, Air Force Research Lab. (United States)

The unique features of both ceramic materials and thin disk lasers (TDL) have been combined to demonstrate multi-kW lasing in Yb:YAG ceramics. Operation of 6.5 kW output at 1030 nm from a single disk with 57% slope efficiency is reported. The 940 nm pumped, 200 µm thick and 9.8% doped gain element is chemically activated diffusion bonded to a 1 mm undoped ceramic YAG. The maximum incident pump intensity was 5 kW/cm2 yielding 2.6 kW/cm2 of multimode laser radiation. The 940 nm laser diode system included six Jen-Optik 2.5 kW, 25 bar-stack laser diodes with collimating spherical-cylindrical lenses, combining polarizing plate and a supraSil homogenizing rod providing 12.7 kW of pump power. The output of the homogenizing rod is relay imaged with a 4th order supergaussian pump profile on the thin disk. Multiple imaging of the pump beam onto the TD insures the absorption of more than 90% of the incident energy. The 37 mm diameter disks were epoxied onto a Cu holder with a 26 mm exposed aperture and an 18 mm pumped spot size. The disk has direct jet impingement cooling on the HR coated side.

To investigate the TD gain saturation, both linear and V-fold resonators were tested using 2 m roc output coupling mirrors of 1 to 13% transmission. The V cavity yielded a maximum output power of 5.5 kW before the control program shut down the pump diodes due to a sudden dramatic in the slope efficiency in order to prevent catastrophic damage to the disk. The repeatable slope efficiency drop at Ppump ~ 4.5 kW/cm2 was a precursor to the cavity becoming unstable due to thermal expansion induced disk flexure producing -3m radius of curvature as indicated by our thermal lensing measurement. Simultaneous lasing of the 1030nm and 1049nm lines was observed only for the V cavity at the lowest output-coupling of 1%. The small signal gain is 5.8 cm-1 and the round trip loss for the linear cavity is 2.1% mostly due to the laser absorption in the undoped cap and observed scattering due to inclusions in the diffusion bonding layer. The pump lasing threshold and output intensities were independent of the pump spot size in the 1 to 13 % transmission output coupling range, indicating that transverse ASE in not a limiting factor in our capped disk.

7578-18, Session 4

Thermal effect of cryogenic Yb:YAG total-reflection active-mirror laser

H. Furuse, T. Saiki, K. Imasaki, M. Fujita, J. Kawanaka, N. Miyanaga, Osaka Univ. (Japan); K. Takeshita, S. Ishii, Mitsubishi Heavy Industries, Ltd. (Japan)

e describe our new concept of amplifier configuration based on the active mirror arrangement. It is using total reflection geometry, and is called "TRAM" (Total Reflection Active Mirror) laser. The TRAM samples were composite ceramics of undoped YAG prism and Yb:YAG disk of 0.18, 0.4, or 0.6 mm-thick. The ceramics has no high reflection coating and was directly cooled by liquid nitrogen. The cryogenic TRAM ensures a high thermal strength and simple pump geometry. The each TRAM sample was pumped using fiber coupled ~ 500 W 940 nm pump diodes. We have achieved 273 W output power with 65% of optical to optical efficiency and 72% of slope efficiency for 0.4 mm thick TRAM with respect to the absorbed pump power in our CW experiments. The cryogenic Yb:YAG TRAM laser showed four level operation even at 1.2 kW/cm2 of high pump density. The laser power and optical efficiency will be improved more when the pump power increases further. We believe that the TRAM laser has the potential to revolutionize high power solid state lasers because of the high heat removal efficiency. To investigate this, we have measured thermal lensing effects for 0.18 mm thick Yb:YAG TRAM for any pump intensity. We will present experimental and theoretical results including thermal lensing and amplified beam quality, and the scalability of our cryogenic Yb:YAG TRAM laser design will be discussed.

7578-19, Session 5

Review of high power bounce geometry solid-state lasers

M. J. Damzen, Imperial College London (United Kingdom) and Midaz Lasers Ltd. (United Kingdom)

A review is made of the excellent performance characteristics of high power (~100W) solid-state lasers employing the bounce amplifier geometry. In the bounce geometry a laser beam undergoes total internal reflection from the pump face of a diode-side-pumped slab crystal during its amplification. We describe how the bounce amplifier technology provides spatial averaging of thermal non-uniformities for high beam quality, leads to extraordinary high gain (103-105) capability, and its simple robust method of diode delivery provides scaling to high powers >100W, TEM00 in CW, Q-switched and modelocked implementations. Key results of experimental systems include high power (>100W) implementation in oscillator and master-oscillator power-amplifier (MOPA) configurations and providing sources for nonlinear conversion (e.g. to create high power UV laser sources). Results are presented of bounce laser Q-switching to order-of-magnitude higher repetition rates (>1MHz) than standard diode-pumped solid-state (DPSS) laser systems. Modelocking is also presented for generation of ultrashort pulses employing SESAM or nonlinear mirror techniques. We also show results of bounce amplifiers employed in new architectures for creation of self-organising lasers with dynamic aberration correction as well as the use of this technology for power scaling by self-organised coherent beam combination.

7578-20, Session 5

400W Yb:YAG planar waveguide laser using novel unstable resonators

I. J. Thomson, H. J. Baker, K. Wlodarczyk, N. Trela, D. R. Hall, Heriot-Watt Univ. (United Kingdom)

The diode-pumped solid-state planar waveguide laser offers an intermediate case between the thin disc and fibre lasers. The thin core offers excellent thermal management, while also enabling power scaling by increasing the length and width of the guided wave region. We report the highest power of 400W from a solid-state planar waveguide laser with a slope efficiency of 75%, comparable to thin disc lasers.

The 2%at. doped Yb:YAG planar waveguide has 13mm x 12mm x 150µm core dimensions and 1mm sapphire claddings. The side facets are angled at 7° and 20°, suppressing parasitic oscillation and minimising the ASE propagation length. The waveguide is double edge-pumped at 940nm using two 450W 6-bar diode stacks, cylindrically focused into the 150µm core. Greater than 90% of the pump light is coupled into the waveguide with an intensity >20kWcm-2 and ~75% pump absorption.

A close-coupled spherical mirror plano-concave resonator gave 400W operation with near single-mode lasing in the transverse direction by an internal waveguide mode selection process with a multi-mode lateral profile. Preliminary improvements to an unstable resonator with 300W output replaces spherical mirrors with custom laser-cut mode-selective toroidal mirrors with ~15mm and ~250mm curvature improving

waveguide coupling.

Uniform gain of 1cm-1 through the waveguide gives an amplification factor of 3-4x per pass, six passes results in a 1000x amplification factor, showing promise for operation as an amplifier for sub-picosecond pulsed lasers.

7578-21, Session 5

Power-scaling Nd:YAG's quasi-four-level transition

J. I. Mackenzie, Univ. of Southampton (United Kingdom)

Increasing the output power of Nd:YAG's 4F3/2 4I9/2 quasi-four-level transition is attractive for providing a high-radiance source with a wavelength below 1micron for applications at the life sciences interface, ranging and sensing, or as a vital element for next-generation display technologies, when frequency converted into the blue-green part of the visible spectrum. Reabsorption losses at the lasing wavelength combined with a relatively low stimulated emission cross-section and competition with the much stronger 1.06micron transition, demands a configuration with high pumping intensity, comparable to the pump saturation intensity at 808nm, to achieve efficient operation. However, even with the availability of increasingly bright diode-lasers, the thermal deficit of the excitation cycle and the thermo-optic properties of the YAG host medium currently limit the achievable output power at 9xxnm. Presented here is a double-clad planar-waveguide Nd:YAG laser, operating at a lasing wavelength of 946nm with an output power in the 100W regime and better than 50% optical to optical conversion efficiency. The enhanced thermal management characteristics of the waveguide structure have enabled power-scaling well beyond that possible in a bulk laser configuration. These advantages and further power-scaling possibilities will be discussed.

7578-22, Session 5

280W INNOSLAB amplifier for sub ns laser pulses with multi 100 MW peak power

M. Höfer, D. Esser, H. Sipma, R. Kasemann, H. Hoffmann, Fraunhofer-Institut für Lasertechnik (Germany)

XUV or soft-X-ray microscopes in the "water window" of 2.3 to 4.4 nm with lateral resolution better than 50 nm and high contrast for organic probes is of high interest for example in the biological or medical sector. Laser induced plasma sources for the generation of XUV light demand compact laser systems in the 100 mJ class with pulse lengths in range of 500 ps to 3 ns for high conversion efficiency and repetition rates above 1 kHz to archive short exposure times in the range of a few 10 s.

We report a MOPA system consistent of a diode seeded regenerative amplifier and a chain of three INNOSLAB power amplifier stages.

Pulses with a duration between 250 ps and 1.5 ns have been amplified both with one linear chain of three slab amplifiers and a three stage configuration with separated amplification of the 2 polarizations in the final stage. With the linear amplifier chain a total average power > 240 W is achieved. With polarisation multiplexing a total power >280W is achieved. The laser is operated at 2 kHz at pulse energies of more than 120mJ and more than 140mJ respectively. The peak power is > 400 MW, the contrast ratio between pre pulses and the main pulse is > 300:1. The beam quality is: M2y< 1.5 and M2x<3. All parameters like power, pulse duration and pulse shape are hands-off adjustable via software. Second harmonic generation with one linear amplifier chain has been demonstrated with a conversion efficiency >50%. At present two lasers are integrated by customers into plasma sources for x-ray microscopy.

7578-23, Session 5

Recent progresses in INNOSLAB lasers and their harmonic generation

D. Li, S. Fu, P. Shi, J. Shen, A. Schell, B. Qi, C. Haas, J. Wang, K. Du, EdgeWave GmbH (Germany)

Through an optimal combination of crystal shape, cooling and resonator design, INNOSLAB lasers possess unified advantageous features of short pulse duration and high peak output power, high pulse repetition rate, high beam quality and high flexibility in beam profile, from circular beam profile, through line shaped one dimensional Top-hat, to two dimensional top-hat with rectangular cross section. We report diode end pumped, electrooptically q-switched Nd:YLF, Nd:YAG and Nd:YVO4 slab laser and their efficient harmonic generation in near field.

7578-01, Session 6

Highly efficient and compact microchip green laser source for mobile projectors

J. Khaydarov, S. Essaian, G. Nemet, A. V. Shchegrov, N. Simanovskaia, Spectralus Corp. (United States); H. Danielyan, G. Gabrielyan, A. R. Poghosyan, S. Soghomonyan, Spectralus CJSC (Armenia)

Compact and efficient green lasers are of high interest to consumer electronics applications such as handheld and pocket projectors. First-generation, LED-based mobile projectors have just appeared in 2008. While RGB lasers offer many advantages in brightness and system design, a viable efficient and low cost green laser platform has been difficult to realize. Since direct green laser sources are not available, a number of nonlinear second-harmonic-based approaches have been proposed recently. In this work, we demonstrate a novel green laser source, based on a monolithic cavity microchip laser platform - monolithic assembly of Nd:YVO4 crystal and PPMgOLN crystal. The use of our highly efficient, periodically poled MgO-doped Lithium Niobate (PPMgOLN) as the nonlinear frequency doubler allows obtaining a significant increase in the overall efficiency of the green microchip laser. The microchip laser platform also offers cost efficient solution for the cost-sensitive market. The laser performs efficiently in both cw and pulsed regimes with repetition rates from 60Hz to 2KHz. We demonstrate 50-150mW green output with wall-plug efficiency exceeding 10% in the temperature range over 40°C. We discuss a compact package for this laser with volume less than 0.4cm3.

7578-02, Session 6

High-power green light generation by second harmonic generation of single-frequency tapered diode lasers

O. B. Jensen, P. E. Andersen, Technical Univ. of Denmark (Denmark); B. Sumpf, K. Hasler, G. Erbert, Ferdinand-Braun-Institut für Höchstfrequenztechnik (Germany); P. M. Petersen, Technical Univ. of Denmark (Denmark)

Green light is useful for a number of applications including display and biomedical applications. Traditionally frequency doubled diode pumped solid state lasers are used, when the power exceeds a few hundred mW's, as suitable high power laser diodes have not been available.

In this work, we demonstrate the use of a newly developed high power tapered diode laser with good spectral and spatial properties in frequency doubling. The tapered diode laser consists of a DBR section for wavelength selectivity, a single-mode ridge section to provide the good beam quality and a tapered amplifier section for increasing the output power. The laser is equipped with two electrodes in order to be able to control the current to the ridge and tapered section individually.

The laser is capable of emitting more than 10 W of output power in a single-frequency, near-diffraction-limited beam.

The output of this laser is frequency doubled using periodically poled MgO:LiNbO3 to generate in excess of 1.5 W of output power at 531 nm in a single-frequency, near-diffraction-limited beam.

We investigate different configurations for generation of the green light and will present the use of the green light source for different applications.

7578-15, Session 6

RGB laser generation from fiber MOPAs coupled to external enhancement cavities

J. P. Anderegg, T. A. Chernysheva, D. F. Elkins, C. L. Simmons, R. C. Bishop, C. L. Pedersen, M. L. Murphy, F. L. Williams, Evans & Sutherland (United States)

Red (631 nm), green (532 nm), and blue (448 nm) continuous-wave (CW) lasers have been developed by Evans & Sutherland (E&S). These multi-watt RGB lasers are used as light sources in E&S' laser projector (ESLP), which delivers ultrahigh-resolution content (8192 × 4096 pixels) to large-surface-area venues (e.g., planetariums, simulators, visualization centers, etc.). Efficient visible wavelength generation is obtained by coupling single-frequency near-infrared (NIR) beams into free-space enhancement cavities containing critically phase-matched lithium triborate (LBO) crystals. The NIR energy is produced by a master-oscillator-power-amplifier (MOPA) system which is fiber-based, thus yielding Gaussian beams which are near-ideal for efficient fundamental-to-harmonic conversion. Both polarization-maintaining (PM) fibers and non-PM fibers have been employed with non-PM fiber systems requiring polarization sensing and control. Green laser light is produced by a second-harmonic generation (SHG) process with a 1064 nm fundamental. Red laser light is produced by a sum-frequency mixing (SFM) process with 1064 nm and 1550 nm as fundamentals. Blue laser light is produced by an SFM process with 1064 nm and 775 nm as fundamentals, where 775 nm is first produced by an SHG process with a 1550 nm fundamental. All resulting visible lasers are single-axial-frequency with FWHM bandwidths less than 200 kHz, and are spatially pure with M^2 values less than 1.05. At least 18 W of CW optical power has been generated at all three visible wavelengths, with available NIR amplifier power as the primary limiting factor.

7578-16, Session 6

Highly reliable 198 nm light source for semiconductor inspection based on dual fiber lasers

S. Imai, K. Matsuki, N. Kikuiri, Advanced Mask Inspection Technology, Inc. (Japan); K. Takayama, O. Iwase, NuFlare Technology Inc. (Japan); Y. Urata, T. Shinozaki, Y. Wada, S. Wada, Megaopto Co., Ltd. (Japan)

Highly reliable DUV light sources are required for semiconductor applications such as a photomask inspection. The mask inspection for the advanced devices requires the UV lightning wavelength beyond 200 nm. By use of dual fiber lasers as fundamental light sources and the multi-wavelength conversion we have constructed a light source of 198nm with more than 100 mW. The first laser is an Yb doped fiber laser with the wavelength of 1064 nm; the second is an Er doped fiber laser with 1560 nm. To obtain the robustness and to simplify the configuration, the fundamental lights are run in the pulsed operation and all wavelength conversions are made in single-pass scheme. The PRFs of more than 2 MHz are chosen as an alternative of a CW; such high-PRF light is equivalent to CW light for inspection cameras. We use reliable devices in the wavelength conversion stages; especially a new CLBO device which is developed in another project is used for doubling the SHG output from the Yb doped fiber laser. Then we can obtain automatic operation for 6 months, which is described as follows. Free running operation gives rise to no power interruptions for a week; weekly maintenance within an hour is automatically done if it is required; monthly maintenance within 4 hours is automatically done on fixed date per month; manufacturer's maintenance is done every 6 month. Now this unique 198 nm light source is equipped in the leading edge photomask inspection machine.

7578-17, Session 6

High average and peak power pulsed fiber lasers at 1030 nm and 515nm

B. Cocquelin, J. Saby, F. L. Salin, A. Meunier, Eolite Systems (France)

Although many applications require high power pulses in the visible, fiber lasers have mostly restricted their range to the near infrared. We will present new results obtained with rod type fiber lasers leading to record high performances. Starting we newly designed large mode area photonic crystal fibers in a very simple architecture, we produced over 110W at 1030 nm with Q-switched pulse duration below 10 ns and M2<1.3. These very high peak and average powers lead to over 60W at 515 nm. We have also obtained diffraction limited beams with an output power exceeding 210 W at 1030 nm and 130 W at 515 nm in a very simple MOPA configuration. Due to the very high gain in these fibers, we can keep pulse durations below 20 ns up to 500 kHz in a purely Q-switched system. We will then present results on very high average power picosecond pulse amplification using the same technology as well as route to the kW average power with 10ns, diffraction limited beams.

7578-24, Session 6

Efficient, green laser based on a blue-diode pumped rare-earth-doped fluoride crystal in an extremely short resonator

M. Strotkamp, T. Schwarz, B. Jungbluth, Fraunhofer-Institut für Lasertechnik (Germany)

Intended for use in mobile projectors, the green cw-laser presented in this work utilises a rare-earth-doped fluoride crystal laser pumped by a blue laser diode. The absorption wavelength of Pr:YLF fits the emission wavelength of GaN laser diodes commercially available, and Pr:YLF emits at 523nm.

The laser consists of a blue laser diode, beamshaping optics, a focussing lens and the hemispherical resonator. Since the aim was to build a compact laser system, the resonator comprises a coated Pr:YLF crystal and a concave outcoupling mirror with an extremely small radius. The resonator is only 10mm long and exhibits high stability against misalignment compared to longer resonator designs.

Available from Nichia the blue pump diodes have an output power of 500mW and 1W. For the lower power diode with a M2 of 1 and 3 in the fast and slow axis, a good overlap with the laser mode can be achieved in the 5mm long crystal. The output of the laser with the higher power diode does not increase as desired due to a M2 of 3 and 6.

With the 500mW diode a laser with M2=1 and an output power of 140mW for an absorbed pump power of 410mW has been achieved. With a threshold of 70mW the laser exhibits a slope of 40% and an electro-optical efficiency of 6.5%.

Despite the reduced overlap with the 1W diode, an output power of 290mW for an absorbed pump power of 850mW and slightly increased M2 has been shown.

7578-25, Session 6

Frequency doubling of fiber laser radiation of large spectral bandwidths

S. Nyga, J. Geiger, B. Jungbluth, Fraunhofer-Institut für Lasertechnik (Germany)

In this work the reduction of conversion efficiency due to the spectral bandwidth of the fiber laser radiation is investigated. Subsequently, compensation optics to correct the spectral phase mismatch inside the nonlinear crystal are dimensioned and tested. For the experimental investigations a laboratory fiber laser setup was used consisting of a seed diode and a three stage fiber amplifier. The laser delivers an average output power of up to 100 W at 1 MHz. Even below the Raman threshold the output is far away from Fourier limit, providing a nearly Lorentz-shaped spectrum with a bandwidth of up to 5.8 nm and a temporal pulse width of 800 ps. As the bandwidth increases nearly linearly with the pump power of the third amplifier stage, this parameter could be easily controlled for the experiments. For a better comparison of measurements with different bandwidths, the input power at the nonlinear converter stage could be kept constant by means of an external attenuator.

All conversion experiments were conducted with a moderate load of the nonlinear crystals, i.e. intensity less than 150 MW/cm2. Without compensation for the spectral phase mismatch, a conversion efficiency of 19% is attained for a Type I configuration with a 20 mm long LBO crystal. The conversion efficiency drops with rising bandwidth and lies at less than 10% at 5.8 nm. With compensation optics to correct the spectral phase mismatch 27 W green are obtained from 60 W infrared with 4.4 nm bandwidth at the same load.

7578-26, Session 7

Compact and efficient continuous wave UV DPSS laser

J. Hellstrom, G. Elgcrona, H. Karlsson, Cobolt AB (Sweden)

Abstract

A compact and efficient continuous wave single-mode diode-pumped solid state laser is reported. The laser is based on cascaded 2:nd order non-linear processes for intra-cavity frequency tripling to 355 nm wavelength using novel periodically poled materials. CW emission exceeding 30 mW for an optical pump power of 8W has been reached. The total size of the laser head is 125x70x40 mm3 (LxWxH) whereas the ring cavity itself takes an area of only 30x20 mm2 (LxW).

The frequency conversion to 355 nm relies on two cascaded non-linear processes[1]. The first process is second harmonic generation (SHG) from 1064 nm to 532 nm in periodically poled Potassium Titanyl Phosphate (PPKTP) and the second process is sum-frequency mixing (SFG) in 3:rd order periodically poled Stoichiometirc Lithium Tantalate (PPSLT). The poling period in the 1:st order required to phase match the SFG process is very short (~2.2 μm) since the refractive index is increasing towards shorter wavelengths. A 3:rd order phase matching has been chosen to circumvent this problem. The lower efficiency of the 3:rd order poling is still substantially more efficient compared to birefringent phase matching frequency mixing in LBO. The PPSLT crystals have in these experiments shown an efficient non-linear coefficient of deff ~2.0 pm/V. The quasi-phase matching (QPM) has also the additional benefit of providing a walk-off free nonlinear interaction.

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7578-27, Session 7

Low-cost frequency-converted laser light sources

J. Konttinen, P. Tuomisto, T. Vallius, P. Leinonen, P. Pietilä, T. Jouhti, EpiCrystals, Inc. (Finland)

We report a fast-switching two-component frequency-converted green laser with reduced speckle contrast in projected output beam. The two-component frequency-converted laser consists of a monolithic single transverse mode ridge-waveguide infrared laser diode and a waveguide-type periodically poled magnesium oxide doped lithium niobate crystal to generate second harmonic light. The laser diode emitting at 1060 nm features integrated electro-absorber section, folding mirror and coupling lens enabling compact, robust and low-cost assembly into industry standard packages. Passively Q-switched pulsed operation realized by the electro-absorber enhances the nonlinear frequency conversion and stabilizes the laser against mode-hopping. In addition, components such as frequency-selective feedback elements may be added or integrated with the laser in order to tailor the spectral output and to improve the temperature performance. Reduced speckle visibility was observed at 530 nm emission wavelength in self-pulsating Q-switched-mode when compared to continuous-wave operation of the same laser. Frequency conversion was realized using 8-mm long nonlinear crystal with uniform quasi-phase-matching grating. By modifying the gain region of the laser diode, the shape of the integrated lens and the properties of the nonlinear crystal, this laser architecture supports producing light at any visible wavelength. Simple construction, modulation capabilities, stability and inherently reduced speckle visibility make this novel laser architecture an attractive solution for all visible wavelengths and numerous applications on the field of metrology, spectroscopy and display industry.

7578-28, Session 7

Half-Watt single frequency yellow 561 nm DPSS laser with record 18% optical conversion efficiency

T. Georges, N. Janvier, OXXIUS (France)

Since the first introduction of DPSS lasers at 561 nm in 2004, the power level required by some biotechnical applications has always increased. Oxxius has contributed to fulfil the demand thanks to the introduction of the SLIM-561 100mW in 2008 and of the SLIM-561 200mW in 2009. More recently, new applications such as Laser Doppler Velocimetry requiring both high power and single frequency operation have appeared.

In this presentation, we demonstrate how to further increase the power. 561 nm emission is obtained by frequency doubling the 1123 nm line of Nd:YAG. The latter transition is significantly weaker than the 1064 nm line. As a consequence, any loss in the cavity significantly increases the laser threshold. Because of the perfect alignment of the crystal interfaces and the low divergence of the intracavity beam, monolithic cavities demonstrate significantly reduced round-trip losses compared to standard cavities. Consequently, laser threshold can be dramatically reduced and the nonlinear loss, responsible for the 561 nm emission, can easily dominate the linear losses. We have taken standard monolithic cavities of our commercial SLIM-561 products and have increased the pumping power up to 2.8 W. Yellow power has not shown any sign of saturation and 0.5 W could be achieved at 561 nm with the maximum power. This results in a record 18% pump to signal optical efficiency. We have checked that the emission remained single frequency whatever the pumping power. Finally, we are currently monitoring the output power over time and no crystal degradation has been observed so far.

Return to Contents

7578-29, Session 7

Short and long term frequency stability of linear monolithic intra-cavity frequency-doubled solid state laser

T. Georges, N. Janvier, OXXIUS (France)

Single longitudinal mode visible DPSS are more and more used in devices where performance can be affected by short term (minutes) frequency drifts and hops. Long exposure holography and Raman spectrometry are applications requiring high frequency stability. Resonant external cavity frequency doubling (to generate CW deep UV) and pumping doubly resonant OPOs may be even more demanding applications in terms of frequency stability. Active piezo-controlled cavity length systems, vibrations and thermal cycles are usual sources of short term frequency variations or instabilities. Monolithic ring cavities (such as NPRO) are known to solve this problem but are quite expensive to manufacture. We will show at the conference that much simpler linear monolithic cavities used in our standard product line (SLIM-561 and SLIM-532) present best of class frequency stabilities compatible with the most demanding applications. Frequency tuning capabilities will be discussed and used in an active stabilization of the laser.

Some applications can benefit from long term wavelength stability as well. Raman spectra can be monitored without control of the pump wavelength if the long term stability is good. In addition, narrow filters can be used to measure small Stokes shifts. We are monitoring several monolithic laser sources. After more than 5000 hours of operations, the wavelength shift is within 1 pm. The laser source has bee restarted more than 1000 times without any change of the operating wavelength. Finally, thermal cycles do not impact the wavelength.

In conclusion, we demonstrate that monolithic linear cavities are best suited for all applications requiring wavelength stability.

7578-30, Session 7

Frequency doubled pulsed single longitudinal mode Nd:YAG laser at 1319 nm with pulse build-up negative feedback controls

R. Bakanas, J. Pileckas, Geola Digital uab (Lithuania)

We report on creation of frequency doubled E-O Q-switched Nd:YAG laser lasing Single Longitudinal and Transversal mode radiation at 1319 nm (4F3/2 to 4I11/2 transition) at repetition rate of 10 Hz. By means of linear resonator stable red-light pulses were obtained at 660 nm having 7mJ output energy and t = 50 ns (FWHM) pulse duration by using NCPM LBO crystal as an extra-cavity frequency doubler. Laser design incorporates particularly made fast negative feedback loop controls for pulse build-up control. It allowed obtaining much more stable laser performance as well as much shorter Optical Jitter and fast pulse build up time. To best our knowledge, these are the first time such pulse energy, rep rate Transversal and Longitudinal mode structure ever achieved in compact flashlamp pumped, E-O Q-Switched laser operating at 1319 nm.

7578-92, Session 7

A 200 mW, CW, 355 nm laser based on DPSS side pumped, internally frequency tripled technology

S. M. Jarrett, G. P. Shellikeri, O. Varela, DPSS Lasers Inc. (United States)

We have developed a new, frequency tripled 355 nm cw laser to produce power up to 200 mW. The noise level of the laser is 0.2% rms within an 8 MHz bandwidth and with a peak- to- peak noise of 2%. Side pumped Nd:YVO4 is the gain medium. The laser mode efficiently samples the diode laser array pump mode. Frequency doubling and tripling is done internal to the laser cavity to take advantage of the high, circulating 1064 nm laser power. The laser produces 355 nm power between 100 and 200 mW. We will discuss the operational characteristics and noise performance of the laser, along with some potential applications.

7578-31, Session 8

Ten years OPS lasers: review, state-of-the-art, and future developments

V. Pfeufer, C. Kannengiesser, V. Ostroumov, W. Seelert, C. Simon, A. Zuck, Coherent Lubeck GmbH (Germany)

OPSL - Optically Pumped Semiconductor Lasers have been introduced in 2001. Their unique features such as power scalability and wavelength flexibility, their excellent beam parameters, power stability and reliability opened this pioneering technology access to a wide range of applications such as flow cytometry, confocal microscopy, semiconductor inspection, graphic arts, metrology.

This talk will introduce the OPSL principles and compare them with ion, diode and standard solid state lasers. It will revue the first 10 years of this exciting technology, its current state and trends. In particular currently accessible wavelengths and power ranges, frequency doubling, ultra-narrow linewidth possibilities and reliability data will be discussed. A survey of key applications will be given.

7578-32, Session 8

GaSb-based optically pumped semiconductor disk lasers emitting at a wavelength of 2.8 µm

B. Rösener, M. Rattunde, R. Moser, C. Manz, K. Köhler, J. Wagner, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany)

In recent years, optically pumped semiconductor disk lasers (SDLs) have attracted increasing interest due to their capability of delivering simultaneously high output power and excellent beam quality [1]. While SDLs reported to date mostly covered the wavelength range between 650 nm and 2300 nm, there is also growing interest in laser sources emitting at wavelengths range around 3 µm. This spectral region is particularly important for medical applications due to the strong water absorption at lambda=2.9 µm.

GaSb-based SDLs incorporating GaInAsSb type-I quantum wells have shown to be capable of multi-Watt output power at wavelengths from 1.9 to 2.3 µm [2]. Recent results obtained for long-wavelength diode lasers have clearly indicated that wavelengths of up to 3.3 µm can be readily achieved using similar QW structures with increased Indium and Arsenic concentrations [3].

Here we report on the realization of a GaSb-based SDL emitting at a wavelength of 2.8 µm. This SDL structure grown by molecular-beam epitaxy, incorporates 10 compressively-strained Ga0.55In0.45As0.19Sb0.81 type-I QWs. The total thickness of the SDL structure was ≈12 µm. For efficient heat extraction, SiC intracavity heat spreaders were bonded to the surface of the cleaved laser chips. The active region was barrier-pumped using a 980-nm diode laser module. In this setup, up to 120 mW output power was obtained in continuous-wave operation at a submount temperature of 20°C. Under pulsed pumping, more than 500 mW peak output power could be achieved. Using an output coupling mirror reflectivity of 99.3%, a slope efficiency of 2.4 % and a threshold pump power density of 2.0 KWcm-2 were derived from the recorded output power characteristic. These results demonstrate the potential of the group III-antimonide material system for the realization of SDLs emitting at wavelengths around and even beyond 3 µm, while still achieving acceptable device performance.

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7578-33, Session 8

~1200-nm tunable fiber vertical-cavity surface emitting laser

S. L. Vetter, N. Laurand, M. D. Dawson, S. Calvez, Univ. of Strathclyde (United Kingdom)

The development of tunable sources with emission wavelength in the 1180-1320nm range is of considerable interest for their potential applications in spectroscopy, sensing (gasoline octane detection at ~1200nm [1] or Optical Coherence Tomography ~1250nm [2]) and/or communications (~1310nm). Because of their inherent compact size, efficient fibre-coupling capabilities, and ease to manufacture, tunable Vertical-Cavity Surface-Emitting Lasers (VCSELs) in either MEMS or fibre-VCSEL configuration are considered as attractive solutions for these applications.

Most of the attention to-date has however been dedicated to the long wavelength side of this spectral region. Here, we investigate the performance of a fibre-VCSEL which combines a ~1200nm semiconductor gain mirror with a HR-coated fibre. The resonant semiconductor chip, whose characteristics as the gain element of a semiconductor disk laser have already been reported in [3], includes 10 strain-compensated GaInNAs/GaAsN quantum-wells and a 29.5-pair AlAs/GaAs distributed Bragg reflector.

Whilst pumping the device through the coated-fibre with two polarisation-coupled 810nm diodes, laser action at 1197.5nm with a threshold of ~77mW and a maximum output power exceeding 0.1mW was obtained. By varying the distance between the gain chip and coated fibre tip, the emission wavelength could be tuned over 13.7nm around 1198nm.

Further improvements in performance and investigations of operation in rapid wavelength-sweeping regime will be reported at the meeting.

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7578-34, Session 8

Low-temperature study of lasing characteristics for 1.3-µm AlGaInAs quantum-well laser pumped by an actively Q-switched Nd:YAG laser

K. Su, S. C. Huang, A. Li, S. C. Liu, Y. Chen, Y. Chen, K. Huang, National Chiao Tung Univ. (Taiwan)

High-peak-power nanosecond pulsed lasers operating with emission in the 1.3-1.6 µm region are of interest in fiber sensing and communication, remote sensing, and eye-safe applications. Recently, the AlGaInAs multi-quantum wells material had been developed to be a gain medium in an optically pumped high-peak-power laser at 1.36 µm. The quantum wells / barrier structure was grown on a Fe-doped InP transparent substrate by metalorganic chemical-vapor deposition. Using a diode-pumped actively Q-switched Nd:YAG 1.06-µm laser to pump the gain chip under room-temperature operation, an average output power of 140mW had been generated at a pulse repetition rate of 10 kHz. Further, the maximum peak output power had been found to be up to 1.5 kW at a pulse repetition rate of 5 kHz. The room-temperature results had been published. However, the temperature dependent laser performance and physics have not been realized. To study the optical characteristics under low-temperature, we made a simple cavity put in the low-temperature vacuum system. The low-temperature system cooled by liquid nitrogen consisted of Janis VPF-100 cryogenic vacuum equipment and Lake Shore 331 Temperature Controller. The fluorescence and lasing characteristics were studied. The average rate of of gain peak shift was found to be 0.54 nm/K between 293-163 K. Even the thermal shrinkage during cooling process may cause a misalignment of laser cavity, the average output power of 330 mW at a controlled temperature of 233K was four times more than the average output power at a controlled temperature of 293K.

7578-35, Session 9

New developments for MOVPE-grown OPS-laser in the 1180 nm emission wavelength range

B. Kunert, NAsP III/V GmbH (Germany); T. L. Wang, Y. Kaneda, J. Hader, J. V. Moloney, College of Optical Sciences, The Univ. of Arizona (United States); S. W. Koch, W. Stolz, Philipps-Univ. Marburg (Germany)

The closed-loop design concept of microscopic modeling, epitaxial realization by MOVPE and device characterization for OPS-lasers is applied to (GaIn)As/Ga(PAs)-based MQWH device structures in the emission wavelength range around 1180 nm. The advantages of the applied specific low-temperature MOVPE growth process as well as the realized OPS-laser characteristics will be presented and compared to the predictive microscopic modelling results.

7578-36, Session 9

A 7-W 1178-nm GaInNAs based disk laser for guide star applications

T. Leinonen, V. Korpijärvi, J. Puustinen, A. Härkönen, M. Guina, M. Pessa, Tampere Univ. of Technology (Finland)

A frequency-doubled disk laser emitting at 589 nm has a high potential for realising laser guide stars, which are useful for adaptive optics based telescopes. This wavelength range has been reached by using gain mirrors based on GaInAs quantum wells with a fundamental emission at 1178 nm. However, GaInAs-based quantum wells (QWs) possess high amount of lattice strain, potentially reducing the laser lifetime. The quantum well strain can be reduced by using dilute nitride, GaInNAs, where a small amount of nitrogen is added to the lattice. In this paper, we report progress towards demonstration of multi-watt 589-nm radiation based on high-power dilute nitride disk laser emitting at 1178 nm.

The gain mirror was grown using a molecular beam epitaxy reactor and comprised 10 GaInNAs QWs and a 27-pair GaAs/AlAs distributed Bragg reflector. A 2.5 mm × 2.5 mm gain chip was attached to a wedged diamond heat spreader, which was also anti-reflective coated to reduce reflection at the air-diamond interface. The gain chip was first characterized in a V-shaped cavity without wavelength selective elements. Next, the gain chip characterized by forcing the operation wavelength to 1178 nm by an intra-cavity birefringent filter (BF).

The maximum output powers in the free-running mode and with the BF were 7 W and 5 W, respectively, both limited by the cooling capacity of the gain chip mount. Using the BF, a continuous tuning range of more than 30 nm was achieved.

7578-37, Session 9

532 nm laser sources based on intracavity frequency doubling of multi-edge-emitting diode lasers

K. Li, Univ. of Glamorgan (United Kingdom); N. J. Copner, Univ. of Glamorgan (United States); C. Gawith, Covesion Ltd. (United Kingdom); I. Knight, Oclaro, Inc. (United Kingdom)

Intra-cavity frequency doubling (ICFD) of multi-edge-emitting 1064 nm laser diode using a periodically poled lithium niobate (PPLN) bulk crystal is demonstrated. Our new cavity design uses an external dichroic mirror coated for high reflectivity in the near-infrared range and transparent for blue light emission is used as output coupling mirror. Ultra-low reflectivity coating on the output facet of a Bookham 1064 nm laser diode gives less than 0.1% in the wavelength range of 1064±10 nm, which eliminates the original diode laser cavity allowing the extended longer laser cavity to dominate. The laser output is imaged through a micro-lens array such that the fast and slow axes beam waist give a near symmetrical 24 µm beam radius focused to the midpoint of a 10 mm-long 5.0 µm period PPLN crystal supplied by Covesion. The beam waist is imaged through a focal lens array such that retro-reflection of the IR light is achieved at the output coupler, providing superior stability. A thin film narrow bandwidth IR filter is inserted in the cavity before the PPLN to restrict the spectral laser bandwidth to <0.1 nm so that optimal frequency conversion can be obtained. Even with this high intracavity loss we were able to demonstrate a highly stable CW output power of 1.2 W with the wavelength of 532.4 nm at 40 A injection current. We will discuss how more stable and efficient ICFD of multi-edge-emitting laser could be achieved by enhancing the properties of anamorphic lens, focusing lens, IR filter and polarisation control.

7578-38, Session 10

Development of rare earth doped ceramic solid state laser host materials

N. S. Prasad, NASA Langley Research Ctr. (United States); V. Shukla, R. K. Sadangi, Rutgers, The State Univ. of New Jersey (United States); U. H. Hommerich, Hampton Univ. (United States); W. Palosz, C. Wang, S. B. Trivedi, Brimrose Corp. of America (United States)

Polycrystalline ceramic laser materials are gaining importance in the development of novel diode-pumped solid-state lasers that may have applications in remote sensing and space exploration. Compared to single-crystals, ceramic laser materials offer advantages in terms of ease of fabrication, shape, size, and control of dopant concentrations. It is also potentially much less expensive to produce ceramic laser materials compared to their single crystalline counterparts because of the shorter fabrication time and the potential for mass production in large customized sizes and shapes.

Recently, we have developed Neodymium doped Yttria (Nd:Y_2O_3) as a solid-state ceramic laser material. A scalable production method was utilized to make spherical non agglomerated and monodisperse metastable ceramic powders of compositions that were used to fabricate polycrystalline ceramic material components. These powders were produced by spraying a solution precursor, made by dissolving Neodymium Nitrate and Yttrium Nitrate in deionized water, into a plasma. The powders were collected in water and were 30-50 nm in size. This processing technique allowed for high doping concentrations without the segregation problems that are normally encountered in single crystalline growth. We have successfully fabricated undoped and Neodymium doped Yttria material disks up to 2" in diameter. We are also in the process of developing other sesquioxides such as scandium Oxide (Sc_2O_3) and Lutesium Oxide (Lu_2O_3) doped with Ytterbium, erbium and thulium dopants. In this presentation, we discuss our results on the material, optical, and spectroscopic properties of the doped and undoped sesquioxide materials. The potential of solution plasma processed doped powders will be discussed.

7578-39, Session 10

Yb:YAG composite ceramic laser

E. Pawlowski, SCHOTT AG (Germany)

No abstract available

7578-40, Session 10

Cryogenically cooled solid-state lasers: Recent developments and future prospects

J. D. Hybl, T. Y. Fan, D. J. Ripin, J. T. Gopinath, A. K. Goyal, D. A. Rand, S. J. August, J. R. Ochoa, Lincoln Lab. (United States)

The properties of solid-state laser materials at cryogenic temperature are attractive for high-power operation and efficiency. In recent experiments, the power scalability and high efficiency have been demonstrated in simple laser architectures.

Operation of lasers at cryogenic temperatures has been used since the very earliest days of laser development. Generally, operation at low temperatures has been viewed as an undesirable and impractical means to improve laser performance. However, many of the fundamental laser materials properties (thermal conductivity, thermal expansion, dn/dT, saturation intensity and fluence) improve significantly as the temperature decreases. Additionally, many rare-earth-ion-doped solid-state lasers that are quasi-three-level lasers at 300 K become 4-level lasers at cryogenic temperature, leading to more efficient laser operation. The overhead associated with cryogenic cooling has been mitigated over time as cryogenics have become increasingly ubiquitous.

Recent laser demonstrations have taken advantage of the improved properties to scale the power of relatively simple end-pumped lasers to 100's of W of output power and provide performance that is not possible with conventional room-temperature lasers. These demonstrations include a 40-W average-power Ti:Al_2O_3 system operating at 10-kHz pulse repetition frequency (PRF) [1], multi-100-W cw lasers in Yb:YAG [2-4], and a 290-W average power Yb:YAG with 6-ps pulses at 80-MHz PRF [5]. This paper provides an overview of cryogenic solid-state lasers, discusses recent demonstrations, and gives a perspective on the future of this technology.

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7578-41, Session 10

Thermally induced aberrations in solid-state lasers

M. M. Tilleman, Elbit Systems of America (United States)

Optical and radiative properties of host materials for solid-state and lasers, saturable absorbers, harmonic generators and other electro-optical functions depend strongly on temperature. The dependence on temperature holds between cryogenic and up to 500C, where many of modern high-power lasers operate. That hinges on the strong dependence of some laser material properties; such as refractive index (dn/dT), thermal expansion coefficient, specific heat, thermal conductivity and thermal diffusivity on temperature. These properties determine the propagation of optical beams through such materials, effecting their trajectory, phase and aberrations. Consequently thermally induced effects in solid-state laser media are analyzed. The analysis begins by

solving the nonlinear heat-conduction with temperature dependence of the coefficient of heat conduction, k. For the case of YAG an inverse proportionality to temperature is approximated. Then, for the nonlinear optical crystal $AgGaSe_2$ useful in the region of 2 - 10 m, the relation k=A+B/T is found. For these and other cases the heat equation is linearized and solved by using Kirchoff's transformation. Further, solved is the elastic compatibility equation permitting the stress and strain analysis in the medium. Thus is determined the refractive index and the local effects on an optical beam propagating through the medium are determined. Predicted are thermally-induced optical effects including the temperature field, stress distribution, refractive index profile, ray trajectories, focal lengths, beam phases and aberrations. Most optimistic results are obtained for thin disk configuration in which the disk is attached to a heatsink and to a conducting cap on either facet.

7578-72, Poster Session

Very compact and high-power CW self-Raman laser for ophthalmological applications

T. A. Ortega, Opto Eletrônica S.A. (Brazil) and Univ. of São Paulo (Brazil); A. Lee, Macquarie Univ. (Australia); G. Z. Costal, Y. C. Fontes, G. Cunha de Castro, A. D. Mota, G. Rossi, F. M. M. Yasuoka, Opto Eletrônica S.A. (Brazil); H. M. Pask, Macquarie Univ. (Australia)

In this work, we report a very compact and high-power CW self-Raman laser for ophthalmological applications. A laser diode operating at 880nm directly pumps a Neodymium-doped Gadolinium Vanadate ($Nd:GdVO_4$). The vanadate crystal acts as the laser and Raman medium. The first Stokes line of this crystal is at 1173nm. This infrared laser is then intracavity doubled by an LBO cristal generating radiation at 586.5nm, the yellow range of the spectrum.

This cavity has an total lenght of less than 40mm and exhibits more than 2.5W CW and 3.5W in a 50% duty cycle regime. The laser operates in the fundamental with a beam quality $M^2<8.5$. The efficiency of the cavity is around 12.5%.

This laser cavity will integrate an ophthalmological photocoagulator for the retina. The equipment will be used in several ophthalmological protocols, such as, proliferative and non-proliferative diabetic retinopathy, retinal detachment, retinal tears, retinal hemorrhage, vein occlusion, glaucoma and macular edema.

This laser is on the edge of the technology for ophthalmic lasers and presents the highest-power and most efficient CW emission at 586.5nm obtained from an intracavity doubled self-Raman laser that we have been reported.

7578-73, Poster Session

A registration algorithm USING 'generalized points' for IKONOS image and LIDAR data in urban area

C. Yao, Wuhan Univ. (China)

The enormous increase in the volume of datasets acquired by LIDAR systems is leading to their extensive exploitation in a variety of applications, such as, surface reconstruction, city modeling, and generation of perspective views. Though being a fairly new technology, LIDAR has been influenced by and had a significant impact on remote sensing images. Such an influence or impact can be attributed to the complementary nature of the information provided by the two systems. For example, The processing of imagery produces accurate information regarding object space break lines (discontinuities). On the other hand, LIDAR provides accurate information describing homogeneous physical surfaces. Hence, it proves logical to combine data from the two sensors to arrive at a more robust and complete reconstruction of 3D objects.

This paper introduces an approach for the registration of the IKONOS data and the points clouds captured by LIDAR systems to a common reference frame using"generalized points" in urban area.

As for the LIDAR data and IKONOS image have obvious differences in object presentation and data characteristics, the registration methods should have some differences from the traditional approaches. Whereas the registration processing can still be divide into four parts, which are the selection of the registration primitives, similarity measure, transformation function and matching strategy respectively. In conventional methods, the registration processing usually requires enough control points of the two source data, however dot points and corner points are usually not enough for transformation and can't get perfect results.what's more, for the LIDAR data, there exist distance between neighbour points, and it is difficult to locate the control points precisely. As a result, the paper presents a registration method based on the characteristics of the lines and planes. And in mathematics, lines and planes can be seen as collections of points, then all the feature can be seen as "points", and the "points" are defined as"generalized points". Since LIDAR provides a discrete set of irregularly distributed object points, during the registration processing,"generalized points" have been used as the registration primitives.This choice is also motivated by the fact that such primitives can be plenteous, reliably, accurately, and automatically extracted from IKONOS images and LIDAR data sets, especially in city areas.The similarity measure mathematically expresses the relationship between the attributes of conjugate primitives in overlapping surfaces. The similarity measure formulation depends on the selected registration primitives and their respective attributes. For the"generalized points",the transformed "points" should coincide with the reference "points" under the ideal circumstance. However in the real condition, outliers are inevitable. If the percentage of outliers in the transformed "points" is less than the threshold, the registration is finished and the percentage threshold is the similarity measure. The most fundamental characteristic of any registration technique is the type of spatial transformation or mapping function needed to properly overlay the two data sets. Here two factors need to be taken:one is the deviation caused by elevation,and the other is the transformation function which can also be subdivided into the "Generalized points" expression and mathematical transfrom. Due to the IKONOS images are captured by the line scanner sensor, the high object in the scan direction may cause height displacement. In reality ,the displacement is not serious enough to consider about. From the calculation, the biggest displacement caused by a 100m height building is about 0.04m, so we can see the IKONOS data as the "true-orth" images. In this research, RPC(Rational Polynomial Coefficient)model and affine transformation are used in the registration transformation. RPC model for the coarse registration and the affine transformation for the preciser process.For the linear scanner system, physical model is very complex and because of the trade secretes, most of the parameters are hard to get. As a result, this paper turns to RPC geometric rectification model. In order to obtain better accuracy, the Affine Transformation should be further used.

The research established the fact that the registration using"generalized points" is efficient and essential to solve the combination of the two sources data. The dataset used in this research consists of a LIDAR data and a IKONOS data which cover the Xianyang city in china. The result of this study showed that the proposed algorithm works efficiently in our architectural environment where an abundant number of"generalized points" .Furthermore, this method can be used to the other type of terrain such as countryside, mountain areas, coastal region and so on. In addition, their distribution of the more types of the"generalized points" in different areas on the accuracy of the registration need to be investigated.

7578-74, Poster Session

Quasi-continuously pumped passively mode-locked 2.4% doped Nd:YAG oscillator-amplifier system in a bounce geometry

M. Jelinek, V. Kubecek, M. Cech, P. Hirsl, Czech Technical Univ. in Prague (Czech Republic)

Return to Contents

Efficient, high repetition diode-pumped solid-state lasers are important sources of high power radiation for wide range of applications as micromachining, ranging, remote sensing, and microsurgery. Side pumping by CW or QCW diode bars of slab active elements in grazing incidence geometry results in high gain and efficient operation. This configuration needs laser crystals with high absorption coefficients for the pump radiation and Nd:YVO4 and Nd:GdVO4 therefore has challenged Nd:YAG due to their stronger absorption at 808 nm. On the other side Nd:YAG crystals have better thermal and mechanical properties than vanadates. For pulsed Q-switched and mode-locked operation their better energy storage capacity due to the longer upper state life-time gives potential to generate more energetic pulses. Recently Nd:YAG crystals with Nd concentrations higher than 1% became available which stimulated new interest in using of such crystals in bounce geometry configuration. High efficiency laser operation of more than 2% doped Nd:YAG crystals was demonstrated.

In this paper we report mode-locked operation of 2.4at.% Nd crystalline Nd:YAG in a bounce oscillator-amplifier configuration under quasi-continuous diode pumping. The oscillator mode-locked by multiple quantum well saturable absorber in transmission mode generated output trains containing more than 100 pulses with total energy of 170uJ. The efficient pulse shortening from 120ps in the beginning to 35ps at the end of the train was observed. The amplification of the single pulse selected from the train using the identical Nd:YAG crystal will be reported as well as the comparison with similar oscillator-amplifier system based on Nd:GdVO4.

7578-75, Poster Session

Four micron radiation generated by dysprosium doped lead thiogallate laser

M. E. Doroshenko, General Physics Institute (Russian Federation); H. Jelinková, J. ?ulc, M. Fibrich, M. Jelinek, Czech Technical Univ. in Prague (Czech Republic); T. T. Basiev, V. V. Osiko, General Physics Institute (Russian Federation); V. V. Badikov, Kuban State Univ. (Russian Federation)

The lead thiogallate (PbGa2S4) crystal doped with trivalent dysprosium ions was used as a laser active medium for obtaining oscillations in mid-IR spectral region. To prove in-band pumping, the Er:YAP laser generating 1.66 um radiation was used. This radiation was focused on the 16 mm long PbGa2S4: Dy3+ crystal by CaF2 lens (f = 100 mm). This crystal was placed inside the resonator formed by an in-coupling flat-dichroic mirror with low reflectivity at pumping wavelength and with high reflectivity within the 4-5 um spectral range, and by an out-coupling mirror with reflectivity of 76, 88, 90, 93, and 95 % with 500 mm curvature. The PbGa2S4:Dy3+ laser was working at room temperature without any temperature control. The maximal reached output energy was as high as 200 uJ for optimal mirror reflectance. The incident pumping energy was 132 mJ, the estimated PbGa2S4:Dy3+ crystal absorption @ 1.66 um was less than 5%. The measured output radiation wavelength was 4325 nm with the spectrum width 25 nm (FWHM). From the point of efficiency it was recognized that the in-band pumping directly into 6H11/2 level results in decrease of lasing threshold and increase of slope efficiency.

7578-76, Poster Session

Cr:ZnSe laser pumped with Tm:YAP microchip laser

P. Koranda, J. ?ulc, Czech Technical Univ. in Prague (Czech Republic); M. E. Doroshenko, General Physics Institute (Russian Federation); H. Jelinková, Czech Technical Univ. in Prague (Czech Republic); T. T. Basiev, V. V. Osiko, General Physics Institute (Russian Federation); V. V. Badikov, D. V. Badikov, Kuban State Univ. (Russian Federation)

Cr:ZnSe laser coherently longitudinally pumped with Tm:YAP microchip laser was realised. The pumping laser consisted of Tm:YAP crystal (3x3 mm) with resonator mirrors deposited directly on its faces (on rear face the dielectric layer with high reflectance for 1998 nm wavelength and high transmittance for 790 nm pumping radiation wavelength; on output face the dielectric layer with reflectance 97% at 1998 nm wavelength). The maximal output power was 5 W and the generated radiation wavelength was 1998 nm. The main advantage of this pumping was fluctuation-free temporaly-stable output.

The Tm:YAP laser radiation was collimated and focused by the set of two CaF2 lenses. The pumping beam spot diameter inside the Cr:ZnSe crystal was 300   m. This crystal, 2.2 mm thick, was prepared by the floating zone method. The Cr:ZnSe laser resonator consisted of flat rear mirror (HT at 1998 nm, HR at 2100 - 2900 nm) and output coupler (R = 95% at 2100 - 2700 nm, r = -150 mm). The maximal output energy of stable radiation was 4 mJ (pulse duration 10 ms, repetition rate 10 Hz). For wavelength tuning the Lyott filter (1.5 mm thick quartz Z-cut plate under Brewster angle) was placed between the Cr:ZnSe crystal and output coupler. The generated radiation wavelength was continuously tunable from 2246 - 2650 nm.

7578-77, Poster Session

Complex behavior of a Yb:GdVO4 laser with bistability and polarization switching

J. Liu, W. Han, Qingdao Univ. (China); H. Zhang, Shandong Univ. (China); H. Yang, Qingdao Univ. (China); V. Petrov, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany)

Optical bistability is an intrinsic feature of a laser containing saturable absorber in its resonator. Recently, we reported bistable behavior of a diode-pumped Yb:LuVO4 laser in continuous-wave (cw) operation. Subsequently, we established that such bistability is shared by all three (Y, Gd and Lu) ordered vanadates doped with Yb and their solid solutions. This bistability is related to the presence of resonant reabsorption losses inherent to a quasi-three-level system which act as an effective saturable absorber. In comparison with Yb:YVO4 or Yb:LuVO4, the Yb:GdVO4 crystal exhibits apparently more complex behavior due to the possible coexistence and switching between the sigma and pi polarization states.

We will report the results from a detailed study of the characteristics of a bistable diode-pumped Yb:GdVO4 laser operating in the cw regime at room temperature. The laser cavity is nearly hemispherical with output coupler radius of curvature of 25 or 50 mm. Pumping with an unpolarized fiber-coupled source, the laser polarization is naturally selected by the crystal. We varied the output coupler transmission from 0.5 to 5%, the crystal thickness from 2 to 3.2 mm and compared doping levels of 0.56 and 0.9 at. %. The bistability range extends over more that 1 W in terms of absorbed pump power while the output power at the up-threshold increases abruptly from 0 to 0.71 W. We analyze in more detail the influence of the Yb concentration, the crystal thickness, the output coupling, and the cavity configuration on the bistability.

7578-78, Poster Session

Pr:YAlO3 and Pr:LiYF4 laser emission comparison under GaN laser diode pumping

M. Fibrich, H. Jelinková, J. ?ulc, Czech Technical Univ. in Prague (Czech Republic); K. Nejezchleb, V. ?koda, Crytur Ltd. (Czech Republic)

Materials doped with trivalent Praseodymium ions Pr3+ appear to be very prospective candidates for realizing laser emission in the visible region of the electromagnetic spectrum. Pr3+-ion offers several laser transitions practically throughout the whole visible range. In combination with high emission cross-section, Pr3+-doped laser hosts provide a great potential for realizing compact and efficient laser sources which can find use in different applications such as display technology, data storage, spectroscopy, and medicine.

So far, a lot has been reported about GaN-diode pumped Pr3+-doped fluoride materials. The reason for the increased attention to this class of materials (compared with oxide materials) is their low phonon energy which is supposed to lead to a weaker non-radiative decay of the upper 3P0 laser level yielding in higher quantum efficiency. Among the oxygen-containing laser compounds, the YAlO3 crystal is of the great interest, because it provides the richest number of stimulated emission intermanifold transitions and simultaneously belongs to oxide crystals with relatively small phonon energy.

In this paper we report on laser result comparison of Pr3+-doped oxide (Pr:YAlO3) and fluoride (Pr:YLF) crystals under GaN laser diode pumping at room-temperature. Pumping was accomplished by a multimode GaN laser diodes capable to provide output powers of up to 1W at the wavelengths corresponding with Pr:YAP and Pr:YLF absorption peaks. Firstly, polarization dependent absorption and emission spectra are described. Subsequently, efficient stimulated emission in the red laser transition has been demonstrated and laser results regarding the output power, threshold, and slope efficiency have been compared.

7578-79, Poster Session

Temperature effects on the operation and input/output wavelengths of a high-power fiber-coupled diode end-pumped Nd:YVO4 laser

A. F. El-Sherif, Military Technical College (Egypt)

A complete characterization for the diode laser module operating at 808 nm was performed. Based on the diode laser electrical and optical characterization, the laser diode operating at room temperature 25oC gave a higher slope efficiency with low consumption electrical power and low threshold current lasing of 1.3 A, which considered as an optimum condition that gave, maximum output performance, maximum slope efficiency of 42% with a final electrical to optical conversion efficiency of 28% at 807.96nm central wavelength with line width of 3.59nm at FWHM. The emitted laser wavelength was affected by the temperature increasing; the peak diode wavelength was shifted by 0.35nm/oC.

Moreover, the appropriate wavelength for pumping Nd3+ doped materials (around 808nm) was obtained at the temperature range of (20-25oC). Typical 808nm diode laser output was obtained with different driving input current at constant temperature of 25oC.

To illustrate the effect of changing diode temperature on the DEPSS output laser wavelength, the diode operating temperature must varied to be (12, 25, and 36oC) and consequently, the pumping central wavelength will be changed, we presented that the output DEPSS (Nd:YVO4) wavelength does not change because the broad band absorbance property for the Nd:YVO4 crystals.

DEPSS (Nd:YVO4) laser system was implemented, and its optical characteristics were measured. Stable wavelength of 1066.08nm with a linewidth of 1.48nm at FWHM at different diode pumped powers (1, 1.4, and 1.75 Watt) and at constant temperature of 25oC was measured. With diode pumping power of 6.6W, the output power was 3.273W with an output coupler reflectivity of 90%. The optical to optical slope efficiency was 56% and the final conversion efficiency was 50%. Using output coupler of 85% reflectivity produced the highest final conversion efficiency 51.5%. The Fundamental mode (TEM00) was examined, and the measured DEPSS divergence angle was 11±0.5 milliradian.

7578-80, Poster Session

Pump laser effect on temporal jittering of pulses from passively Q-Switched Nd:YVO4 laser

K. Lee, Y. Kim, J. Kwon, J. Yi, Yeungnam Univ. (Korea, Republic of)

Temporal jittering has been obstacle in practical application of passively Q-switched laser in industry. To address this, we tried two methods. The first is preventing pump laser absorption in the Cr:YAG, which is used for saturable absorber. The saturation of the Cr:YAG should be controlled by intracavity photon numbers generated by stimulated emission in Nd:YVO4 crystal for reliable Q-switching operation. For this we applied 808 nm mirror coating on the Cr:YAG crystal. This coating also enhanced efficiency of pump laser utilization because the reflected beam was reabsorbed in the Nd:YVO4 crystal. Further, as the second method, we applied pulsed current to the laser diode. The Q-switched laser is generated only after the pulse diode laser beam was absorbed in the Nd:YVO4 crystal. The pulsewidth of current pulse was carefully adjusted to secure one Q-switched output pulse per each pump pulse. The temperature of whole cavity was stabilized within 0.1°C. Air circulation is reduced by contacting crystals together and applying output coupler coating on the Cr:YAG crystal surface. These measures reduced the fluctuation considerably.

7578-81, Poster Session

Carbon nanotube saturable absorber mode-locked Tm:LiLuF4 laser

W. B. Cho, Ajou Univ. (Korea, Republic of); A. Schmidt, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany); F. Rotermund, S. Y. Choi, J. H. Yim, S. Lee, Ajou Univ. (Korea, Republic of); U. Griebner, G. Steinmeyer, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany); D. Parisi, M. Tonelli, Univ. di Pisa (Italy); V. P. Petrov, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany)

Mode-locked solid-state lasers in the 2-µm spectral range are of great interest for various applications in time-resolved spectroscopy, as pump sources for synchronously-pumped OPOs operating in the mid-IR above 5 µm, and for IR supercontinuum or THz generation. Recently, numerous Tm3+-doped materials showed high efficiency and output powers in the continuous-wave and Q-switched laser regimes. However, only active mode-locking has been demonstrated up to now with bulk Tm-lasers, except our most recent demonstration of first passive mode-locking with a Tm-doped tungstate laser.

Here, we demonstrate a self-starting passively mode-locked Tm:LiLuF4 (Tm:LLF) laser using a transmittive single-walled carbon nanotube based saturable absorber (SWCNT-SA). Arc-made SWCNTs with the absorption band around 2 µm corresponding to the E11 transition of SWCNTs were utilized for laser mode-locking. The nonlinear dynamics of the SWCNT-SA were investigated by the pump-probe technique at 1.92 µm. The recovery time of the SWCNT-SA was estimated to be ~1.2 ps. For passive mode-locking, the SWCNT-SA was inserted into an additional focusing section of the Tm:LLF laser cavity and mounted under Brewster angle to minimize reflection losses. In the mode-locked regime, without any dispersion compensation, a maximum average output power of 140 mW was achieved with a 1.5% output coupling. The RF spectrum at the fundamental beat note of 126.1 MHz was recorded with an extinction ratio of >50 dBc. This high signal-to-noise ratio and an additional 1-GHz wide span measurement clearly indicate stable cw single-pulse mode-locking without Q-switching instabilities. Further investigation will be directed towards generation of broadband femtosecond pulses.

7578-82, Poster Session

Coherently pumped Er:YAlO3 lasers

M. Nemec, H. Jelinková, J. ?ulc, Czech Technical Univ. in Prague (Czech Republic); K. Nejezchleb, V. ?koda, Crytur Ltd. (Czech Republic)

The main goal of this work was the investigation of Er:YAlO3 crystals as active materials for coherent pumping by Er:glass laser. For comparison, three various Er:YAG crystals in the same conditions was also evaluated. Pulse pump radiation was generated at the wavelength 1535 nm with 0.5 Hz repetition rate and was simple focused into the active crystal by CaF2 lens.

For designed laser, the 10 mm and 20 mm long Er:YAlO3 crystals with 1 at.% concentration Er/Y ions were used as active materials. The curved pumping mirror of oscillator had high transmittance at the pumping wavelength (T > 95% @ 1535 nm) and maximal reflectance at the generating wavelength around 1640 nm. The output flat dielectric coupler reflectance was 90 % at 1640 nm.

For 555 mJ incident pump energy, the output generated energy was 20 mJ at the resonant lasing wavelength 1623 nm. The slope efficiency of the output energy to the absorbed energy was 44 % with 10 mm Er:YAlO3 active crystal. The laser threshold was obtained for 150 mJ incident pump energy. The spatial beam structure was closed to the fundamental profile.

Due to the low quantum defect the systems were operated without any cooling of active materials and the stability of laser systems output parameters was still excellent.

7578-83, Poster Session

Medium range high accuracy semiconductor laser range finder

J. Chen, Chung-Hua Univ. (Taiwan)

A medium range high accuracy semiconductor laser range finder, measures range of 30cm to 100m, with high accuracy of ±1mm, using the semiconductor laser source, with modularized avalanche photo-detector high sensitive receiver, will be present and analysis in detail. The transceiver of the laser range finder is the optimized semiconductor laser transmitter in conjunction with the modularized APD high sensitive receiver. The high frequency phase resolved algorithm makes the measure accuracy better than ±1mm. We will present the novel technologies and the system configuration.

7578-84, Poster Session

Influence of temperature on Nd:YAG/V:YAG compact laser generation at 1444 nm

J. ?ulc, J. Novak, H. Jelinková, Czech Technical Univ. in Prague (Czech Republic); K. Nejezchleb, V. ?koda, Crytur Ltd. (Czech Republic)

Compact Q-switched diode-pumped laser emitting radiation at eye-safe wavelength 1444 nm was studied. This laser was based on composite crystal (diameter 5 mm) consisting of 4 mm long Nd:YAG active medium diffusion bounded with 1 mm long V:YAG saturable absorber (initial transmission @ 1440 nm 94 %). The laser resonator mirrors were directly deposited onto the composite crystal surfaces. These mirrors were designed to ensure emission at 1444 nm and to prevent parasitic lasing at other Nd^{3+} transmissions. The pump mirror (R < 10 % for pump radiation @ 808 nm, R < 2 % @ 1064 nm, R < 15 % @ 1330 nm, HR @ 1444 nm) was placed on the Nd^{3+}-doped YAG part. The output coupler with reflectivity 94 % for the generated wavelength 1444 nm was placed on the V^{3+}-doped part (R < 5 % @ 1064 nm, R < 15 % @ 1330 nm). The laser was operating under pulsed pumping for the duty-cycle up to 50 %. Temperature dependence of giant pulse energy and length was studied independently on pumping pulses duty cycle. It was found that for constant duty cycle 0.75 % and for crystal holder temperature rise from 8 to 34 °C the pulse width dropped from 31 to 5.4 ns and pulse energy rose from 17 to 54 µJ. This represents peak power increase from 0.54 up to 10 kW. The laser threshold was not changed significantly with temperature. From a mathematical model of passively Q-switched laser follows that this behavior can be explained by temperature caused decrease of excited-state absorption cross-section of V:YAG saturable absorber at wavelength 1444 nm.

7578-86, Poster Session

Powerful narrow-line source of blue light for laser cooling Yb/Er and Dysprosium atoms

S. M. Kobtsev, Novosibirsk State Univ. (Russian Federation) and Tekhnoscan JSC (Russian Federation); B. Lev, Univ. of Illinois at Urbana-Champaign (United States); J. Fortágh, Univ. of Tuebingen (Germany); V. I. Baraulya, Tekhnoscan JSC (Russian Federation)

This report for the first time presents the results of parameter optimisation of ultra-narrow-linewidth frequency-doubled CW Ti:Sapphire lasers pumped with 12.5-18.5 W of 532-nm light. Proposed laser systems are designed for atom cooling and provide output radiation power of more than 700 mW at 399/401 nm (Ytterbium/Erbium) when pumped at 12.5 W and more than 1 W at 421 nm (Dysprosium) pumped at 18.5 W. The output power of single-frequency radiation at 421 nm achieved during the present work is the highest published to-date for a commercially available system achieving a 10 kHz linewidth. It is relevant to note that these high powers of frequency-doubled radiation were generated without the use of periodically-poled non-linear crystals or complicated approaches with injection of single-frequency radiation into the Ti:Sapphire laser in order to raise its output power. This paper discusses specific features of generation in single-frequency ring Ti:Sapphire lasers at high pump radiation levels, including cases of Ti:Sapphire crystals with FOM > 500. Also studied are the effects of thermal lensing inside the active laser medium upon spatial parameters of the output beam. Additionally, we analyse parameters of resonant radiation frequency doublers required for generation of well-shaped beam in the blue range and highly efficient reliable operation possible because of an automated electronic system that is able to re-lock the transmission peak maximum of the doubler cavity to the frequency of the input radiation. The width of the blue radiation line does not exceed 10 kHz and the intensity fluctuations of the frequency-doubled radiation are within 6%. This study demonstrates the results of successful application of the presented powerful sources of ultra-narrow-linewidth blue light in experiments on laser cooling and trapping of atoms.

7578-87, Poster Session

LIBS system with compact fiber spectrometer, head mounted spectra display and hand-held eye-safe erbium glass laser gun

M. J. Myers, J. D. Myers, J. T. Sarracino, C. R. Hardy, B. Guo, S. M. Christian, J. A. Myers, F. Roth, A. G. Myers, Kigre, Inc. (United States)

LIBS (Laser Induced Breakdown Spectroscopy) systems are capable of real-time chemical analysis with little or no sample preparation. A Q-switched laser is configured such that laser induced plasma is produced on targeted material. Chemical element line spectra are created, collected and analyzed by a fiber spectrometer. Line spectra emission data is instantly viewed on a head mounted display. “Eye-safe” Class I erbium glass lasers provide for in-situ LIBS applications without the need for eye-protection goggles. This is due to the fact that Megawatt peak power Q-switched lasers operating in the narrow spectral window between 1.5um and 1.6um are approximately 8000 times more “eye-safe” than other laser devices operating in the UV, visible and near infrared.

In this work we construct and demonstrate a LIBS system that includes a hand held eye-safe laser gun. The laser gun is fitted with a micro-integrating sphere in-situ target interface and is designed to facilitate chemical analysis in remote locations. The laser power supply, battery pack, computer controller and spectrophotometer components are packaged into a utility belt. A head mounted display is employed for “hands free” viewing of the emitted line spectra. The system demonstrates that instant qualitative and semi-quantitative chemical

analyses may be performed in remote locations utilizing lightweight commercially available system components ergonomically fitted to the operator.

7578-88, Poster Session

Dynamic 3D modeling of solid state laser resonators using a coupled thermo-optical finite element analysis

M. Wohlmuth, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany); K. Altmann, LAS-CAD Gmbh (Germany); J. Werner, C. Pflaum, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany)

The complex behavior of the optical wave in laser resonators requires a combined model of thermal lensing and the dynamic 3-dimensional behavior of the laser beam. In this work, we explain how a finite element analysis (FEA) can be used to model the optical wave in the resonator accurately. Up to now, common techniques like beam propagation methods or Gaussian mode analysis cannot provide a dynamic 3-dimensional simulation of the laser beam. For example, beam propagation methods are not able to simulate long periods. To overcome this difficulty, we introduced in a previous work a "Dynamic Multimode Analysis (DMA)" which is able to analyze mode competition. This approach provides good results for output power and beam quality of Q-switched resonators. However, the DMA using Gaussian modes is restricted to the paraxial approximation and requires assumptions on transverse mode coherency. Therefore, we now propose an immediate FEA of the wave equation. From a numerical point of view, the simulation of the optical wave by finite elements is a challenging task. For this reason, we apply a two-wave ansatz to the wave equation which leads to a modified Schroedinger equation for the optical wave. Furthermore, we explain how different kinds of optical elements and thermal lensing can be modeled in this context. By coupling the FEA of the optical wave to a dynamic model of thermal lensing and to space-dependent rate equations, we analyze the dynamic interaction of thermal lensing, mode competition, pulse generation, and other physical effects in the resonator.

7578-89, Poster Session

Enhanced 5-μm emission in Tm,Tb: KPb2Br5 and Tm,Nd:KPb2Br5 for mid-infrared laser applications

A. G. Bluiett, Elizabeth City State Univ. (United States); E. Brown, U. H. Hommerich, Hampton Univ. (United States); S. B. Trivedi, Brimrose Corp. of America (United States); J. M. Zavada, North Carolina State Univ. (United States)

There continues to be a significant current interest in the development of new solid-state gain media for mid-infrared (MIR) lasers. Ternary lead halide materials have recently emerged as novel laser hosts with low maximum phonon energies, which lead to reduced non-radiative decay and efficient emission in the MIR region. Among these halides, KPb2Br5 (KPB) is especially attractive for laser applications due to its low moisture sensitivity and low maximum phonon energy of only ~138 cm-1. In this work, we report on the 5 um emission characteristics and energy transfer properties of Tb3+ doped KPB and Nd3+ doped KPB sensitized by Tm3+ ions. A series of co-doped samples of Tm,Tb: KPB and Tm,Nd: KPB samples were prepared from purified starting materials of PbBr2, KBr, and rare earth halides. Resonant excitation into the 3F4->3H6 absorption transition of Tm3+ at ~1760 nm resulted in an enhanced 5 um emission from Tb3+ and Nd3+ ions in Tm,Tb: KPB and Tm,Nd: KPB, respectively. The existence of energy transfer between Tm -> Tb and Tm -> Nd in KPB was further evidenced by the quenching of the emission decay times of the 3F4 -> 3H6 transition of Tm3+ in doubly doped Tm,Tb: KPB and Tm,Nd: KPB compared to singly doped Tm: KPB. More detailed studies on the energy transfer properties in Tm, Tb: KPB and Tm, Nd: KPB and its relevance for mid-IR laser applications will be discussed at the conference.

7578-90, Poster Session

Single frequency monolithic green DPSS laser

J. Sotor, A. Antonczak, K. Abramski, Wroclaw Univ. of Technology (Poland)

We present the concept and practical realization of a monolithic single frequency diode pumped Nd:YVO4/YVO4/KTP microchip laser operating at 532nm. Theoretical analysis of the single mode operation of such a laser configuration is presented. The single frequency operation has been obtained in a birefringent filter, where an YVO4 beam displacer acts as an ideal polarizer. Experimental results are in good agreement with theoretical analysis. Laser radiation spectral analyzes at 1064nm are presented. We have obtained stable single frequency operation, tunable over 0.5nm in the spectral range around 1064nm. In order to show pure single frequency operation the heterodyne of the lasers were built. The heterodyne spectra are presented. The laser operated with output power up to 110mW at 532nm. The total optical efficiency (808nm to 532nm) was 14%.

7578-43, Session 11

Multi-kHz multi-mJ phase stabilized OPCPA amplifier system

M. Hemmer, A. Vaupel, B. Webb, M. C. Richardson, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

An OPCPA system that amplifies pulses emitted by a Ti:Sapphire oscillator producing pulses as short as 5 fs is nearing completion at TLI. The OPCPA system is designed to provide 8 fs pulses with 2 mJ of energy at repetition rates between 10 and 20 kHz. The OPCPA amplifier chain comprises several amplifiers using both fiber and solid-state laser technology. A fiber preamplifier is a key element of the system as it seeds a chain of solid state amplifiers consisting of a Nd:YVO4 based regenerative amplifier, a double pass Nd:YVO4 amplifier and a Nd:YAG booster amplifier. The entire amplifier chain is designed to produce 40 ps pulses with energy up to 20 mJ at repetition rates beyond 10 kHz.

Optical synchronization between the pump and signal in the OPA is achieved by sampling a low energy, narrow spectral line around 1064 nm from the signal beam. Amplification of the 10 pJ seed pulses while maintaining excellent signal to ASE ratio is achieved in the fiber preamplifier by a two stage design enabling ASE filtering between stages. The preamplifier produces 20 ps pulses at 85 Mhz with an overall gain of ~20 dB resulting in an output pulse energy of up to 5 nJ. The use of polarization maintaining single mode fiber ensures perfect TEM00 spatial profile and linear output polarization. Overview of the overall system will be presented with stronger emphasis on the fiber preamplifier and the solid state amplifier chain.

7578-44, Session 11

Intensity scaling of non-cryo-cooled Ti:sapphire amplifiers

A. R. Fry, J. Y. Heritier, K. J. Chu, R. Viselga, A. Magana, Coherent, Inc. (United States)

The predictable trend in commercial Ti:sapphire based ultrafast amplifiers has been increased power and pulse energy and decreased pulse width. In recent years significant advances in power and pulse width have come at corresponding increases in cost and complexity of the systems, for example the use of cryogenic cooling of the amplifiers to sustain increased power and the use of active spectral phase control to achieve shorter pulse widths. In this talk we review recent improvement in amplifier performance that use refinements of conventional designs and do not require the higher cost technology previously implemented to achieve this performance. Significant performance gains have resulted,

including pulse energy of >10mJ at 1kHz, average power of >15W at 5kHz, and pulse width of <25fs.

7578-45, Session 11

Sectional chirped volume Bragg grating compressors for high-power chirped-pulse amplification

O. G. Andrusyak, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); L. Canioni, Univ. Bordeaux 1 (France); I. Cohanoshi, OptiGrate Corp. (United States); M. Delaigue, Amplitude Systemes (United States); E. V. Rotari, V. I. Smirnov, OptiGrate Corp. (United States); L. Glebov, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

Chirped Bragg Gratings (CBGs) recorded in photo-thermo-refractive (PTR) glass have been successfully used as ultrashort pulse stretchers and compressors in a variety of solid-state and fiber chirped pulse amplification (CPA) laser systems. Compared to traditional pairs of surface gratings, CBG-based stretchers and compressors offer significant advantage in compactness and robustness. They are insensitive to polarization, require virtually no alignment and can handle high average and peak power. At the current technology stage PTR-glass CBGs can provide up to 30 nm spectral bandwidth and up to 300 ps stretched pulse duration.

In this paper we propose a concept of sectional CBGs, where multiple CBGs with different central wavelengths recorded in separate PTR glass wafers are stacked and phased to form a single grating with effective thickness and bandwidth larger than each section.

We present results of initial experiment in which pulses from a femtosecond oscillator centered at 1028 nm are stretched by a 32-mm thick CBG to about 160 ps and recompressed by a monolithic 32-mm CBG with 11 nm bandwidth and by a sectional CBG with two 16-mm thick sections each having ~ 5 nm bandwidth and offset central wavelengths: 1025.5 and 1031 nm. In both cases, compressed pulse duration of 350-400 fs, ~ 1.1 × transform-limit was obtained.

These results allow CBG-based pulse stretchers and compressors with high stretch ratio and wide bandwidth to be constructed from multiple sections.

7578-46, Session 11

A compact dispersive delay generator using angular dispersion amplification

S. Basu, Sparkle Optics Corp. (United States)

In this paper, we will present the design of a novel dispersive delay generator that is capable of producing 1 ns / nm dispersive delay in a compact footprint. The path length delay produced by a grating and free space is amplified by introduction of a total internal reflection surface operating at an angle of incidence near the critical angle. Both positive and negative amplification may be realized by changing the orientation of the angular dispersion amplifier optic. Because this method produces significant pulse stretching for a given pulse bandwidth, it may lead to higher peak power laser sources in the future.

In a design example, a p-polarized input beam at 1050 nm is incident on a diffraction grating. The diffracted beam propagates through space and enters a prism at normal incidence through one of the faces. The transmitted beam is then incident on the prism to air interface at an angle close to the critical angle. When the beam leaves the prism, the angular dispersion is greater than what is present in the beam entering the prism. The net result is an amplification of the angular dispersion produced by the grating alone [1]. The beam then propagates through free space and enters another prism-grating combination and a retro reflector. This produces the path delay. The delay may be conveniently controlled by varying the spacing between the two prisms. The beam travelling in the reverse direction, retraces its path for each wavelength component until it meets the first grating where the wavelength components are again multiplexed along the same propagation direction with a slight offset between the plane of incidence and plane of exit. This allows physical separation of the output beam from the input beam.

This delay generator has applications in pulse compressor, pulse stretcher or pulse shaper in chirped pulse amplification and high-resolution time gated spectroscopy.

References

1. S. Basu, U.S. Patent 7,139,447 (2006)

7578-47, Session 11

Time-gating processes in intra-cavity mode-locking devices like saturable absorbers and Kerr cells

N. S. Prasad, NASA Langley Research Ctr. (United States); C. Roychoudhuri, Univ. of Connecticut (United States)

Photons are non-interacting entities. Light beams do not interfere by themselves [1]. Light beams constituting different laser modes (frequencies) are not capable of re-arranging their energies from extended time-domain to ultra-short time-domain by themselves without the aid of light-matter interactions with suitable intra-cavity devices [2]. In this paper we will discuss the time-gating properties of intra-cavity "mode-locking" devices that actually help generate a regular train of high energy wave packets.

[1] C. Roychoudhuri, "Inevitable incompleteness of all theories: an epistemology to continuously refine human logics towards cosmic logics"; Ch.6 in The Nature of Light: What is a Photon? by C. Roychoudhuri, A. F. Kracklauer & Kathy Creath; CRC/Taylor & Francis (2008).

[2] C. Roychoudhuri & N. S. Prasad, "Light-matter interaction processes behind intra-cavity mode locking devices." SPIE Conf. Proc. Vol.7193, paper #67 (2009).

7578-48, Session 12

Q-switched resonantly diode-pumped Er:YAG laser

I. Kudryashov, A. Katsnelson, Princeton Lightwave, Inc. (United States)

To address the imperative for high power lasers for use in the eye-safe spectral domain beyond 1.4 μm, recent development efforts have been directed towards demonstrating solid-state lasers (SSLs) based on Er3+-doped materials. The resonant pumping of SSLs allows for the shifting of a significant portion of the laser system thermal load from the gain medium itself to the pump diodes, thus greatly reducing gain medium thermal distortions which prevent SSL power scaling with high beam quality.

In this paper we report results of our investigation of a resonantly diode-pumped Q-switched Er:YAG laser. These experiments employed an end-pumping geometry and a rod with 0.5% Er doping. The SSL was pumped by the 1475 nm laser diode pumping source based on the spatial combination of multiple individual emitters. This source provided >60 W peak power in 6ms/40Hz operation. The pump diodes provided high spectral brightness achieved by implementing volume Bragg gratings for narrowing the spectral width to less than 1 nm, thereby allowing "in-line" pumping of Er3+. We used an acousto-optic modulator to obtain Q-switched operation. The Q-switched Er:YAG SSL provides output pulses with more than 11 mJ in 50 ns pulse widths at 1645 nm. The beam quality of laser was characterized to be M2 < 1.2.

7578-49, Session 12

Efficient, 1.5W CW and 7 mJ quasi-CW TEM00 mode operation of a compact diode-laser-pumped 2.94µm Er:YAG laser

G. Sousa, Sheaumann Laser, Inc. (United States)

An efficient, compact diode-laser-pumped 2.94µm Er:YAG laser operating at 1.5 W continuous output power in a TEM00 beam with M^2<1.17 has demonstrated pulsed operation in the quasi-cw regime with energies up to 7mJ. Power scaling and output beam fiber-coupling at 85% efficiency in a hermetic package will be described.

7578-50, Session 12

Two-micron cryogenically cooled solid state lasers: recent progress and future prospects

J. I. Mackenzie, J. W. Kim, L. Pearson, W. O. S. Bailey, Y. Yang, W. A. Clarkson, Univ. of Southampton (United Kingdom)

Efficient powerful laser sources in the two-micron regime are in demand for many applications in the areas of remote-sensing, defence, medicine, and materials interactions. Dramatic progress has been demonstrated in cw-power scaling of 2-micron fibre lasers; however, power-scaling in a pulsed mode of operation is limited by nonlinear effects and a relatively low damage-threshold-power. To fully capitalise on the potential advantage for high pulse-energies of the conventional 'bulk' 2-micron solid-state laser, extreme measures have to be taken to mitigate the three-level character and thermal effects in the laser medium resulting from heat generated during the pump cycle. Alleviation of these detrimental effects can be achieved by simply cooling the gain medium to cryogenic temperatures, benefitting from lower population in the terminal laser levels, and a large increase in the thermal conductivity, with a proportional decrease in the thermo-optic coefficient (dn/dT) and expansion coefficient. Combined these result in a massive reduction in thermo-optic aberrations. In this paper, we report on improved measurements of the spectroscopic properties of Ho:YAG at various temperatures between room and liquid nitrogen (LN) temperatures, utilising a multi-Watt Tm:fibre ASE source we have been able to properly identify the absorption features of interest with an accuracy better than 0.2nm. Results for other Ho-doped gain media will be discussed and the latest performance of a cooled 2-micron Ho:YAG laser in-band pumped by a narrow-linewidth Tm fibre laser presented.

7578-51, Session 12

Atmospheric propagation testing with a high-power tunable thulium fiber laser system

T. S. McComb, L. Shah, R. A. Sims, V. Sudesh, M. C. Richardson, Townes Laser Institute, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

A tunable master oscillator power amplifier fiber laser system based on thulium doped silica fiber designed for investigation of multi-kilometer propagation through atmospheric transmission windows existing from ~2030 nm to ~2050 nm and from ~2080 nm to beyond 2100 nm is demonstrated. The system includes a master oscillator tunable over >160 nm of bandwidth from 1947 nm to beyond 2110 nm capable of up to 10 W of linearly polarized, stable, narrow linewidth output power with near diffraction limited beam quality. Output from the seed laser is amplified in a power amplifier stage designed for operation at up to 200 W CW. Tests running the power amplifier stage as an oscillator indicate the ability to run at full power for over one hour with <1% power drop, critical for some long duration propagation tests. Theoretical modeling of this amplifier will also be presented. The system is designed to be robust and portable and fit on a 6' x 2' breadboard. Field testing of this system at the Innovative Science & Technology Experimental Facility (ISTEF) laser range on Cape Canaveral, Florida will be discussed. Results presented will include investigation of transmission versus wavelength both in and out of atmospheric windows, in different environmental conditions, and at a variety of distances. Investigations of beam quality degradation at ranges up to 1 km at a variety of wavelengths both in and out of atmospheric transmission windows will be also presented. Available theoretical models of atmospheric transmission are compared to the experimental results.

7578-52, Session 13

Optically dense Fe:ZnSe crystals for energy scaled gain switched lasing

N. Myoung, Univ. of Alabama at Birmingham (United States); V. V. Fedorov, S. B. Mirov, Univ. of Alabama at Birmingham (United States) and Ctr. for Optical Sensors and Spectroscopies (United States)

Fe:ZnSe have recently been shown to lase over 3.9-5.1µm spectral range at room temperature in a gain-switched regime of oscillation. However, the gain element featured a small optical density and was easily saturated, which resulted in an output energy not exceeding 0.5 mJ. This work is focused on study and optimization of diffusion of Fe in ZnSe from the metal phase, comparative spectroscopic characterization of kinetic properties of Fe:ZnSe crystals with a wide range of concentrations, and energy scaling of the Fe:ZnSe gain-switched laser. Iron doping of ZnSe polycrystals was performed by thermal diffusion from the iron film made by thermal evaporation process. Special cleaning of the ZnSe surfaces and optimization of the ZnSe substrate temperature and the rate of Fe evaporation resulted in significant enhancement of the diffusion process and enabled fabrication of high optical density crystals with Fe concentration up to 2x10^20cm^-3. The diffusion coefficient and diffusion length of iron in ZnSe at 1000   were estimated as 6.6x10^-10cm^2/s and 1.8mm, respectively. We report a detailed absorption, emission, and kinetics of fluorescence of Fe:ZnSe spectroscopy performed over a broad range of Fe concentrations (3x10^18 to 2x10^20 cm^-3) and temperatures (14-300K) under direct 2.92µm and 0.532µm excitation via photo-ionization transitions. In our presentation we will also discuss lasing of the highly doped Fe:ZnSe crystals under short pulse (5ns) 2.92µm pump laser based on 2nd Stokes D2 Raman shifted Nd:YAG laser, and issues specific to energy scaling of Fe:ZnSe gain switched laser.

7578-53, Session 13

Laser-spectroscopic study of Er doped PbWO4 as laser and stimulated Raman scattering active crystals

I. S. Mirov, Univ. of Richmond (United States); V. V. Fedorov, The Univ. of Alabama at Birmingham (United States); S. Beloglovsky, S. Burachas, Y. Saveliev, North Crystals (Russian Federation)

The objective of this work is to analyze the feasibility of making an Erbium doped PbWO4 solid state laser system capable of operating at room temperature at 1.9 and 3.6µm for pumping Cr:ZnSe/S and Fe:CdMnTe crystals and mid-infrared medical and trace gas analysis applications.

Two technologies are combined for this laser system. First, a fiber-bulk or diode-bulk hybrid laser approach for direct pumping of the 4I13/2 and/or the 4I11/2 multiplets featuring a long fluorescence lifetime that allows for the high energy storage capability of Er and the effective conversion of the CW pump into a Q-switched 1.6 or 2.7 µm radiation. The second was to use PbWO4 Raman crystal as a host for Er ions that can provide self stimulating Raman lasing at 1.9 and 3.6µm.

The PWO crystals were grown using the Czochralski method with concentrations from 0.2% to 4%. The polarized optical absorption, emission, and kinetics of fluorescence were measured at both low (14K)

and room temperature and over a spectral range of 0.2 to 3 microns. The spectroscopic data were then used to calculate the absorption and luminescence cross sections.

Studies of Raman laser threshold of 1.9 and 3.6 µm in Er:PWO are presented. Experiments on the self-Raman shifting in the Er:PWO lasers with Cr:ZnSe passive Q-switch are discussed. In this configuration Cr:ZnSe crystal acts simultaneously as a saturable absorber as well as amplifying medium for Raman-shifted wavelength.

7578-54, Session 13

Cr-ZnSe passively Q-switched fiber-bulk Ho:YAG hybrid laser

Y. Terekhov, I. S. Moskalev, V. V. Fedorov, D. V. Martyshkin, The Univ. of Alabama at Birmingham (United States); S. B. Mirov, The Univ. of Alabama at Birmingham (United States) and Photonics Innovations, Inc (United States)

It has been shown that direct resonant laser pumping of the Ho 5I7 manifold, featuring high cross-section and long fluorescence lifetime, results in a high energy storage capability and efficient Q-switched operation of holmium lasers. Resonantly pumped Q-switched Ho:YAG lasers have been successfully documented in the literature. However, only a few of them were based on passive Q-switched regimes of operation.

The objective of this work was to develop a compact and efficient TEM000 Tm-fiber-Ho:YAG, hybrid laser passively Q-switched by Cr:ZnSe saturable absorber. We used a folded semi-hemispherical 10 cm long cavity with a plane output coupler and a 0.5 m concave high reflector. Such an arrangement allows one to accommodate a Brewster-cut Cr:ZnSe passive Q-switch while preserving it from saturation by the pump beam. In these experiments we studied the performance of two high optical quality Cr2+:ZnSe crystals as saturable absorbers with initial transmissions of 93.9% and 70% at 2.1 micron. With the 93.9% transmission crystal, passive Q-switching was realized with a maximum output power of 5 W, pulse energy of 0.5 mJ, pulse duration of 150 ns, and Q-switched-to-CW-mode extraction efficiency of 60%. With the 70% transmission crystal, passive Q-switching was achieved with a 75% Q-switched-to-CW-mode extraction efficiency, pulse energy of 3.5 mJ, and duration of 7ns. The laser demonstrated sustained damage-free, TEM000 operation with 0.5 MW of peak power showing promise for applications requiring high-peak-power, diffraction-limited beams, and single-frequency regimes of operation.

7578-55, Session 13

InP diode-pumped Cr:ZnS and Cr:ZnSe highly-efficient widely-tunable mid-IR lasers

I. S. Moskalev, V. V. Fedorov, The Univ. of Alabama at Birmingham (United States); S. B. Mirov, The Univ. of Alabama at Birmingham (United States) and Photonics Innovations, Inc. (United States)

We present compact, highly-efficient, widely-tunable CW lasers based on Cr2+:ZnS and Cr2+:ZnSe gain media longitudinally pumped by a single-emitter, 1.5 W, 1685 nm InP semiconductor laser. The Cr2+:ZnSe laser demonstrates 35% slope, and 24% real optical efficiency, respectively, up to 400 mW of output power, and is tunable from 2200 to 2700 nm. The Cr2+:ZnS laser shows 44% slope, and 31% real optical efficiency, respectively, up to 500 mW of output power, and is tunable over 2100-2700 nm. The single-emitter diode pumping of chromium-doped chalcogenides allows for fabrication of middle-infrared tunable laser sources where low- or mid-range output powers are sufficient, while low footprint and miniature packaging are strictly required. In our presentation we will discuss the laser design issues specific to diode pumping, demonstrate the performance of the Cr:ZnS and Cr:ZnSe laser systems with different transmissions of the output couplers, describe several approaches for convenient wavelength tuning, and perform a comparison of diode pumping efficiency to that of fiber-laser pumping.

7578-56, Session 14

Physical and engineering aspects of passively Q-switched microlasers

Y. Y. Kalisky, Nuclear Research Ctr. Negev (Israel)

The issue of microlasers and micro-chip devices, passively Q-switched and doped with rare earth lasing ions is well established. The various components of such monolithic lasers are diffusion-bonded to the gain medium or alternatively separated. Laser performance of several configurations based on various hosting crystals, as well as analytical modeling of the Q-switching process will be presented and discussed. The effect of various types of Q-switches on the laser performance will be presented and analyzed.

7578-57, Session 14

An injection seeded single frequency Nd:YAG Q-switched laser with precisely controllable laser pulse firing time

F. F. Wu, A. Khizhnyak, V. B. Markov, MetroLaser, Inc. (United States)

We have realized a single frequency Q-switched Nd:YAG laser with precisely controllable firing time and thus enable synchronization of multi-laser systems. The use of the injection seeding to the slave ring oscillator results in unidirectional Q-switched laser oscillation with suppression of bidirectional Q-switched oscillation that otherwise would be initiated from spontaneous emission if the seeding laser is not presented. Under normal condition, the cavity is in high loss during pumping period; then a Pockels cell opens the cavity to form the pulse build up, with a second Pockels cell to perform cavity dumping, generating the Q-switched pulse output with optimized characteristics. The two Pockels cells can be replaced by a single unit if an adjustable gated electrical pulse is applied to Pockels cell in which the pulse front to open the cavity and the falling edge to dump the laser pulse. Proper selection of the pump parameters and Pockels-cell gating enables operation of the system in a mode in which the Q-switched pulse can be formed only under the seeding condition. The advantage of the realized regime is in stable laser operation with no need in adjustment of the seeded light wavelength and the mode of the cavity. It is found that the frequency of the Q-switched laser radiation matches well to the injected seeded laser mode. By using two-stage amplifiers, an output energy better than 300 mJ has been achieved in MOPA configuration without active control of the cavity length with pulse width adjustability from several nanoseconds to 20 ns.

7578-58, Session 14

2-MHz repetition rate, 200-ps pulse duration from a monolithic passively Q-switched microchip laser

A. Steinmetz, D. Nodop, J. Limpert, Friedrich-Schiller-Univ. Jena (Germany); A. Tünnermann, Friedrich-Schiller-Univ. Jena (Germany) and Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); R. Hohmuth, W. Richter, BATOP GmbH (Germany)

In this contribution we report on a diode-pumped, monolithic and passively Q-switched microchip laser generating 200 ps pulses at a wavelength of 1064 nm with a repetition rate of up to 2 MHz. By varying the pump intensity we can change the repetition rate in the range from 100 kHz to 2 MHz and achieve pulse energies from 400 nJ to 130 nJ,

while still maintaining singe transversal and longitudinal mode operation. The microchip laser is based on Nd:YVO4 as the gain medium and a SESAM as the passive Q-switch, and monolithically bonded with spin-on-glass as bonding agent. The timing jitter was measured to be shorter than 40 ns for low and 2.5 ns for high repetition rates resulting in a relative timing jitter smaller than 1%.

In addition, the signal can be amplified easily to the range of few tens of watts using only one stage amplification based on a photonic crystal fiber. It has been shown that picosecond pulses are more advantageous over nanosecond pulses mostly in terms of precision. Another important aspect is the high repetition rate of the pulses, which enables a high processing speed. The combination of picoseconds pulses, high average power and high repetition rates makes this system very suitable and interesting for many applications e.g. micromachining like micromilling and microdrilling.

To the best of our knowledge these are by far the highest repetition rate and widest range of 100 kHz to 2 MHz obtained from a single monolithic passively Q-switched microchip laser.

7578-59, Session 14

Intracavity frequency doubled Nd:YAG laser with dual-stability-range cavity emitting high-power near-diffraction-limited radiation in CW and Q-switched mode

D. Woll, J. Gregg, J. Lefort, J. J. Morehead, J. Lindahl, JDSU (United States)

Diffraction-limited, high-power radiation in the visible and ultraviolet is well suited for numerous applications in precision material processing and micro machining. A laser providing both, high-power CW radiation and high-energy nanosecond pulses is a versatile tool for such applications. We demonstrated a diode-pumped frequency-doubled Nd:YAG laser that can emits 7.1 W of 532 nm radiation in the cw mode, as well as 20 ns, 2.58 mJ pulses at a repetition rate of 10 kHz in the Q-switched mode. The high power in both modes was achieved by intra-cavity second harmonic generation in Lithium Triborate. The nonlinear output coupling through SHG in this laser causes a factor of 6.3 change of intra-cavity power between the CW and the Q-switched mode. The resulting variation of the thermal lens in the laser rod makes it challenging to maintain a geometrically stable cavity in both operation regimes, which is essential for diffraction limited beam quality. Diffraction limited beam quality with M^2 values of less than 1.06 in the cw and 1.21 in the Q-switched regime was achieved by a novel dual-stability-range cavity design. This design provides geometrically stable cavity configurations in both operation regimes, which are separated by an unstable region. This cavity makes it possible to switch between the two operation regimes, without moving any laser components. The switching time from CW to pulsed mode was measured to be less than 200 ms and is limited only by the thermal time constants of the laser rod and nonlinear crystal.

7578-60, Session 14

Reduction in timing jitter for a Q-switched Nd:YAG laser by direct bleaching of a Cr:YAG saturable absorber

B. Cole, J. Lei, T. DiLazaro, B. Schilling, C. W. Trussell, L. Goldberg, US Army RDECOM CERDEC, Night Vision and Electronics Sensors Directorate (United States)

The passively Q-switched Nd:YAG laser has many desirable qualities that include simplicity in laser design, compactness, low cost and weight. However, for certain applications the high pulse-to-pulse timing jitter associated with passive Q-switching mandates the use of active Q-switching despite the increase in cost and complexity. To address this problem, we have developed a technique where direct bleaching of the Cr:YAG saturable absorber could be applied to the otherwise passively Q-switched laser to optically trigger the Q-switched pulse at a prescribed time. With this method, the energy from a single laser diode bar was used to bleach a thin sheet within the saturable absorber from a direction orthogonal to the lasing axis. A strong anisotropy within the Cr:YAG saturable absorber was observed, with the polarization of the bleaching beam influencing the efficacy of jitter reduction. With appropriate orientation of the bleaching pulse polarization, the optical triggering was evaluated on a passively Q-switched Cr:YAG/Nd:YAG laser of monolithic construction. Operated at 10Hz PRF, the laser produced a 13ns long Q-switched pulse with an energy of ~33mJ. Through the use of custom electronics, we were able to trigger the Q-switched pulse at the time corresponding to the steepest slope for change in transmission during bleaching, which occurred ~1μs after the bleaching diode trigger. This laser was then measured to have a 13X reduction in timing jitter, where the jitter improved from about 130ns for free running operation to less than 10ns with optical triggering.

7578-61, Session 15

Comparison of small fiber connectors for high-power transmission

S. Campbell, O. Blomster, M. Pålsson, Optoskand AB (Sweden)

Small fiber connectors capable of handling medium powered lasers are available on the market from multiple suppliers. Typical connector types are the SMA905 and LD80. The capability to handle power losses, for example radiation falling outside the fiber core is, due to the small size and restrictive design, limited. A new type of SMA fiber connector, designed for high-power loss capability will be presented. The basic principle is to strip off the losses in terms of radiation rather than being absorbed in the fiber connector. The radiation is instead absorbed in the female connector housing or within the laser housing, where it can easily be cooled away. In this paper both the principles and measurement of power capability will be presented. Furthermore, in order to give a perspective of the available high-power SMA fiber connectors on the marked today a comparison between the best competitive products will be presented.

7578-62, Session 15

Ultrashort pulse long distance fiber delivery

T. Le, G. Tempea, Z. Cheng, M. Hofer, A. Stingl, FEMTOLASERS Produktions GmbH (Austria)

Although fiber delivery of 25 fs laser pulses were recently shown possible reported results are restricted to 1 to 2 m single-mode optical fiber due to the high amount of group delay dispersion, guiding losses or fiber nonlinearities. On the other hand conceivable applications of ultrashort laser pulses in inhospitable environment, their use for security or even telecommunication purposes require optical pulses to be delivered over much longer fiber distances. Here we show how optical pulses as short as 140 fs from a Ti:Sapphire laser can be simply sent through 50 m single-mode fiber with the help of dispersive mirrors.

7578-63, Session 15

Reflective phase retarders enable multi-mJ hollow fiber pulse compression

G. Tempea, M. Hofer, T. Prikoszovits, Z. Cheng, T. Le, A. Assion, FEMTOLASERS Produktions GmbH (Austria)

It was recently demonstrated that adverse nonlinear effects (e.g. ionization and self-focusing outside the waveguide) in hollow fiber compressors are reduced by employing circularly polarized pulses (X. Chen et al., CF3.6, CLEO-Europe 2009). The energy-scaling potential of this approach is limited by the maximum manufacturable aperture of

quarter-wave retardation plates and by nonlinearities in the waveplate material. We developed reflective quarter-wave retarders with retardation errors <5% over 400nm@800nm. Consisting of a Silver layer and a dielectric overcoating, these phase retarders can be arbitrarily scaled in aperture and exhibit virtually no nonlinear effects. They are employed for seeding a hollow-fiber compressor with 5-mJ, 30-fs, 1-kHz circularly polarized pulses and for recovering the linear polarization after compression.

7578-64, Session 15

Faraday isolators for high average power fundamental mode radiation

K. Nicklaus, T. Langer, JT Optical Engine GmbH + Co. KG (Germany)

Recent developments in fiber and solid state lasers led to compact, robust and less costly laser sources with an average power of some hundred watts to kilowatts with fundamental mode, both cw and pulsed. These lasers may open new areas of application, e.g. in the industrial, medical and scientific field. Unfortunatley many of these lasers are, due to their high gain, susceptible to backreflections from the workpiece leading to power fluctuations and ultimately the destruction of the laser source.

Faraday isolators prevent backreflections from entering the laser source, thereby protecting the laser and stabilizing the application process. The use of these isolators in the high power regime is limited by the residual absorption in the isolator optics, which leads to thermal lensing and thermal birefringence. In the case of unpolarized radiation, the separation into two orthogonal polarizations and recombination requires special considerations to maintain fundamental mode and pointing in changing environmental conditions. Furthermore the industry demands compact, robust and low cost components to enable highly reliable low cost laser machining tools.

A highly compact isolator for unpolarized radiation up to 400 W fundamental mode for industrial application surrounding with minimal thermal lensing has been developed. At 400 W and 10-40 °C a transmission of 97 %, an isolation larger 20 dB, a thermal focus shift of less than 2 rayleigh ranges and a M^2 smaller than 1.2 have been achieved.

Detailed experimental and simulation results, design rules and concepts for further power scaling and thermal lens reduction will be presented.

7578-65, Session 15

Deterministic single shot and multiple shots bulk damage thresholds for doped and undoped crystalline and ceramic YAG

B. T. Do, Sandia National Labs. (United States); A. V. Smith, AS-Photonics, LLC (United States)

We measured single-shot and multiple-shot damage thresholds of pure and Nd-doped ceramic Yttrium Aluminum Garnet (YAG), and of pure, Nd-doped, Cr-doped, and Yb-doped crystalline YAG. We tightly focused 9.9 ns, single-longitudinal-mode, TEM00 1064-nm laser pulses inside the ceramic and crystalline YAG samples. The radius of the focus spot was 8 microns, it was found by measuring the surface third harmonic signal. As the laser beam was tightly focused, the laser powers at the damage thresholds of the ceramic and crystalline YAGs are below the SBS threshold and the effect of self focusing is small.

In this experiment we collected the temporal profiles of the incident pulse, the transmitted pulse, and the white light emitted from the YAG samples. By comparing the profiles of the incident and the transmitted pulse, we can find the time location on the incident pulse when the optical breakdown occurred. We found the single-shot and multiple-shots damage thresholds are deterministic. For single-shot damage threshold, unlike the optical breakdown in fused silica that always starts at the peak of the laser pulse, the optical breakdown in pure crystalline YAG always starts on the trailing edge of the laser pulse. For multiple-shot damage threshold, the optical breakdown always starts at the peak of the laser pulse.

The single shot and multiple-shots damage thresholds of pure and doped YAG, ceramic and crystalline YAG range from 1.1 to 2.2 kJ/cm^2. We also report on their damage morphologies.

7578-66, Session 16

Solid state laser tools for solar crystalline silicon wafer processing

A. Ashmead, Coherent, Inc. (United States)

Solid state lasers have made a significant impact in the processing of thin film solar devices but have only recently started to be deployed in crystalline Si manufacturing. The drive to reduce the dollars per Watt through increased efficiency and reduced cost will cause manufacturers to adopt laser based processing as feature sizes reduce, wafers get thinner and enhanced selective doping techniques become more prevalent. Coherent has developed a number of tools to address these applications focusing on edge isolation, diffusion doping, dielectric film ablation and through silicon hole drilling using Q-switched and modelocked Nd solid state lasers. This talk will discuss these applications in general and describe the lasers and tools in particular.

7578-67, Session 16

New developments in STED microscopy

A. Giske, J. Sieber, M. Dyba, H. Gugel, V. Seyfried, D. Gnass, Leica Microsystems CMS (Germany)

STED microscopy has gained recognition as a method to break the diffraction limit of conventional light microscopy. Despite being a new technique, STED is already successfully implemented in life science research. The resolution enhancement is achieved by depleting fluorescent markers via stimulated emission. The performance is significantly dependent on the laser source and the fluorescent markers. Therefore the use of novel fluorescent markers in conjunction with the right laser system was the main focus of our research. We present new developments and applications of STED microscopy, unraveling structural details on scales below 90 nm and give an overview of required specification for the solid state laser systems.

7578-68, Session 16

Drilling of aluminum with a high-power Q-switched 532-nm laser

L. R. Migliore, Coherent, Inc. (United States)

Recent advances in the design of gain modules for diode-pumped solid-state lasers have allowed the manufacture of extremely compact high power products. Their high Q-switched pulse energy combined with good mode quality enable highly efficient harmonic conversion, resulting in a product producing several hundred watts of average power at a wavelength of 532nm.

Among the applications for which this product is suited is the rapid drilling of high-quality holes in aluminum sheet. This paper examines the parameter range for efficient drilling and suggests areas where the process might be used.

Plates of several aluminum alloys were drilled under a variety of conditions. The drilled holes were sectioned and subjected to optical and SEM analysis. Evidence of microstructual damage was noted, allowing the development of drilling conditions that produced improved hole quality.

7578-69, Session 16

Enhanced productivity with high-power short and ultrashort thin disk lasers

J. Stollhof, TRUMPF Inc. (United States); S. Weiler, U. Stute, S. Massa, B. Faisst, C. Stolzenburg, D. Sutter, TRUMPF Laser GmbH & Co. KG (Germany)

TRUMPF presents the flexibility of the thin disk laser technology in this paper. Used on CW lasers, short pulsed laser based on cavity-dumping including intracavity frequency conversion and ultrafast MOPA systems, lasers based on disk technology are important tools for the Automotive, Semicon , Flat Panel Display, Aerospace and Photovoltaics industry.

CW thin disk lasers make use of the high brightness and an optical-optical efficiency of about 60 % in applications for cutting, welding, brazing and hybrid welding. The platform of theses CW laser offers a great base for the realization of short pulsed lasers at high average power. The lifetime of the upper energy state of Yb:YAG is relatively high. In addition the relatively small gain in the thin disk laser leads to the typical pulse duration of a simple q-switched disk laser in the order of a few hundred nanoseconds. By employing a cavity-dumped configuration, the flexibility of the setup is increased and a wider range of pulse durations is available. Using a Pockels cell inside a cavity-dumped configuration an industrial laser with average output power of 750 W and pulse durations pulse durations ranging from a few 10 ns to several 100 ns was demonstrated. In addition, TRUMPF's TruMicro 7250 combines this technology with intracavity frequency conversion. This laser delivers up to 400 W at 515nm.

In 2007 TRUMPF introduced an ultrafast disk laser system for micro machining applications. Today the next and compact generation of the TruMicro Series 5000 boasts six picosecond pulse duration, diffraction limited beam, 50 W average power together with a pulse energy of up to 250 µJ. These parameters enable drilling of high quality holes, high speed structuring of thin films and sublimation cutting of metal and non-metals.

7578-70, Session 16

Industrial high-power high-energy pulsed laser with feeding fiber for thin layer removal

A. Straesser, Rofin-Sinar Laser GmbH (Germany)

Industrial production needs laser systems with high stability and efficiency. Laser systems with high pulse energies and high average power are needed for instance in cleaning processes of general kind with high removal rates. A diode pumped laser system with maximum pulse energy of 200mJ and pulse width of 40ns will be presented. The beam quality of the laser source is M^2 = 25. The repetition rate can be varied between 5kHz and 40kHz. In addition to that the output power can be continuously varied between 0W and 1500W while the pulse width is constant and a power stability of 2% is achieved. The laser is especially designed for applications where even at the highest gain no leakage power is allowed. The laser beam can be transmitted through a fiber as a flexible tool to the workpiece. The beam profile is round or square depending on the choice of fiber. For high capacity utilization the beam can also be split into two fibers. Removal rates of more than 10m/s can be achieved by means of a scanner. This is how various removal processes can be realized.

7578-71, Session 16

Applications of INNOSLAB lasers with tailored beam profiles

K. Du, P. Shi, A. Schell, D. Li, C. Haas, S. Fu, EdgeWave GmbH (Germany)

INNOSLAB lasers are characterized by: short pulse length and high peak power, high pulse repetition rate, high beam quality and flexibility in beam profile, from circular beam profile, through line shaped one dimensional Top-hat, to two dimensional top-hat with rectangular or square cross section. Their tailor able beam profiles open for INNOSLAB laser a variety of applications with high energy efficiency, such as glass milling, parallel scribing, high throughput ablation, particle imaging velocimetry and pumping of dye lasers.

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7579-01, Session 1

Laser power feeding to electric vehicle from solar power

K. Ueda, The Univ. of Electro-Communications (Japan)

No abstract available

7579-02, Session 1

Effective frequency doubled Nd:YAG laser with high beam quality

I. V. Glukhikh, D. V. Efremov Scientific Research Institute of Electrophysical Apparatus (Russian Federation); S. A. Dimakov, S.I. Vavilov State Optical Institute (Russian Federation); S. V. Frolov, D. V. Efremov Scientific Research Institute of Electrophysical Apparatus (Russian Federation); V. Y. Shur, Ural State Univ. (Russian Federation)

For second harmonic generation we have used the single pass elements based on periodically poled MgO doped lithium niobate crystal (PPMgO:LN) 1-mm-thick and 5-mm-length with 6,95-µm-period, dual bands antireflective coating, and QPM temperature 45°C. Conversion efficiency of extracavity frequency doubled diode pumped Nd:YAG laser was achieved 32%. Green beam quality was near to the diffraction limit (M2~1,2).

7579-03, Session 1

Laser beam formation with adaptive optics

A. V. Kudryashov, Moscow State Open Univ. (Russian Federation)

No abstract available

7579-05, Session 1

New paradigms for old problems: some (small) advances in laser resonator research at the CSIR

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

In this presentation we will give an overview of current research in laser resonators at South Africa's CSIR National Laser Centre, where the focus is on intra-cavity laser beam to create novel laser resonators, and the application of these resonators to real-world problems. In particular we will highlight two examples of recent advances in intra-cavity mode selection by amplitude-only elements, and by phase-only elements. In both cases a new approach to an old problem yielded better insights into the resonator properties, and has led to a new paradigm in thinking about these systems.

7579-14, Session 1

Fast widely tunable external cavity laser (ECL)

C. Moser, F. Havermeyer, Ondax, Inc. (United States)

We have developed a fast switching tunable laser platform. We show a prototype self-aligned external cavity laser (ECL) based on five multiplexed volume holographic gratings in glass which is tunable from 760 nm to 785 nm. The tuning mechanism is based on a micro-mirror array DLP chip from a commercial pico-projector. Switching time between wavelengths is only limited by the switching time of the DLP mirrors, which is in the millisecond range.

We demonstrate single frequency operation at each wavelength and linewidth smaller than 1 MHz. All components for the external cavity including laser diode are mounted on a 10 mm x 20 mm TEC. With temperature control and constant current operation, the stability of the tuned wavelength is 8 pm and power fluctuation is 4% over a 12-hour period. We show the implementation of the DLP in the external cavity laser and wavelength tuning.

The wavelength of the ECL can be precisely set by mechanically rotating the multiplexed volume holographic grating. We show fine wavelength tuning to the D2 Rubidium line at 780.246 nm.

The tunable external cavity architecture is applicable to other wavelengths from blue-violet to the infrared. To our knowledge, the combination of millisecond wavelength switching, sub-MHz linewidth and wide tuning range from a compact laser source has not been reported.

7579-07, Session 2

Saturation characteristics of gain guiding in index-antiguided waveguides

T. Her, X. Ao, L. Casperson, The Univ. of North Carolina at Charlotte (United States)

Lasing in gain-guided index-antiguided (GG-IAG) fibers with a single transverse mode up to 400 micrometers in diameter has been experimentally demonstrated. Laser oscillators and amplifiers based on such scheme have the potential to deliver robust single transverse mode, ultra-large-mode area, and extremely low divergence beam quality, which are desired for many applications.

Index antiguided waveguides are equivalent to unfolded unstable resonators. In IAG waveguides, all modes are intrinsically leaky with higher loss for higher-order modes, and single mode operation is made possible with appropriate optical gain. Extensive analysis has been performed for GG-IAG waveguides with constant and uniform gain; in practice, however, gain is subject to saturation effects. Since gain guiding relies on gain to sustain a confined mode, it is important to understand the effect of gain saturation on the modal stability in GG-IAG waveguides.

In this work, we investigate numerically and analytically the effects of gain saturation on a propagating gain guided mode in a strongly index-antiguided waveguide with homogeneous line broadening in the core. We show that gain saturation has little effect on the field distribution in the core, whereas this saturation causes exponential decay of both the modal gain and the mode confinement. Steady state is reached when the effective gain balances the diffraction loss, where the mode becomes cutoff-like and maximum power is reached. Because the field distribution in the core is almost unchanging, the power and gain profiles can also be modeled analytically.

7579-08, Session 2

Shaping of dark beams in resonators with a bi-lens reflector

Y. N. Parkhomenko, B. Spektor, J. Shamir, Technion-Israel Institute of Technology (Israel)

Laser beams containing singularities are of increasing technical importance in metrology, particle manipulation, laser patterning etc. While the conventional procedure is the transformation of a fundamental laser beam into the required structure by some external component, it is of advantage to generate the desired beam structure directly within the resonator. In this work a laser resonator configuration is proposed in which the fundamental oscillating mode is an odd mode containing a line singularity. The resonator is based on the replacement of one reflector by a bi-lens split mirror. The beam emitted by such a laser is an ideal source for a recently introduced singular beam microscopic procedure. We numerically investigate resonators containing a bi-lens reflector with convex and concave faces. It is shown that resonators of the latter type of reflectors have high effectiveness in shaping modes with linear singularity. The mode selectivity is also higher than resonators with roof-mirrors that were investigated earlier.

7579-09, Session 2

Propagation of 3-D beams using a finite-difference algorithm: practical considerations

A. H. Paxton, Air Force Research Lab. (United States)

No abstract available

7579-10, Session 2

Precision control of the transfer matrix method for transverse-mode fields of laser resonators

D. Ling, Dongguan Univ. of Technology (China)

Because the Fox-Li diffraction integral iteration method is not suitable to calculate transverse-mode fields of a resonator with big Fresnel number, the tansfer matrix method is used for analysis of the eigen modes of an optical resonator. The process of this method is as follows: from the Collins Formula, the diffraction integral equation of a resonator is obtained and transformed to the finite-sum matrix equation. Finally, the transverse-mode distribution and loss of the resonator can be calculated by use of the eigen function and eigen value of the matrix. In this paper, the transfer matrix method is discussed, and the precision of the method is control. It is shown from the simulated results of a general confocal resonator that numberical results by use of the transfer matrix method are accord with that of the intergral iterative method, and the convergence problem of the intergral iterative method can be overcome and the analysis of laser resonators can be met by the transfer matrix mothod, as long as the calculation precision is reasonably controlled.

7579-51, Session 3

Photonic devices and circuits for electronic-photonic integration and on-chip interconnects in deeply scaled CMOS processes

M. A. Popovic, Massachusetts Institute of Technology (United States) and Univ. of Colorado at Boulder (United States); J. S. Orcutt, A. M. Khilo, C. W. Holzwarth, H. Li, Massachusetts Institute of Technology (United States); A. Joshi, Massachusetts Institute of Technology (United States) and Boston Univ. (United States); B. R. Moss, M. Georgas, J. Leu, F. X. Kärtner, R. J. Ram, V. Stojanovic, Massachusetts Institute of Technology (United States)

The increasing computational power of electronics on a single chip and the current trend to many-core processors are posing significant challenges related to on- and off-chip communication in terms of bandwidth, power budget and footprint. Photonic devices based on high-index-contrast materials available in scaled CMOS processes (silicon, SiN) can support strong confinement of light and dense, front-end photonic integration alongside state-of-the-art electronic circuits, and offer a new avenue to address the foregoing communication challenges. However, the requirement to accept minimal or no process modifications in the CMOS flow places significant challenges in photonic device design. Performance requirements of on-chip photonic links place further challenging demands on design.

In this paper, we present the design of photonic components and circuits to meet these constraints and enable on-chip links in standard CMOS. We address optical waveguide design, nonlinearity limits, filters and switches, ultra-low-loss waveguide crossings, fiber-to-chip coupling and modulation. We also review results showing the first demonstration of a silicon nanophotonic wavelength-channel multiplexer in a 65nm and 32nm bulk-silicon CMOS process with no modifications.

7579-52, Session 3

Engineering optical forces in waveguides and cavities based on optical response

P. T. Rakich, Sandia National Labs. (United States); Z. H. Wang, M. A. Popovic, Massachusetts Institute of Technology (United States)

We present a new treatment of optical forces, revealing that the forces in virtually all optomechanically variable systems can be computed exactly and simply from only the optical phase and amplitude response of the system. This treatment, termed the response theory of optical forces (or RTOF), provides conceptual clarity to the essential physics of optomechanical systems, which computationally intensive Maxwell stress-tensor analyses leave obscured, enabling the construction simple models with which optical forces and trapping potentials can be synthesized based on the optical response of optomechanical systems. A theory of optical forces, based on the optical response of systems, is advantageous since the phase and amplitude response of virtually any optomechanical system (involving waveguides, ring resonators or photonic crystals) can be derived-with relative ease-through well-established analytical theories. In contrast, conventional Maxwell stress tensor methods require the computation of complex 3-dimensional electromagnetic field distributions; making a theory for the synthesis of optical forces exceedingly difficult. Through numerous examples, we illustrate that the optical forces generated in complex waveguide and microcavity systems can be computed exactly through use of analytical scattering-matrix methods and compared to Maxwell stress-tensor methods. The RTOF method will be applied to coupled microcavity systems, illustrating the means by which optical potential-wells can be synthesized. Finally, we will discuss novel dynamic signal processing applications which are being developed through use of this formalism.

7579-53, Session 3

Large tunable birefringence in silicon microcantilever waveguides via optomechanics

M. L. Povinelli, J. Ma, The Univ. of Southern California (United States)

Optical forces have recently been investigated as a way of repositioning microphotonic elements such as waveguides and microcavities. In previous work, we have shown that the separation between parallel, suspended silicon waveguides can be adjusted by tuning the power and/or polarization of input light. Recent experiments in the literature have confirmed these predictions.

Here we calculate the tunable birefringence that can be achieved by using an optical force to adjust the separation between parallel, suspended, strip silicon waveguides. The force arising from the evanescent coupling between the modes of the two waveguides deforms both waveguides, changing the air-slot width. Such behavior results in all-optically adjustable giant birefringence. We characterize the two-waveguide system, and optimize the frequency and polarization of input light to achieve a considerable optical force at a moderate laser power. We calculate the resultant displacement of both waveguides based on the finite-element method (FEM). A 9nm displacement is obtained for an input power of 20mW. We evaluate the change in phase and group birefringence induced by deformation. Maximum values of 0.026 and 0.13 are achieved for the tunable phase and group birefringence, respectively. We show that the optomechanical approach is characterized by widely tunable birefringence. We explore the applications of the two-waveguide system for tunable linear-to-circular polarization conversion. Conversion is achieved within a length of 30 microns for a pump power of 67mW.

7579-54, Session 3

Integration of chalcogenide and titanium-diffused lithium-niobate waveguides

M. Solmaz, C. K. Madsen, Texas A&M Univ. (United States)

We present our work on arsenic trisulfide (As_2S_3) waveguides vertically integrated on titanium-lithium niobate (Ti:$LiNbO_3$). As_2S_3 is a member of chalcogenide glass family and As_2S_3 ridge waveguides are fabricated on top of Ti:$LiNbO_3$ waveguides to create bent structures that are not achievable with Ti:$LiNbO_3$ waveguides alone. Ti:$LiNbO_3$ waveguides are intrinsically low-index contrast and requires centimeter scale bends to alleviate radiated losses from the side. As_2S_3 waveguides are much smaller in size compared to Ti-diffused waveguides and create enough index contrast to realize tight waveguide shapes. Taper structures are used to minimally perturb the diffused waveguide mode and transfer power. As_2S_3 is chosen because of its refractive index (~2.4) being close to bulk $LiNbO_3$ index. The amount of vertical coupling into the chalcogenide waveguide can be tailored by modifying the As_2S_3 waveguide shape and the taper length. In this talk, we will show theoretical review of the structure, and give insight to operation principles. We will also demonstrate the measured results of S-shaped bends and ring resonators that are successfully fabricated using As_2S_3. Further modifications to waveguide design will enable rings with radii less than 50μm.

7579-04, Session 4

Multi dither adaptive system based on Shack-Hartmann wavefront sensor

J. V. Sheldakova, Moscow State Open Univ. (Russian Federation)

No abstract available

7579-11, Session 4

Generation of multikilowatt radially or azimuthally polarized CO2 laser beams by a triple-axicon optical resonator

M. Endo, Tokai Univ. (Japan)

Radially or azimuthally polarized beams are of interested in recent years due to their unique characteristics. For small-power applications, holographic conversion of linearly polarized Gaussian beam into axially symmetric polarization is commonly practiced. On the other hand, high-power applications such as material processing, none of the known methods have been accepted by industrial sector because of their complexity. When radially polarized beam is applied to the material processing, its productivity is expected to be doubled compared to the widely used circular polarization because the beam contacts the cut front always with p-polarization regardless the cut direction. Azimuthally polarized beam is beneficial for drilling because the wall reflectivity of the drilled hole is nearly perfect. We have developed an optical resonator that includes a triple-axicon retroreflector. The triple-axicon unit is composed of a waxicon and an axicon accurately fitted together. The polarization selection is made based on the reflectivity difference between s-polarization and p-polarization on the conical surfaces. Since these elements construct a retroreflector, it is robust to misalignment compared to the conventional axicon-optics. A set of mirrors designed to oscillate in azimuthally polarized mode was fabricated and applied to a commercial transverse-flow cw CO_2 laser (Amada OLC-H420). The output power recorded was 1.3 kW, and it will be increased to 2 kW as soon as the minor modification to the other mirrors of the resonator is made. A mode converter made of four quarter-wave plates were developed and demonstrated the conversion of azimuthally polarized beam into radially polarized beam with a 95% throughput.

7579-12, Session 4

Tolerance analysis for stable laser resonators

M. Kuhn, LightTrans GmbH (Germany); F. Wyrowski, Friedrich-Schiller-Univ. Jena (Germany); C. Hellmann, T. Schoening, LightTrans GmbH (Germany)

Recently the importance of numerical simulations for the design of laser resonators has grown considerably. This applies in particular if the alignment of components within the resonator is crucial for its stability. In such cases a tolerance analysis is required that can be done most efficiently using numerical simulation tools.

In this talk we discuss the concepts with respect to geometry and simulation that are required for tolerance analysis and efficient eigenmode computations.

First, each optical component of the resonator is represented by a component in the computer model that is defined by geometrical and physical parameters.

It is possible to align them relative to each other on the one hand and to shift or tilt them independent of each other as required for a sensitivity analysis on the other hand.

Second, it turns out that a single simulation technique is not sufficient in order to ensureboth, small physical error and fast simulation, at the same time. We present the principles of Unified Optical Modeling that allow the coupling of several propagation methods within one modeling task. For laser resonators this involves in particular free space propagation methods (Fresnel, spectrum of plane waves), geometrical optics and split step beam propagation methods. This approach covers in particular general eigenmode models and general geometries including micro-structured surfaces that can be used for additional beam control.

Simulation results obtained by the Laser Resonator Toolbox of VirtualLab(TM) (www.lighttrans.com) are presented.

7579-13, Session 4

Optimized high-power CO2 laser resonators for direct laser engraving

M. Bohrer, Dr. Bohrer Lasertec GmbH (Austria); D. Schuoecker, Technische Univ. Wien (Austria)

CO_2 laser resonators are well established on todays markets. High

security applications like micro perforation of banknotes and passports or direct laser engraving of print forms need a power, mode and pointing stability which requires new designs. How to get lasers more stable than ever and make them even more reliable is very challenging. Such a stabilized laser beam can then be used in combination with an Acousto Optical Modulator for pulses on demand up to 1 mega hertz.

Especially for security applications it is thus not surprising that this topic enjoys much research and industrial interest. Improvements of the resonator structure and the beam shape as well as applications are demonstrated. High speed infrared videos show the influence of the source to the AOM crystal and the process itself. The results of this work can be seen in many applications of daily used products.

7579-15, Session 4

Common cavity resonators for passive laser beam combining: effects of path length errors

J. R. Leger, M. Khajavikhan, Univ. of Minnesota (United States)

Coupled cavities can be used to establish coherence across several lasers. A modal analysis of several architectures shows that the field distribution among the individual lasers and the associated loss of each mode is a function of the specific common cavity design. The mode shape and loss is also a function of the optical path lengths associated with each laser arm. Unless these path lengths are carefully controlled, the associated modal loss can be excessive, reducing the power of the combined laser beams. In this paper, we show cavity designs that are capable of trading modal discrimination for path length error tolerance. Thus, it is possible to engineer a cavity that has improved path length error tolerance while maintaining sufficient modal discrimination to operate in a single spatial mode. A Nd:YAG laser has been constructed to measure these mode shapes and losses, and the resulting data are compared to theory.

7579-16, Session 4

A novel technology based on CO2 lasers for surface finishing and direct fiber fusion of beam delivery optics

G. Curatu, LightPath Technologies, Inc. (United States)

This paper presents a unique technology consisting of two advanced processes used in the fabrication of high-quality and robust beam delivery optics for fiber lasers.

The technology described here is based on CO2 lasers, which are used to reshape the spherical surface of plano-convex fused-silica rod-lenses, and then fuse the optical fiber directly to these lenses.

The first process is aimed at correcting the spherical aberration of the optical system in order to improve the insertion loss and M2 in fiber collimators. A CO2 laser beam is focused onto the spherical surface of the lens, reflowing the glass to obtain an aspheric surface.

The second process also uses a CO2 laser beam focused onto the flat surface of the lens, at the interface between the optical fiber and the lens in order to fuse the fiber to the lens without using any adhesives in the optical path. This process eliminates any interface between fiber and lens, dramatically reducing the return loss of the system.

A few fiber collimating systems are presented and discussed in terms of their aberrations, insertion loss, M2, and return loss. Test results are compared to the theoretical modeling, demonstrating the accuracy and repeatability of these fabrication processes.

7579-17, Session 4

All-fiber optical isolator for high-power optical transmission

T. Liebig, A. Voss, T. Graf, Univ. Stuttgart (Germany)

A novel optical isolator allowing for fiber-integrated unidirectional transmission at high power levels is presented. The isolator consists of two polarizers based on evanescent coupling between a side-polished fiber and a birefringent crystal and a Faraday rotator using the fused silica core of a specialty optical fiber as the magneto-optical medium. This design avoids any absorbing effects near the fiber core and therefore leads to a high power handling capability and an insertion loss of less than 0.5 dB. The non-reciprocal optical rotation is achieved by the Faraday effect inside the optical fiber induced by a magnetic field of approx. 50 mT, which is generated by a toroidal electro-magnet. The control of the state of polarization (SOP) along the fiber used for the Faraday rotator is crucial for achieving the required 45° of rotation; this is addressed by a special fiber design. Furthermore, this setup can also be used as a continuously variable and fast (~ 100 μs) power switch by rotating the polarization axis at the rotator output by up to ± 45°. The discussed isolator will be useful for various applications such as separation of high-power fiber amplifier stages or the isolation of back reflections from the workpiece in laser materials processing.

7579-18, Session 5

Gaussian beam shaping based on multimode interference

X. Zhu, A. Schulzgen, H. Li, J. V. Moloney, N. Peyghambarian, College of Optical Sciences, The Univ. of Arizona (United States)

Laser beam transformation utilizing the effect of multimode interference in multimode (MM) optical fiber is thoroughly investigated. When a Gaussian beam is launched to an MM fiber, multiple eigenmodes of the MM fiber are excited. Due to interference of the excited modes, optical fields that vary with the MM fiber length and the signal wavelength are generated at the output facet of the MM fiber. Diffractive propagation of these confined fields can yield various desired intensity profiles in free space. Our calculations show that, an input fundamental Gaussian beam can be transformed to frequently desired beams including top-hat, donut-shaped, taper-shaped, and low-divergence Bessel-like within either the Fresnel or the Fraunhofer diffraction range, or even in both ranges. Experiments on a monothic fiber beam transformers consisting of a short piece of MM fiber (~ 10 mm long) and a single-mode signal delivery fiber were carried out. The experimental results indicate the functionality and high versatility of this simple fiber device. The performance of this fiber device can be easily and widely manipulated through parameters including the ratio between the core diameters of the SM and MM fiber segments and the length of the MM fiber segment. In addition, the intensity profile of the output beam can be controlled by tuning the signal wavelength. Most importantly, this technique is highly compatible with the technology of high power fiber lasers and amplifiers and fiber delivery systems.

7579-19, Session 5

Applying refractive beam shapers in creating spots of uniform intensity and various shapes

A. Laskin, Molecular Technology GmbH (Germany)

Different scientific and industrial laser techniques require not only intensity profile transformation but also creating various shapes of final spots like circles of different diameter, lines and others. As a solution it is suggested to apply combined optical systems consisting of a refractive beam shaper of field mapping type providing a required intensity transformation and additional optical components to vary the shape of final spots. The said beam shapers produce low divergence collimated

flattop beam that makes it easy to vary the shape of the beam spot with using either ordinary relay imaging optics, including zoom one, or anamorphotic optics. And the design features of the refractive beam shapers allow controlling the intensity distribution in the final spot (most often flattop one) and providing wide range of spot sizes. This paper will describe some design examples of combined beam shaping systems to create round spots of variable diameter as well as linear spots of uniform intensity. There will be presented results of applying these systems in such applications as laser hardening, flow cytometry and others.

7579-20, Session 5

Overview: process-optimized beam transformers and their impact on high-power laser applications

O. Homburg, T. Mitra, L. Aschke, LIMO Lissotschenko Mikrooptik GmbH (Germany)

Micro-lenses and micro-lens arrays are widely used for various applications. Monolithic arrays of cylindrical lenslets made of glass, semiconductors or crystals provide great advantages to laser applications, e.g. high efficiency, intensity stability and very low absorption. However, up to now, mainly symmetrical micro-lens surfaces are utilized in most applications due to design and manufacturing restrictions.

The manufacture and application benefits of asymmetrical cylindrical-like micro-lens surfaces are enabled by LIMO's unique production technology. The asymmetrical shape is defined by uneven-polynomial terms and/or an asymmetrical cut-off from an even polynomial surface. Advantages of asymmetrical micro-lenses are off-axis light propagation, the correction of aberration effects or intensity profile deformations when the illuminated surfaces are not orthogonal to the optical axis.

First application results of such micro-lens arrays are presented for beam shaping of high power diode lasers. The generation of a homogeneous light field by a 100 W laser with tilted illumination under an angle of 30-50° is shown. A homogeneity of better than 90% was achieved for a field size of 270 mm x 270 mm.

In other applications like laser-direct patterning a top hat profile has several advantages compared to Gaussian profiles, especially the throughput of the system and quality of the structures. Additionally, a well-defined intensity dip in the middle of the beam profile might be advantageous in some other applications like plastics welding.

Concludingly, several specific beam shapes with their impact on various applications are outlined and discussed.

7579-21, Session 6

Spatial laser beam characterization: state of the art

M. Duparré, Friedrich-Schiller-Univ. Jena (Germany)

No abstract available

7579-22, Session 6

Novel multi-sensor polarimeter for the characterization of inhomogenously polarized laser beams

T. Liebig, M. Abdou-Ahmed, A. Voss, T. Graf, Univ. Stuttgart (Germany)

Recently, several approaches for the efficient generation of radially as well as azimuthally polarized kW-class laser beams have been demonstrate allowing for several new high performance materials processing applications. Up to now, the polarization state of such laser beams has been characterized either by observing the transmitted intensity distribution behind a rotating linear polarizer or by locally measuring the polarization state at several points across the beam. Since these methods are either inaccurate or very time consuming, we propose to apply the well-known basic principles of imaging Stokes polarimeters, as used e.g. for astronomical applications, to the analysis of the polarization state of inhomogenously polarized laser beams. This approach also allows to characterize locally disturbed states of polarization (SOP), e.g. due to local birefringence inside a laser resonator or an optical beam path. Outbound from a mW-level laboratory demonstration, a setup is shown to analyze the polarization distribution over the cross section of a 1 kW radially polarized beam emitted from a solid-state laser with a local resolution well below 5 µm. Numerical simulations regarding the anticipated errors connected with the principle of a rotating waveplate, especially in conjunction with a position sensitive detector, are presented. Also the assembly of the local polarization data to a global specification - as required e.g. for resonator optimization - is discussed. The approach presented here will strongly support the implementation of high power radially and azimuthally polarized laser beams in new laser materials processing applications. Additionally, this device can be used to determine the propagation parameters of the analyzed beam, enabling a compact and efficient combined sensor.

7579-23, Session 6

Complete description of optical fields propagating in passive LMA fibers regarding amplitude, relative phase delay and polarization by means of optical correlation filters

D. Flamm, Friedrich-Schiller-Univ. Jena (Germany); S. Schroeter, Institut für Photonische Technologien Jena (Germany); M. Duparré, Friedrich-Schiller-Univ. Jena (Germany)

There have been different efforts to qualify passive optical fibers for high power beam delivery, where the occurrence of more than the fundamental mode comes along with the enlargement of the mode field diameter (Large Mode Area fiber). The coexistence of different guided modes in such a LMA fiber, with different attenuation and different propagation velocities, determines the properties of the light emerging from it. If a certain application has specific requirements concerning focusability or beam pointing stability for example, knowledge of the modal content is one key to understand the underlying physical effects and to control the light properties.

The situation gets even more complicated taking into account local perturbations which violate the orthogonality relation of the eigenmodes, and finally lead to mode conversion effects.

Even if (under certain fortunate circumstances) the excitation of the fiber in pure fundamental mode is possible, the light emerging from the fiber end can still contain a remarkable amount of higher order mode content, depending on the bending radius of the fiber, for example. Thus, a metrology becomes mandatory for the transversal modal content (strength and relative phase delay) at the exit of an optical fiber. Different approaches for this exist, such as interferometry, M2 measurement or phase retrieval methods with either high experimental complexity, or ambiguity regarding modal content.

In this paper we present new results achieved by direct measurement of modal content, phase delay and polarization state, using optical correlation analysis (polarization dependent!), applied to different step index fibers with V parameters of 3.96 and 5.2, respectively. At a working wavelength of 1064 nm, these fibers can carry 10 respectively 16 different LP eigenmodes. Achieved experimental results for modal strength, phase delay and polarization state are used to "reconstruct" the analyzed optical field. Comparing these reconstructed fields with synchronously measured optical near fields demonstrates the huge potential of this direct and online method.

7579-24, Session 6

Spectral shifts of stochastic electromagnetic beams in negative refractive index materials

Z. Tong, O. Korotkova, Univ. of Miami (United States)

It is well known that the spectrum of light may change, due to source correlations, as it travels, even in free space. Similar result was obtained as light beams propagate in various deterministic and random media and scatter from particulate media. Both types of spectral shifts blue and red can be, in general, obtained. On the basis of the unified theory of coherence and polarization of light and the ABCD tensor method for partially coherent beam-like fields we derive the expression for the evolution of the spectral density of a random beam in a material having arbitrary refractive index and absorption properties. As a model for the source of light we take a scalar Gaussian-Schell model beam. Under assumption that the initial spectrum of light is having Gaussian profile we investigate the spectral shifts and spectral switches that occur in the light beam as it impinges onto the interface between a left-handed material (LHM) and right-handed material (RHM). Then by performing a general analysis of beam propagation in the stack of LHM and RHM layers we find that by adjusting the widths of the layers the changes in the spectrum of light can be readfily controlled.

7579-25, Session 6

Spatial control and diagnostics of femtosecond pulses with programmable micro-optics

R. Grunwald, M. Bock, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany)

Because of the commercial availability of powerful femtosecond lasers and emerging applications in fields like medicine, cell biology, chemical spectroscopy, micromachining or ultrafast measuring techniques, new approaches for a reliable spatial and temporal control of the beam parameters of such sources are urgently required. Here we present recent results of experimental investigations of spatial light modulators based on high-resolution, phase-only, reflective liquid-crystal-on-silicon micro-displays with respect to their capability to flexibly shape complex wavefields from intense femtosecond pulses. It is shown that, for properly chosen types of devices, the spectral and temporal pulse transfer characteristics well enable for nearly undistorted adaptive spatial shaping of microoptical phase profiles linearly dependent on gray values even at pulse durations between 10 and 20 fs as generated by a Ti:sapphire laser oscillator. To verify this, second order autocorrelation was compared to phase measurements with a modified real-time measuring system for spectral phase interferometry for direct electric field reconstruction with a thick nonlinear crystal (LX-SPIDER). Rotationally symmetric and asymmetric arrangements of individually programmable pulsed Bessel-like beams and related types of pseudo-nondiffracting localized wavepackets were generated. In particular, arrays of needle beams and laminar beam structures of aspect ratios up to more than 600:1 were generated. The cross-talk was minimized by exploiting phase self-apodization and diffractive background management. Applications like stable ultrafast image transfer, two-dimensional autocorrelation, adaptive wavefront sensing and advanced methods of secure encoding in spectral and temporal maps are discussed in detail. Currently, specific limitations by damage resistance, diffraction and flickering are under investigation.

7579-26, Session 6

Fractional power in the bucket and M square

S. Basu, Sparkle Optics Corp. (United States); L. Gutheinz, Boeing-SVS, Inc. (United States)

In this paper, we will give expressions to calculate the fraction of power, fPIB, from a given multimode laser beam that can be deposited within a bucket of radius, rT, on a target at a range, zT, using a focusing optic of diameter, Df. The fractional power within the bucket, fPIB, can be experimentally measured and is a very useful parameter in designing a laser-target interaction experiment. We relate the power in the bucket, fPIB, to the M2 parameter of a multimode laser beam that can also be experimentally measured. We propose fPIB and M2 to be used as standard design parameters for laser-target interaction tests. In this paper, we have also presented relationships between these two parameters and BQ and Strehl, which are also used in the literature but are not uniformly defined for a multimode laser beam.

7579-27, Session 7

Intracavity frequency conversion: from bow-ties to whispering galleries

I. Breunig, Univ. Bonn (Germany)

Providing optical feedback by a resonator enhances the efficiency of nonlinear optical effects, e.g. frequency conversion. The bow-tie cavity is known to be a very successful scheme and it has made its way into the commercial world of second harmonic generation and parametric oscillation. Another type of ring cavity becomes more and more popular: the whispering gallery resonator. This system offers unequaled opportunities because of its low loss leading to a high finesse. Based on our successful demonstration of parametric processes, converting continuous-wave near infrared light into terahertz radiation in a bow-tie cavity, we discuss challenges and perspectives for transferring this scheme to whispering gallery resonators.

7579-28, Session 7

Tuning of whispering gallery modes of polymeric micro-spheres and shells using external electric field

T. Ioppolo, U. Ayaz, V. Otugen, Southern Methodist Univ. (United States)

The electrostriction effect on the whispering gallery modes (WGM) of polymeric micro-spheres is investigated analytically and experimentally. Electrostriction is the elastic deformation (mechanical strain) of a dielectric material due the force exerted by an electric field. The elastic deformation also leads to mechanical stress which perturbs the refractive index of the sphere. Both if these effects (strain and stress) induce a shift in the WGM of the dielectric microsphere. We develop analytical expressions for the WGM shift due to electrostriction for solid and thin-walled micro-shells. The analytical results show that detection of electric fields < 1000 V/m is possible using water filled PDMS micro-shells. The electric field sensitivities for solid spheres, on the other hand, are significantly smaller. Results of experiments carried out using solid polydimethylsiloxane (PDMS) spheres agree well with the analytical prediction. These results are encouraging for future development of WGM-based optical switches/filters as well as electric field sensors.

7579-29, Session 7

Whispering-gallery-mode carousel nanoparticle sensors

F. Vollmer, Harvard Univ. (United States); S. Arnold, New York Univ. (United States)

Light forces interacting with mechanical systems provide a unique tool for studying small biological objects. In the case of a whispering-gallery-mode (WGM) bio-sensor where the intensity within the evanescent volume is built up resonantly a light-force may answer a puzzling question. Measured binding rates of bioparticles in aqueous solution using a toroidal WGM bio-sensor at ultra-low concentrations appear to be about one hundred times higher than calculated based on diffusive and convective transport theory. Traditionally Brownian motion of ultra-low concentration analytes crossing the boundary layer has been considered as a major hurdle for the practicality of miniature bio-sensors. There is no comprehensive model to explain the physical mechanism of enhanced binding rates in the case of WGM biosensors. Here we report an observation and analysis of an optical mechanism that enhances the transport rate to the sensing volume of a microspherical silica resonator by more than 50x. Polystyrene nanoparticles are drawn toward this volume by evanescent optical gradient forces generated with just a few microwatts driving the resonator. At low ionic strength an addition electrostatic force repels the nanoparticle from the surface, contributing to a radial trap. Here the particle finds itself in the tangential momentum flux of the WGM and is driven to orbit by scattering forces. The radial trapping potential is elucidated from fluctuations in the microcavity's resonance frequency, allowing the use of the Carousel as a surface-potential nanoprobe. The maximum fluctuation enables the size and mass of the trapped nanoparticle to be determined without binding, suggesting that the WGM Carousel mechanism can be used for size/mass spectrometry in solution. At a considerably high ionic strength the electrostatic field is screened to a much shorter depth, and the particle is drawn closer to the surface where it is caught by a van der Waal interaction and binds. Resonance shifts due to these binding events are found to be steps having uniform heights.

7579-30, Session 7

PDMS-based microfluidic lasers using whispering gallery modes for lab-on-a-chip applications

J. D. Suter, D. J. Howard, Univ. of Missouri, Columbia (United States); E. Hoppmann, I. M. White, Univ. of Maryland, College Park (United States); X. Fan, Univ. of Missouri, Columbia (United States)

Microfluidic lasers, which utilize liquid as a gain medium, are of great interest for lab-on-a-chip devices due to their small size, tunability, and cost-effectiveness. We demonstrate a soft-lithography-based opto-fluidic ring resonator (OFRR) laser which can be produced in arrays of identical rings in polydimethyl siloxane (PDMS). The PDMS structures are produced from a silicon mold fabricated using reactive ion etching (RIE) and are both robust and reusable. Using rhodamine 6G in a tetraethylene glycol (TEG) dye solvent provides enough refractive index contrast with PDMS to generate a multimode lasing signal from rings 200 to 400 microns in diameter and lasing thresholds near 1 µJ/mm2 centered around 590 nm. These rings are coupled to liquid waveguides which conveniently direct the lasing emission to other on-chip processes. Since the rings and waveguides are not in fluidic contact, however, many rings may be coupled into a single waveguide for multi-color emission. Separating the ring and waveguide fluidics also prevents unwanted absorption of the lasing signal by extra dye molecules. Further investigation has begun with other PDMS cavity geometries including spoked rings and spiral ring resonators that will add further functionality to these microfluidic arrays.

7579-31, Session 8

RF photonic devices with WGM resonators

V. S. Ilchenko, OEwaves, Inc. (United States)

No abstract available

7579-32, Session 8

Resonant millimeter wave optical modulators

W. H. Steier, Y. S. Lee, S. S. Lee, H. Tazawa, The Univ. of Southern California (United States); B. J. Bortnik, Y. Hung, H. R. Fetterman, Univ. of California, Los Angeles (United States); J. Luo, A. K. Y. Jen, L. R. Dalton, Univ. of Washington (United States)

Recently ring and disk micro-resonator based modulators have attracted great interest because they are compact and require low driving power. High Q optical resonances result in increased modulation efficiency but the RF bandwidth is limited by the resonator line-width. The modulators can be operated at this bandwidth either at baseband or at an RF frequency equal to a multiple of the free spectral range (FSR) of the resonator. For example a modulator with a linewidth of 7 GHz and 28 GHz FSR can be used at baseband from 0-3.5 GHz or can be used in a 7 GHz band around multiples of 28 GHz. We will review our published work on a traveling wave polymer micro-resonate modulator operating at 28 GHz, 84 GHz, 112 GHz, 140 GHz, and 168 GHz. We will present an analysis to show that these devices have better tolerance for velocity mismatches and for microwave loss of the electrode than traveling wave Mach-Zehnder modulators. We will conclude the presentation with some recent work showing that the limitation on the sensitivity-bandwidth product of these FSR modulators can be overcome by using two coupled resonators. We show here that by using two coupled discs, the bandwidth at the FSR can be significantly increased while keeping V low.

7579-33, Session 8

Frequency combs with resonators

S. Diddams, National Institute of Standards and Technology (United States)

No abstract available

7579-34, Session 8

Tunable photonic RF phase shifter using silicon microring resonator

Y. Su, Shanghai Jiao Tong Univ. (China)

We experimentally demonstrate a tunable photonic radio frequency (RF) phase shifter using a silicon microring resonator, which can delay a two-tone 40-GHz signal up to 4.6 rad.

7579-35, Session 9

Cavity optomechanics with nano- and microscale oscillators at millikelvin temperatures

T. J. Kippenberg, Max-Planck-Institut für Quantenoptik (Germany)

No abstract available

7579-36, Session 9

Mechanical amplification in cavities and ions

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

No abstract available

7579-37, Session 9

Photonic MEMS vibrating at x-band (11-GHz) rates

T. E. Carmon, Univ. of Michigan (United States)

No abstract available

7579-38, Session 9

Squeezing light from optical resonators

S. Creagh, The Univ. of Nottingham (United Kingdom)

It is described how strongly directional emission may be achieved from whispering gallery modes in optical resonators which are only very slightly deformed from spherical or circular geometry. A theoretical description is offered which uses an extension of eikonal approximation to complex ray families.

Moving to the complex rays which describe the evanescent wave just outside the resonator, and the emitted wave in the far-field, sees a qualitative change in the nature of the calculation. Although the real ray families underlying whispering gallery modes do not differ qualitatively from their spherical and circular counterparts — and may, for example, exhibit none of the island chains and chaos that are often exploited to produce and explain directionality — a symmetry breaking occurs in their complex extension which has a dramatic effect on the evanescent wave outside the resonator. Effectively, the nature of the eikonal ansatz is to exaggerate small differences in complex ray properties. For elliptical deformations a complete description of this mechanism can be given which extends to larger deformations. For generic perturbations, perturbative approximations applied to the rays rather than the wave itself can predict strong directionality even for very small deformations.

7579-39, Session 10

Strong coupling of single atoms with microtorodial resonators

N. P. Stern, D. J. Alton, H. J. Kimble, California Institute of Technology (United States)

No abstract available

7579-40, Session 10

Hybrid approaches towards single emitter coupling to optical microresonators

O. Benson, Humboldt-Univ. zu Berlin (Germany)

No abstract available

7579-41, Session 10

Slow light rotation sensors and gyroscopes

J. Scheuer, Tel Aviv Univ. (Israel)

Recent studies on optical rotation sensors employing slow-light media show great potential for the realization of compact, yet sensitive devices. In particular, the rapid progress in micro and nano fabrication methods render coupled cavity based slow-light structures as promising candidates for the realization of such devices. In slow-light structures, the impact of rotation is manifested in a completely different way than it does in conventional Gyros, thus giving rise to extremely different characteristics such as exponential sensitivity, phase-shift control and more. In this presentation, I review the principles of slow-light rotation sensors with emphasis on the differences from conventional optical Gyros. The underlying physical mechanisms of the variously studied slow-light Gyros as well as the expected performances will be presented and compared.

7579-42, Session 10

Three mode opto-acoustic interactions in optical cavities: introducing the three mode opto-acoustic parametric amplifier

F. A. Torres, D. G. Blair, L. Ju, C. Zhao, H. Miao, The Univ. of Western Australia (Australia)

Three mode opto-acoustic interactions can occur in optical cavities when a mirror acoustic mode has the appropriate mode shape and frequency to scatter carrier light into a cavity high order mode that has matching mode shape and frequency. The interaction can be very strong since the strength scales as the product of two optical and one acoustic quality factor. The phenomenon enables a new class of transducer, amplifier or optical cooler. Small scale devices are predicted to enable efficient cooling to the quantum ground state, while in the long optical cavities of gravitational wave detectors, the phenomenon can lead to acoustic instability. Experimental results are presented for both large and small scale systems, and the design of systems for optical cooling to the quantum ground state is discussed.

7579-43, Session 11

High-Q optical resonators: characterization and application to stabilization of lasers and high spectral purity microwave oscillators

A. Bouchier, P. Merrer, O. Llopis, LAAS-CNRS (France)

In order to design compact and high performances microwave oscillators, an elegant solution is to use optical waves as a carrier for the RF frequencies. RF resonators become optical ones and create optical frequency combs with microwave spacing. To obtain a RF Q factor higher than the one of WGM sapphire RF resonators, they must present an optical Q factor around 109.

One first possibility is to use whispering gallery modes in mini spheres and disks in silica, quartz...Optical Q factors from 108 to 109 are demonstrated. They can allow to build compact devices but because of laser launching stability difficulties, investigations on different types of resonator are interesting. Resonant fibre rings, built with few-meter-long fibres and fibered couplers, are alsopromising and easily integrated. Optical Q factors higher than 109 are demonstrated. These optical Q factors can be measured thanks to different methods we will present in this communication. These resonators can be used as bio- or physico-chemical sensors thanks to their sensitivity due to their high-Q factors, or as reference cavities to stabilize lasers or to build new microwave oscillators. The laser stabilization is in fact the first step toward the development of optoelectronic oscillators. We demonstrate an OEO at 10 GHz based on a passive fibre ring resonator. It presents phase noise performances comparable to the ones of dielectric resonator oscillators. With improvement of the resonators and OEO systems, compact low noise and high spectral purity microwave oscillators can be developed.

7579-44, Session 11

Ultra-narrowband fiber Bragg gratings for laser linewidth reduction and RF filtering

M. Poulin, Y. Painchaud, M. Aubé, S. Ayotte, C. Latrasse, G. Brochu, F. Pelletier, M. Morin, M. Guy, J. Cliche, TeraXion Inc. (Canada)

We review the improved performances of a narrow linewidth laser using negative electrical feedback obtained through advances on narrowband FBG filters. Noteworthy, the tolerance of the laser to vibrations is significantly improved. As an extension of this work, these narrow filters are proposed for filtering optical signals in RF photonics systems.

7579-45, Session 11

Single cavity filters on end-faces of optical fibers

S. Meister, M. Dziedzina, D. Schweda, A. Al-Saadi, B. A. Franke, C. Scharfenorth, Technische Univ. Berlin (Germany); B. Grimm, D. Dufft, S. Schrader, Univ. of Applied Sciences Wildau (Germany); H. Eichler, Technische Univ. Berlin (Germany)

We have developed thin film Fabry-Perot filters directly coated on optical fibers to archive a high level of integration with a reduction of optical elements. Such band pass filters can be used in fiber optical sensor systems, and for CWDM applications.

The filters cavities consist of a single spacer and two dielectric mirrors. The filters are deposited by PVD directly on end-faces of single-mode optical fibers. We have investigated the optical performance of filters with first (/2) as well as higher order spacers. Dielectric as well as polymeric materials are applied as the spacer layer.

Fiber preparation and the layer design were optimized by laser-induced damage measurements to improve the optical power resistance and the layer adhesion.

Filters with different mirror reflectivities and the influence of the Gaussian output beam of the single-mode fiber on the filter performance are investigated. The experimental results are compared with numerical analysis of Fabry-Perot cavities on the end-face of cylindrical waveguides. The spectral characteristic of the filters are calculated using a software solving Maxwell´s equations by a FDTD method.

The layer design of the filters and the deposition process were optimized for maximum transmission, and narrow bandwidth of the transmission peak. Band pass filters fabricated for a transmission wavelength of 945 nm show maximum transmission values of up to 90 %. Bandwidths as narrow as 1 nm could be achieved.

7579-46, Session 11

Active critical coupling of a resonant cavity

J. H. Chow, The Australian National Univ. (Australia); D. S. Rabeling, Vrije Univ. Amsterdam (Netherlands); M. B. Gray, National Measurement Institute (Australia); D. E. McClelland, The Australian National Univ. (Australia)

Critical coupling of a resonant cavity occurs when the reflected laser carrier power is zero. This is a special condition also often referred to as impedance matched. It is an important operating condition of a resonant cavity, as it occurs when the circulating power in the cavity is at maximum, and the transmitted optical intensity is optimized for a given input laser power. In numerous applications, such as cavity enhanced spectroscopy, and nonlinear optics in micro-resonators, active critical coupling is desired not only to optimize sensitivity, but also to control the circulating optical power.

We describe a technique, using radio frequency amplitude modulation of a laser, to actively lock the coupling condition of an optical cavity, while the laser is held on resonance. This interferometric technique provides an error signal voltage upon demodulation, whose polarity corresponds to over- and under-coupling, and has a zero crossing exactly at critical coupling. Hence this error signal can be used as a cavity coupling readout, as well as for active feedback for impedance matching. Active control requires a means to actuate a coupler in the cavity, which can be controlled by the feedback servo output.

We present experimental results and discuss the implementation of this technique in three types of cavities: a fiber ring cavity with a variable coupler, a free space cavity with a variable reflectivity mirror, and a micro-resonator.

7579-47, Poster Session

Optical-axis perturbation in triaxial ring resonators II: induced by spherical mirror’s axial displacement

X. Long, J. Yuan, National Univ. of Defense Technology (China)

In summary, the mirror’s axial displacement-induced optical-axis perturbation which has not been discussed before has been discussed in this article by modifying the augmented 5×5 matrix with the consideration of the mirror’s axial displacement. By applying this method to triaxial ring resonator, the mismatching error of the triaxial ring resonator has been found out that it can be decreased and can be even reduced to 0 by choosing appropriate axial displacement of the spherical mirrors. That is to say, for any real triaxial resonator, the optical-axes of all its three monoaxial ring resonators can be made pass through the center of their diaphragms simultaneously by controlling the perturbation source of mirror’s axial displacement properly. By utilizing this method, the alignment precision can be greatly improved and the total diffraction loss will be lowest in any monolithic triaxial ring resonator. These interesting findings are important to cavity design, cavity improvement and alignment of monolithic triaxial ring resonator

7579-48, Poster Session

Numerical analysis of random lasing properties in a waveguide structure surrounded by a random medium

H. Fujiwara, Hokkaido Univ. (Japan) and JST-PRESTO (Japan); K. Sasaki, Hokkaido Univ. (Japan)

Wavelength-scale-disordered structures composed of strong scattering nanoparticles (random structures) have attracted attention as low-cost and easily fabricated resonators, because of their potential for photon localization due to the interference of multiply scattered light. However, the difficulty in the control of localized modes due to the randomness becomes a critical issue for their applications. For this issue, we have numerically proposed a simple method to control the resonant properties by deliberately making a defect region within a random structure, due to the average reflectance of the emsamble of size-monodispersed scatterers. From the previous results, we had found that long-lived modes can be bound in the defect region if the structural parameters, e.g., refractive index, diameter, and filling factor of scattering centers, are optimized. In the presentation, we introduce the lasing properties observed at the defect region calculated by employing a two-dimensional finite-difference time-domain method including rate equations. From the results, we confirm that a strong lasing spot is induced primarily at the defect region by optimizing the structural parameters, even when multimode lasing occurs due to the high pumping rate.

7579-49, Poster Session

Spectra, coherence, and polarization of diffracted electromagnetic Gaussian Schell-model beams

L. Pan, Luoyang Normal Univ. (China); C. Ding, Sichuan Univ. (China); Z. Zhao, Luoyang Normal Univ. (China)

In the past years there has been an increasing interest in stochastic electromagnetic sources and in the beams which they generate. A class of electromagnetic Gaussian Schell-model (EGSM) beams, which is the

simplest known model of stochastic electromagnetic beams, has been investigated widely owing to its importance in theories of coherence and polarization of light and in some applications. However, most previous works on the subject were restricted to propagation of EGSM beams through unapertured system, and the behavior of spectra, coherence and polarization of diffracted EGSM beams has not been studied in great detail. In this paper we derive an approximate analytical formula for the cross-spectral density matrix of the electric field of diffracted EGSM beams by using the method of the complex Gaussian function expansion. We show both analytically and by numerical examples the aperture effects of spectra, coherence and polarization of electromagnetic Gaussian Schell-model beams. It is shown that the larger the truncation parameter the spectral degree of polarization becomes non-uniform on propagation, and increases with increasing z, the spectral density shape in the far zone with high truncation parameter is more tightly, and the spectral degree of coherence oscillates, and the larger the value of truncation parameter the spectral degree of coherence exhibits rapid oscillation.

7579-50, Poster Session

Temperature-dependent random lasing from GaAs powders

T. Nakamura, T. Takahashi, S. Adachi, Gunma Univ. (Japan)

Compound semiconductor GaAs is a material used for an injection-type semiconductor laser because of its high radiative electron-hole recombination rate due to the direct bandgap nature. Traditional GaAs-based semiconductor lasers have well-defined cavities, such as Fabry-Perot, distributed feedback, distributed Bragg reflector type structures. Recently, stimulated emission sources without any precise external cavities are proposed, called random lasers, and random laser emissions are observed from ZnO, GaN powders and ground Nd doped YAG particles. The random lasers consist only of irregular shaped particles with a few hundreds nano meter size, and the laser actions are caused by strong multiple scattering of emitted lights within these particles. However, because of such simplicity the control of the lasing properties is quite difficult. In this work, we demonstrate that GaAs powders can exhibit temperature-dependent random lasing, i.e., the lasing wavelength and threshold are strongly dependent on the temperature. Furthermore, we show that their dependences are mainly determined by the gain function of GaAs itself.

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LASE SPIE Photonics West

7580-01, Session 1

Programmable lasers: design and applications

A. Villeneuve, AGT Lasers (Canada)

A rapidly tunable, electronically controlled, pulse duration adjustable, arbitrarily programmable wavelength, picosecond mode-locked fiber laser is presented. The laser is tunable over 80 nm with a wavelength variation rate of over 10 millions wavelengths per second. Pulse duration is adjustable over tens of picoseconds with nearly Fourier limited linewidth. The laser can be harmonically mode-locked over 1 GHz. This laser design allows easy synchronization with our picosecond MOPA. Such laser systems are so versatile that they can be used for medical imaging, material machining and nonlinear optics. It proves also to be a valuable research tool since all the parameters are adjustable in µsec.

7580-02, Session 1

High-energy Q-switched Tm3+-doped polarization maintaining silica fiber laser

L. Shah, C. C. Willis, T. S. McComb, R. A. Sims, V. Sudesh, M. C. Richardson, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

The performance of a 795 nm diode-pumped Q-switched Tm3+-doped polarization maintaining (PM) silica large mode-area (LMA) fiber laser will be reported. The laser generates pulse energies up to 350 µJ with 115 ns pulse duration at 20 kHz, and average powers up to 28 W at 100 kHz repetition rate. The output polarization extinction ratio of the system is >10 dB. The maximum output pulse energy is limited by free-lasing when the system gain exceeds the Q-switch hold-off.

Two techniques are investigated to provide control of the spectral output of the system, alternately a 600 l/mm gold-coated reflection grating and a volume Bragg grating (VBG) are incorporated into the cavity as feedback elements. With the gold reflection grating, the laser produces 325 µJ pulses with 125 ns duration at 20 kHz at 1992 nm before wavelength control is lost. Using the VBG, the laser generates 225 µJ pulses with 200 ns duration at 20 kHz before parasitic lasing was observed at the peak of amplified spontaneous emission at ~1980 nm rather than the reflectivity peak of the VBG at 2052 nm. The limitations of wavelength and polarization control will be discussed, along with applications requiring single-polarization and high peak-power with sub-nanometer spectral widths, at wavelengths within the Tm3+ emission band of ~1950-2060 nm.

7580-03, Session 1

100-Watt fiber-based green laser with near diffraction-limited beam quality

D. Hu, E. C. Eisenberg, K. Brar, T. Yilmaz, E. C. Honea, Lockheed Martin Aculight (United States)

An air-cooled, light-weight, fiber-based, 100-Watt, green laser with M2 < 1.4 has been prototyped. The system consists of an all-fiber-based IR pump laser at 1064 nm and a frequency-conversion module in a compact and flexible configuration. The IR laser can produce more than 200 Watt linearly-polarized diffraction-limited output beam with high spectral brightness for frequency conversion. The IR laser package is <50 lb in weight and the doubler module weights <15 lb. The IR laser operates in QCW mode, with 10 MHz pulse repetition frequency and <5 ns pulse width, to generate sufficient peak power for frequency doubling in the converter module. The converter module has an input telescope and an oven with a nonlinear crystal to efficiently convert the 1064-nm IR fiber laser output to 532-nm green beam. The IR laser and conversion module are connected via a stainless-steel protected delivery fiber for optical beam delivery and an electrical cable harness for electrical power deliver and system control. An overview of the system and full characterization results will be presented. Such compact, high-brightness, green laser sources are expected to enable various scientific, defense, as well as industrial applications.

7580-04, Session 1

Yb-doped fiber laser system generating 12 ns, 0.7 mJ pulses at 82 kHz at 977 nm

J. Boullet, E. Cormier, Univ. Bordeaux 1 (France); R. Dubrasquet, R. Bello Doua, N. Traynor, ALPhANOV (France)

Abstract: We demonstrate an Ytterbium-doped fiber laser system generating high energy pulses at the non-conventional wavelength of 977 nm. An actively Q-switched master fiber oscillator delivers 1.2 W of average power in 12 ns pulses at adjustable multi-10 kHz of repetition rate. This pulsed fiber source is then amplified in an ultra-large core photonic crystal fiber amplifier up to 71 W. Deducing the fraction of power contained in interpulse ASE, we obtained 0.7 mJ pulses at 977 nm, resulting in a pulse peak-power of ~55 kW. To the best to our knowledge, this system delivers the highest performances ever demonstrated in this spectral window.

Summary:

During the last few years, fiber lasers have demonstrated their capabilities to generate short pulses with multi-MW peak power in sub-ns pulse, with average power > 100 W. However, these impressive performances of pulsed Yb-doped fiber laser systems traditionally exploit the quasi-four-level laser transition in the 1020 nm - 1100 nm spectral range, whereas very few demonstrations were made in the 970 nm - 980 nm spectral range. To our knowledge, the highest performances in nanosecond regime for a fiber system operating around 977 nm were limited to an average power of 110 mW of 15 µJ pulses, at the repetition rate of 7 kHz.

In this contribution, we report on a system comprising a Q-switched fiber oscillator and a power fiber amplifier generating up to 71 W of average power in pulsed regime, at adjustable multi-10 kHz repetition rate. The fiber oscillator, actively Q-switched by an acousto-optic modulator, delivers 1.2 W of average power, in 12 ns FWHM pulses. The interpulse amplified spontaneous emission, measured in the time domain, is ~20%, leading to an energy extraction of 0.7 mJ, corresponding to a pulse peak-power of ~55 kW. The main amplifier consists is a 1.2 m long ultra-large core (MFD~70µm) photonic crystal fiber amplifier. Finally, first demonstrations of frequency doubling around 488 nm blue spectral range are under investigations and will be presented at the conference.

7580-05, Session 1

100micron core, Yb-doped, single-transverse-mode and single-polarization rod-type photonic crystal fiber amplifier

F. Di Teodoro, Northrop Grumman Aerospace Systems (United States)

Pulsed fiber laser sources provide an attractive solution for applications requiring low power consumption such as high-duty-cycle micromachining and space-based imaging/sensing. In fact, the superior optical efficiency of rare-earth doped fibers and simpler thermal management project wall-plug efficiencies clearly exceeding those of bulk solid-state lasers. Another major benefit is the excellent beam quality (even when large heat loads are present) afforded by the fiber single-transverse-mode (STM) waveguidance. Work is still required, however, towards generating high pulse energies and peak powers, which, for fibers, is hampered by optical nonlinearities triggered by high in-core irradiance.

In this paper, we report on the development of a fiber-based laser transmitter aimed at long-range remote sensing/imaging applications, for which a challenging set of concurrent requirements must be met including high efficiency, excellent beam quality and pointing stability, linear polarization, pristine spectral quality, and precisely timed pulse firing. Our laser source is configured as a master-oscillator/power-amplifier (MOPA) architecture and features as the final amplifier a rod-type, single-polarization photonic crystal fiber featuring a ultra-low-nonlinearity, STM Yb-doped core of over 5000um2 mode field area (~100um core diameter), the largest reported to our knowledge for an active, polarizing or polarization-maintaining STM fiber. The MOPA is driven by an actively triggered, pulse programmable single-frequency gain-switched diode of minimal pulse jitter (<50ps) and delivers a multi-mJ energy, multi-MW peak power, >100W average power, ns-pulse, robustly linearly polarized output of STM spatial quality, excellent spectral brightness over a range of actively selected pulse durations and multi-kHz repetition rates.

7580-06, Session 1

Over 55W of frequency doubled light at 530nm pumped by an all-fiber, diffraction limited, picosecond fibre MOPA

S. Alam, K. Chen, J. R. Hayes, D. Lin, A. Malinowski, Univ. of Southampton (United Kingdom); H. J. Baker, N. Trela, Hariot-Watt Univ. (United Kingdom); R. McBride, PowerPhotonic, Ltd. (United Kingdom); D. J. Richardson, Univ. of Southampton (United Kingdom)

We report the realisation of a high-power, picosecond pulse source at 530 nm pumped by an all-fiber, single-mode, single-polarisation, Yb-doped MOPA. The pump MOPA comprised of a gain-switched seed source generating 20 ps pulses at a repetition frequency of 910 MHz followed by three amplification stages. An output power in excess of 100 W was obtained at 85% slope efficiency with respect to 975nm launched pump power. A 15mm long LBO crystal was used to frequency double the single-mode, single-polarisation output of the fiber MOPA. To satisfy the phase matching condition, the internal temperature of the LBO crystal was maintained at 1500C and a frequency doubled power in excess of 55 W was obtained corresponding to 56% optical-to-optical conversion efficiency with respect to incident pump at the crystal facet. The output power at 530 nm began to roll-off relative to theoretical expectations beyond 50 W of incident pump power due to self-phase modulation (SPM) assisted spectral broadening of the fundamental light within the final stage amplifier. Further enhancements in conversion efficiency should be possible by optimising the amplification stages so that the spectral integrity of the fundamental light is better maintained. Such high power green light is ideal for a variety of material processing applications including solar/photovoltaic cell manufacture, resistor trimming and marking of transparent materials to name but a few.

7580-07, Session 2

Ytterbium-doped fibers co-doped with Cerium: Next generation of fibers for high power fiber lasers?

M. Engholm, Fiber Optic Valley AB (Sweden); L. O. Norin, Acreo AB (Sweden)

We recently showed that the photodarkening (PD) resistivity in Yb/Al-doped fibers is greatly improved by adding cerium (Ce) to the core glass composition. We are now further investigating the laser performance and long term stability of Yb/Ce/Al fibers in high inversion applications such as 980nm lasers and amplifiers. Our objective is to study the limitations of Yb/Ce/Al fibers and elaborate on their potential of becoming the next generation of fibers for high power fiber lasers and amplifiers.

7580-08, Session 2

Temperature dependence of photodarkening kinetics

M. Leich, S. Jetschke, S. Unger, J. Kirchhof, IPHT Jena (Germany)

Photodarkening (PD) in Yb-doped fibers is a critical factor for the long-term stability of lasers and amplifiers. Various methods for characterization have been suggested, especially to accelerate the process and to standardize the measurement technique at short fiber samples.

We concentrate on the inversion-accelerated measurement of PD, characterizing the transmission of short fiber samples (1 to 2 cm in length) during core-pumping. Photodarkening losses measured at room temperature can be fitted quite well, e.g. with a stretched exponential function, but there is still no proper understanding of the parameter's meaning. At room temperature, the PD loss aspired for longtime pumping was interpreted as an equilibrium value [1]. But, in more detailed investigations we have found that the PD evolution is strongly influenced by thermal processes. Elevation of temperature accelerates the PD process [2] and affects the measured loss values, e.g. caused by thermal annealing taking place in parallel. Actually, the loss decreases after passing a maximum value, and the real equilibrium state can be achieved only for much longer time of pumping. For this reason, the measured curves do not cope with standard fitting procedures. The effect is pronounced at temperatures above 200°C but can also be observed at lower temperatures.

We report on the characterization of PD kinetics at Yb-doped fiber samples, inducing the PD loss by core-pumping at 975 nm with respect to different fiber temperatures in the range of 77 to 670 K. We will present the thermal dependency of important PD parameters. Additionally, we develop a qualitative model to include thermal effects in the description of the PD loss evolution and to improve the understanding of the PD process.

7580-09, Session 2

Mitigation of photodegradation in 790nm-pumped Tm-doped fibers

G. P. Frith, Macquarie Univ. (Australia); A. L. G. Carter, B. N. Samson, J. Faroni, K. Farley, K. Tankala, Nufern (United States); G. E. Town, Macquarie Univ. (Australia)

The capability of Tm-doped silica fibers pumped at 790nm to efficiently produce high power emission in the 1.9~2.1µm region has been well documented to date but little has been presented on the reliability of this technology. Early experiments highlighted that photodarkening can be a significant concern when Tm-doped fibers are exposed to high intensity blue light. We present a discussion of the process responsible for the production of blue light in Tm-doped fibers pumped at 790nm, how fiber composition and core temperature influences this process and how waveguide design can also effect the reliability of lasers and amplifiers. Through optimization of these parameters we have demonstrated highly efficient lasers exhibiting less than 1% output power degradation per thousand hours.

7580-10, Session 2

Thermal bleaching of photodarkening in ytterbium-doped fibers

M. J. Söderlund, J. J. Montiel i Ponsoda, Helsinki Univ. of Technology (Finland); J. P. Koplow, Sandia National Labs. (United States); S. K. Honkanen, Helsinki Univ. of Technology (Finland)

We study thermal bleaching of photodarkening-induced loss in ytterbium-doped fibers. Pristine and photodarkened samples are subjected to thermal ramp-up/down cycling pulses while the fiber absorption coefficient is monitored using a probe signal and lock-in detection. Recovery of the fiber absorption coefficient is seen to initiate at ~350 C while complete recovery is reached at ~650 C. Interestingly, prior to the recovery, the photodarkened fiber exhibits further heat-induced increase of absorption loss. This increase of loss is attributed to both a permanent increase of loss-inducing color centers and a temperature dependent broadening of the absorption spectrum. By selecting the probe wavelength near 612 nm (where the spectral broadening of absorption is minimized), we measure the heat-induced darkening to constitute to roughly 20 % of total induced losses. Post-irradiation heat-induced formation of color centers suggests the presence of an intermediate energy state in the near-infrared photochemical mechanism for photodarkening.

Further, we apply the demarcation energy curve approach of Erdogan (J. Appl. Phys. Vol 76, p. 73, 1994) to derive the thermal activation energy of the induced defects. The observed power-law time dependence of normalized absorption coefficient (upon exposing the sample to a known constant temperature) is well represented by Erdogan's thermal decay model. For the studied commercial 20-µm-core-diameter LMA fiber, the energy distribution consists of a single peak, located at ~1.3 eV with a FWHM of ~0.31 eV. Full recovery of absorption coefficient to pre-photodarkened state corresponds to ~1.9 eV.

7580-11, Session 3

High-power single-mode and single-frequency Tm-doped fiber amplifier amenable to coherent beam combination

G. D. Goodno, L. D. Book, J. E. Rothenberg, Northrop Grumman Aerospace Systems (United States)

We report on a diode-pumped Tm-doped fiber amplifier generating continuous-wave power >600W (>50% optical conversion efficiency) in a single-frequency (<5-MHz linewidth), stimulated-Brillouoin-scattering (SBS)-free, single-transverse-mode (M2 = 1.05), 2040nm-wavelength output beam. To our knowledge, this result represents the highest power obtained from any single-frequency and single-mode fiber laser source. We also describe our experimental and analytical investigation of further power scaling in individual Tm-doped fiber laser/amplifiers based on thermal and SBS management considerations. Moreover, power scalability via coherent beam combining is addressed by demonstrating active phase locking of the Tm-fiber amplifier at the 150W-output level.

7580-12, Session 3

23 watt 77% efficient CW OPO pumped by a fiber laser

A. J. Henderson, P. Esquinasi, Lockheed Martin Aculight (United States)

Continuous wave optical parametric oscillators (CW OPOs) using fiber laser pump sources provide high power widely tunable output in the near to mid-infrared range. Single frequency fiber lasers used to pump OPOs are relatively complex and expensive, using a master-oscillator power amplifier configuration, with multistage amplification. They are ultimately limited in power by the onset of nonlinear effects and the practical ability to provide output isolation. By contrast, fiber lasers in oscillator configuration, with a bandwidth consistent with the acceptance width of typical nonlinear materials, are simple, lower in cost and scalable in power to hundreds of Watts. They are also insensitive to feedback. We have used a 30 Watt fiber laser oscillator to pump a CW OPO, and have demonstrated 23 Watts total output power from the OPO. We believe this to be the highest total power output yet demonstrated from this class of device. The OPO was based on MgO-doped PPLN and was pumped by a 30 Watt fiber laser. The external efficiency was 77 % and the corresponding pump depletion was 83%. Output of 16.8 Watts at 1.5 microns and 6.2 Watts at 3.6 microns were demonstrated. We have also demonstrated simultaneous output of 10 Watts at 1.96 microns and 8 Watts at 2.34 microns in the same device using different MgO:PPLN poling periods.

7580-13, Session 3

Efficient near-infrared light conversion to visible and mid-infrared radiation in an endlessly single-mode photonic crystal fiber

D. Nodop, C. Jauregui, D. N. Schimpf, J. Limpert, Friedrich-Schiller-Univ. Jena (Germany); A. Tünnermann, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

We report on the efficient conversion of near-infrared pulsed light into visible and mid-infrared radiation exploiting degenerate Four-Wave Mixing (FWM) in an endlessly single-mode photonic crystal fiber (PCF). The characteristics of this fiber make it an ideal medium for FWM-based light conversion. The fiber geometry allows obtaining good overlaps even between modes with very distant frequencies since the mode field diameter changes only slightly with the wavelength, which enables an efficient exchange of energy almost independently of the wavelength. Additionally, the zero dispersion wavelength lie around 1250nm, which implies that pumping with light in the Yb-amplification band will result in phase matching to very distant signal and idler wavelengths, namely in the visible and mid-infrared bands respectively. Furthermore, since the PCF is made of IR-graded crystal it presents low attenuation up to ~3 m.

To experimentally demonstrate the suitability of these fibers for FWM-based light conversion, we employed a 1.4m long, 10 m core diameter, endlessly single-mode PCF and we pumped it with 200ps pulses of 100kW peak power and at 1MHz repetition rate. We obtained 3W of average power at 673nm and 450mW at 2539nm with an input average power of 8W. These results imply conversion efficiencies of ~35% into the 673nm signal and of ~7% into the 2539nm idler. We believe that these output powers are the highest reported so far in the visible and Mid-infrared bands obtained by FWM in an optical fiber. The converted power can be further scaled by increasing the repetition rate of the pump source.

7580-14, Session 3

Spectral narrowing and wavelength stabilization of thulium fiber lasers using guided-mode resonance filters

R. A. Sims, T. Dax, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); Z. A. Roth, The Univ. of North Carolina at Charlotte (United States); T. S. McComb, L. Shah, V. Sudesh, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); M. K. Poutous, E. G. Johnson, The Univ. of North Carolina at Charlotte (United States); M. C. Richardson, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

Guided mode resonance filters (GMRF) were used to stabilize the center wavelength and spectrally narrow the output from Tm fiber

lasers operating in the 2 μm wavelength regime. GMRFs are thin film structures composed of a waveguide and a sub-wavelength diffractive array allowing particular an evanescent diffracted order to couple into the waveguide then leak back on itself. This mode feeds back into the laser resonator with a stabilized narrow spectrum.

The GMRF feedback devices were characterized using an amplified spontaneous emission source (ASE) to determine the peak reflectivity, resonance wavelength, and the spectral linewidth of the elements. In these spectral reflectivity measurements the GMRFs were placed in the output path of the ASE and the transmitted light through the GMRF was measured producing a notch in the spectrum where resonances occur. The above measurements resulted in various resonance wavelengths depending on the fabricated GMRF features, as well as linewiths varying from 0.50-1.5 nm.

GMRFs were placed as external feedback elements to a Tm fiber laser pumped at 790 nm resulting in slope efficiencies of 30-45% with respect to launched pump power and output powers up to 10 W with narrow, stable linewidths before the onset of parasitic lasing set. In order to scale to higher powers and maintain narrow linewidths, a master oscillator power amplifier setup was employed using a GMRF stabilized the master oscillator. In addition to the laser and amplifier characteristics, thermal and damage testing of the GMRFs was preformed and will be reported.

7580-01, Session 4

Highly efficient and compact microchip green laser source for mobile projectors

J. Khaydarov, S. Essaian, G. Nemet, A. V. Shchegrov, N. Simanovskaia, Spectralus Corp. (United States); H. Danielyan, G. Gabrielyan, A. R. Poghosyan, S. Soghomonyan, Spectralus CJSC (Armenia)

Compact and efficient green lasers are of high interest to consumer electronics applications such as handheld and pocket projectors. First-generation, LED-based mobile projectors have just appeared in 2008. While RGB lasers offer many advantages in brightness and system design, a viable efficient and low cost green laser platform has been difficult to realize. Since direct green laser sources are not available, a number of nonlinear second-harmonic-based approaches have been proposed recently. In this work, we demonstrate a novel green laser source, based on a monolithic cavity microchip laser platform - monolithic assembly of Nd:YVO4 crystal and PPMgOLN crystal. The use of our highly efficient, periodically poled MgO-doped Lithium Niobate (PPMgOLN) as the nonlinear frequency doubler allows obtaining a significant increase in the overall efficiency of the green microchip laser. The microchip laser platform also offers cost efficient solution for the cost-sensitive market. The laser performs efficiently in both cw and pulsed regimes with repetition rates from 60Hz to 2KHz. We demonstrate 50-150mW green output with wall-plug efficiency exceeding 10% in the temperature range over 40°C. We discuss a compact package for this laser with volume less than 0.4cm3.

7580-02, Session 4

High-power green light generation by second harmonic generation of single-frequency tapered diode lasers

O. B. Jensen, P. E. Andersen, Technical Univ. of Denmark (Denmark); B. Sumpf, K. Hasler, G. Erbert, Ferdinand-Braun-Institut für Höchstfrequenztechnik (Germany); P. M. Petersen, Technical Univ. of Denmark (Denmark)

Green light is useful for a number of applications including display and biomedical applications. Traditionally frequency doubled diode pumped solid state lasers are used, when the power exceeds a few hundred mW's, as suitable high power laser diodes have not been available.

In this work, we demonstrate the use of a newly developed high power tapered diode laser with good spectral and spatial properties in frequency doubling. The tapered diode laser consists of a DBR section for wavelength selectivity, a single-mode ridge section to provide the good beam quality and a tapered amplifier section for increasing the output power. The laser is equipped with two electrodes in order to be able to control the current to the ridge and tapered section individually. The laser is capable of emitting more than 10 W of output power in a single-frequency, near-diffraction-limited beam.

The output of this laser is frequency doubled using periodically poled MgO:LiNbO3 to generate in excess of 1.5 W of output power at 531 nm in a single-frequency, near-diffraction-limited beam.

We investigate different configurations for generation of the green light and will present the use of the green light source for different applications.

7580-15, Session 4

RGB laser generation from fiber MOPAs coupled to external enhancement cavities

J. P. Anderegg, T. A. Chernysheva, D. F. Elkins, C. L. Simmons, R. C. Bishop, C. L. Pedersen, M. L. Murphy, F. L. Williams, Evans & Sutherland (United States)

Red (631 nm), green (532 nm), and blue (448 nm) continuous-wave (CW) lasers have been developed by Evans & Sutherland (E&S). These multi-watt RGB lasers are used as light sources in E&S' laser projector (ESLP), which delivers ultrahigh-resolution content (8192 × 4096 pixels) to large-surface-area venues (e.g., planetariums, simulators, visualization centers, etc.). Efficient visible wavelength generation is obtained by coupling single-frequency near-infrared (NIR) beams into free-space enhancement cavities containing critically phase-matched lithium triborate (LBO) crystals. The NIR energy is produced by a master-oscillator-power-amplifier (MOPA) system which is fiber-based, thus yielding Gaussian beams which are near-ideal for efficient fundamental-to-harmonic conversion. Both polarization-maintaining (PM) fibers and non-PM fibers have been employed with non-PM fiber systems requiring polarization sensing and control. Green laser light is produced by a second-harmonic generation (SHG) process with a 1064 nm fundamental. Red laser light is produced by a sum-frequency mixing (SFM) process with 1064 nm and 1550 nm as fundamentals. Blue laser light is produced by an SFM process with 1064 nm and 775 nm as fundamentals, where 775 nm is first produced by an SHG process with a 1550 nm fundamental. All resulting visible lasers are single-axial-frequency with FWHM bandwidths less than 200 kHz, and are spatially pure with M^2 values less than 1.05. At least 18 W of CW optical power has been generated at all three visible wavelengths, with available NIR amplifier power as the primary limiting factor.

7580-16, Session 4

Highly reliable 198 nm light source for semiconductor inspection based on dual fiber lasers

S. Imai, K. Matsuki, N. Kikuiri, Advanced Mask Inspection Technology, Inc. (Japan); K. Takayama, O. Iwase, NuFlare Technology Inc. (Japan); Y. Urata, T. Shinozaki, Y. Wada, S. Wada, Megaopto Co., Ltd. (Japan)

Highly reliable DUV light sources are required for semiconductor applications such as a photomask inspection. The mask inspection for the advanced devices requires the UV lightning wavelength beyond 200 nm. By use of dual fiber lasers as fundamental light sources and the multi-wavelength conversion we have constructed a light source of 198nm with more than 100 mW. The first laser is an Yb doped fiber laser with the wavelength of 1064 nm; the second is an Er doped fiber laser with 1560 nm. To obtain the robustness and to simplify the configuration,

the fundamental lights are run in the pulsed operation and all wavelength conversions are made in single-pass scheme. The PRFs of more than 2 MHz are chosen as an alternative of a CW; such high-PRF light is equivalent to CW light for inspection cameras. We use reliable devices in the wavelength conversion stages; especially a new CLBO device which is developed in another project is used for doubling the SHG output from the Yb doped fiber laser. Then we can obtain automatic operation for 6 months, which is described as follows. Free running operation gives rise to no power interruptions for a week; weekly maintenance within an hour is automatically done if it is required; monthly maintenance within 4 hours is automatically done on fixed date per month; manufacturer's maintenance is done every 6 month. Now this unique 198 nm light source is equipped in the leading edge photomask inspection machine.

7580-17, Session 4

High average and peak power pulsed fiber lasers at 1030 nm and 515nm

B. Cocquelin, J. Saby, F. L. Salin, A. Meunier, Eolite Systems (France)

Although many applications require high power pulses in the visible, fiber lasers have mostly restricted their range to the near infrared. We will present new results obtained with rod type fiber lasers leading to record high performances. Starting we newly designed large mode area photonic crystal fibers in a very simple architecture, we produced over 110W at 1030 nm with Q-switched pulse duration below 10 ns and M2<1.3. These very high peak and average powers lead to over 60W at 515 nm. We have also obtained diffraction limited beams with an output power exceeding 210 W at 1030 nm and 130 W at 515 nm in a very simple MOPA configuration. Due to the very high gain in these fibers, we can keep pulse durations below 20 ns up to 500 kHz in a purely Q-switched system. We will then present results on very high average power picosecond pulse amplification using the same technology as well as route to the kW average power with 10ns, diffraction limited beams.

7580-24, Session 4

Efficient, green laser based on a blue-diode pumped rare-earth-doped fluoride crystal in an extremely short resonator

M. Strotkamp, T. Schwarz, B. Jungbluth, Fraunhofer-Institut für Lasertechnik (Germany)

Intended for use in mobile projectors, the green cw-laser presented in this work utilises a rare-earth-doped fluoride crystal laser pumped by a blue laser diode. The absorption wavelength of Pr:YLF fits the emission wavelength of GaN laser diodes commercially available, and Pr:YLF emits at 523nm.

The laser consists of a blue laser diode, beamshaping optics, a focussing lens and the hemispherical resonator. Since the aim was to build a compact laser system, the resonator comprises a coated Pr:YLF crystal and a concave outcoupling mirror with an extremely small radius. The resonator is only 10mm long and exhibits high stability against misalignment compared to longer resonator designs.

Available from Nichia the blue pump diodes have an output power of 500mW and 1W. For the lower power diode with a M2 of 1 and 3 in the fast and slow axis, a good overlap with the laser mode can be achieved in the 5mm long crystal. The output of the laser with the higher power diode does not increase as desired due to a M2 of 3 and 6.

With the 500mW diode a laser with M2=1 and an output power of 140mW for an absorbed pump power of 410mW has been achieved. With a threshold of 70mW the laser exhibits a slope of 40% and an electro-optical efficiency of 6.5%.

Despite the reduced overlap with the 1W diode, an output power of 290mW for an absorbed pump power of 850mW and slightly increased M2 has been shown.

7580-25, Session 4

Frequency doubling of fiber laser radiation of large spectral bandwidths

S. Nyga, J. Geiger, B. Jungbluth, Fraunhofer-Institut für Lasertechnik (Germany)

In this work the reduction of conversion efficiency due to the spectral bandwidth of the fiber laser radiation is investigated. Subsequently, compensation optics to correct the spectral phase mismatch inside the nonlinear crystal are dimensioned and tested. For the experimental investigations a laboratory fiber laser setup was used consisting of a seed diode and a three stage fiber amplifier. The laser delivers an average output power of up to 100 W at 1 MHz. Even below the Raman threshold the output is far away from Fourier limit, providing a nearly Lorentz-shaped spectrum with a bandwidth of up to 5.8 nm and a temporal pulse width of 800 ps. As the bandwidth increases nearly linearly with the pump power of the third amplifier stage, this parameter could be easily controlled for the experiments. For a better comparison of measurements with different bandwidths, the input power at the nonlinear converter stage could be kept constant by means of an external attenuator.

All conversion experiments were conducted with a moderate load of the nonlinear crystals, i.e. intensity less than 150 MW/cm2. Without compensation for the spectral phase mismatch, a conversion efficiency of 19% is attained for a Type I configuration with a 20 mm long LBO crystal. The conversion efficiency drops with rising bandwidth and lies at less than 10% at 5.8 nm. With compensation optics to correct the spectral phase mismatch 27 W green are obtained from 60 W infrared with 4.4 nm bandwidth at the same load.

7580-18, Session 5

The impact of the economy and technology evolution on the market for fiber lasers

T. Hausken, Strategies Unlimited (United States)

No abstract available

7580-19, Session 5

Power scaling of fiber lasers

J. Thieme, IPG Laser GmbH (Germany)

The power scaling of SM fiber lasers to 10kW SM and higher power is limited by three primary factors: pump brightness, thermal issues, and non-linear effects in the fibers. These limitations, and the methods we have devised to overcome them, are reviewed. The latest results in high power SM and MM lasers are provided. Advantages of fiber lasers versus competing technologies are discussed. Applications of high power fiber lasers are reviewed.

7580-20, Session 5

Industrial fiber lasers

U. Hefter, Rofin-Sinar Laser GmbH (Germany)

Over the last years, the fiber laser technology has exhibited huge technological po-tential in terms of output power, brilliance and pulsing, which enabled this technology to penetrate the industrial materials processing applications. Today cw fiber lasers are capable to generate a few kW single mode and many kW multi mode output beams while pulsed fiber lasers cover the pulse width spectrum from ms to ps with output powers up to a few 100W. This presentation will discuss fiber laser concepts for Macro, Micro and Marking applications.

 TEL: +1 360 676 3290 · +1 888 504 8171 · customerservice@spie.org

7580-21, Session 6

Fiber lasers for surface Navy applications

D. H. Kiel, Naval Sea Systems Command (United States)

The Navy is working on the integration of commercial fiber lasers into potential future laser weapon systems. The current approach is to integrate on the existing Close In Weapon System (CIWS) incoherently combined fiber lasers to obtain weapons level power. Recent test results demonstrated the utility of this approach by shooting down 5 of 5 tactically relevant UAV's. The basic program will be discussed along with the reasons for using commercial fiber lasers. Challenges to commercial fiber laser business to support future Navy needs of brighter, more robust fiber lasers will also be discussed.

7580-22, Session 6

Leveraging fiber laser technology into micro-machining applications

A. P. Hoult, A. V. Babushkin, IPG Photonics Corp. (United States)

Having consolidated their position at the high average power multi-kilowatt end of the industrial laser spectrum, it is clear that the major limitations associated with fiber lasers are now well understood. This has allowed the development of a wide range of high brightness pulsed and modulated lasers. The intrinsically scalable concept of fiber lasers has been used to scale pulsed nanosecond lasers up to 500W average power. Conversely, this has also led to fiber lasers being scaled down to low nanosecond pulse lengths and high repetition rates up to < 1 MHz. Polarization-maintaining source lasers have also now been developed enabling very efficient frequency conversion to 532 nm. The well understood benefits of fiber lasers will therefore be available for many micro-machining processes that have previously been the preserve of higher cost diode pumped solid state lasers or less efficient flashlamp-pumped solid state lasers. A description of these new lasers along with applications results will be presented.

7580-23, Session 6

20 mW, 70 nm bandwidth ASE fiber optic source at 1060 nm wavelength region for optical coherence tomography

I. Trifanov, Multiwave Photonics, S.A. (Portugal); P. Caldas, Instituto de Engenharia de Sistemas e Computadores do Porto (Portugal); L. P. Neagu, R. Romero, M. O. Berendt, J. R. Salcedo, Multiwave Photonics, S.A. (Portugal); A. G. Podoleanu, Univ. of Kent (United Kingdom); A. B. Lobo Ribeiro, Univ. Fernando Pessoa (Portugal)

Broadband sources (BBSs) are commonly used in a wide range of applications in optical communication systems and biophotonics. They are key elements for biomedical imaging techniques such as optical coherence tomography (OCT), because an OCT system's axial resolution is given ultimately by the coherence properties of the light source. Optical coherence tomography (OCT) imaging at 1060 nm region have recently been proved to be successful in ophthalmology not only for resolving intraretinal layers, but also for enabling sufficient penetration to monitor the sub-retinal vasculature in the choroids when compared to most commonly used OCT imaging systems at 800 nm region. To encourage further clinical research using this technology at this particular wavelength we have developed a compact fiber optic source based on amplified spontaneous emission cantered at ~1060 nm with a spectral bandwidth (FWHM) of ~70 nm and output power >20 mW. Our approach in obtaining a broad and smooth emission is based on a combination of slightly shifted ASE emission spectra around 1 micron region from a combination of two different rare-earth doped fibers (Ytterbium and Neodymium) integrated into double-pass backward optical configurations. Spectral shaping and power optimization have been achieved using long period fiber gratings (LPGs) as in-fiber filtering solution. A study of the LPG position in different configurations has been performed for establishing the optimum source parameters in terms of output power and bandwidth as a function of the pump power. The source has been tested in an OCT system optimized for this wavelength.

7580-24, Session 6

Optically switched erbium fiber laser using a tunable fiber Bragg grating

R. J. Williams, N. Jovanovic, G. D. Marshall, M. J. Withford, Macquarie Univ. (Australia) and Ctr. for Ultrahigh bandwidth Devices for Optical Systems (CUDOS) (Australia)

Fibre Bragg gratings inscribed using infrared femtosecond laser pulses offer narrow linewidth, increased resilience to temperature and intense optical fields, and compatibility with all-fibre laser architectures. This has provided scope for exploring novel all-optical fibre laser switching geometries. In this work, we report on a switchable erbium all-fibre laser, realised by optically-tuning a high-reflector fibre Bragg grating on and off resonance with an output-coupler grating.

The high-reflector grating was inscribed in a ytterbium-doped fibre, and the output coupler grating was inscribed in an undoped fibre. These gratings were spliced onto opposite ends of the erbium-doped fibre to complete the fibre laser cavity. While pumping the erbium fibre at 976 nm, lasing output was observed at 1536.4 nm.

By pumping the ytterbium-doped fibre (with a second 976 nm diode), the high-reflector grating was tuned off-resonance from the output-coupler grating, and the erbium fibre ceased lasing (> 40 dB extinction). By modulating the pump for the high reflector, the erbium fibre laser output was switched on and off repetitively. Successful switching at 4 kHz was achieved with full extinction, limited only by the switching time of the pump diode driver.

The output of the fibre laser maintained narrow linewidth (< 12 pm) at all modulation frequencies.

These results demonstrate an all-optical technique for controlling the output of a fibre laser, with potential for polarization switching, rapid wavelength tuning or power modulation applications.

7580-25, Session 7

Picosecond laser processing of semiconductor and thin film devices

B. W. Baird, Summit Photonics (United States)

Next generation semiconductor, photovoltaic and display devices require precise, highly reliable, and cost-effective laser processing system solutions capable of high average power output at pulse repetition frequencies substantially exceeding 100 KHz. Emerging 45 nm and 32 nm node logic devices contain increasingly complex stacks of difficult to process materials, such as copper and low K dielectrics, demanding precise laser micromachining with minimum heat affected zones and melt effects. Laser memory repair of 5x nm node DRAM memory devices requires fine control of the fuse stack removal to avoid damage to adjacent circuitry. Significant improvements to patterning processes essential to the production of thin film photovoltaic devices are necessary to drive increased device efficiency and reductions in module prices. Similar challenges are faced in devising laser process solutions for crystalline silicon photovoltaic and advanced display devices. Robust picosecond laser architectures, including diode-pumped solid state master oscillator power amplifier or regenerative amplifier, fiber master oscillator power amplifier and fiber-bulk hybrids are broadly employed in investigations to identify solutions for these important industrial thin film laser processing applications. The prospects for broader adoption of industrial picosecond laser processing systems will be addressed along with related implications for advanced picosecond laser and laser system design requirements.

7580-26, Session 7

The supercontinuum laser as a flexible source for quasi-steady state and time resolved fluorescence studies

R. Fenske, Edinburgh Instruments Ltd. (United Kingdom) and Heriot Watt Univ. (United Kingdom); D. U. Näther, R. B. Dennis, S. D. Smith, Edinburgh Instruments Ltd. (United Kingdom)

Commercial fluorescence lifetime spectrometers have long suffered from the lack of a simple, compact and relatively inexpensive spectrally broad light source for both quasi-steady state and time resolved measurements (using both Time Correlated Single Photon Counting (TCSPC) and Multi-Channel Scaling (MCS) techniques).

This paper reports the integration of an optically pumped, photonic crystal fibre supercontinuum source as a light source in a Fluorescence Lifetime Spectrometer. Single photon counting was used to investigate the output of the source between 375-1700nm. The performance of the next generation of sources, with higher spectral brightness and deeper UV output will also be reported.

The spectrally dependant pulse width of the supercontinuum source has been investigated using a streak camera and concomitantly with a MCP. The competing nonlinear processes involved in supercontinuum generation are investigated by studying the temporal nature of the Instrument Response Function (IRF), together with pulse height distribution.

A novel interference filter based system for the spectral selection of supercontinuum radiation will be reported. The device allows continuous control of bandwidth and wavelength throughout the visible region whilst maintaining beam quality. The performance of this device will be compared and contrasted with a tuneable acousto-optic filter. The device is ideal for applications requiring high spectral purity, good beam quality and the ability to offset bandwidth against intensity e.g. STED.

Other fluorescence applications of the source will also be discussed, including employing bursts of pulses in a variable envelope, for lifetime measurements in the micro- and milli-second range e.g. TR FRET of Eu-cryptate.

7580-27, Session 7

Fiber laser intensity noise suppression using cascaded resonators

T. T. Nguyen, J. H. Chow, C. M. Mow-Lowry, T. T. Lam, D. E. McClelland, The Australian National Univ. (Australia)

Single frequency fiber lasers are emerging as an important alternative to solid state lasers for high performance interferometric instrumentation in sensing, metrology and quantum cryptography. To optimise performance, many of these applications require that the relative intensity noise of the laser source be minimized, ideally limited only by quantum noise. The most common method to suppress intensity in fiber lasers is by active feedback to the laser pump diode. However, this technique often has limited feedback bandwidth, and is thus ineffective above a few MHz.

We present a technique to passively filter the intensity noise of a fiber laser by using two cascaded fiber ring resonators. The two optical cavities in tandem facilitate second order filtering to minimize intensity noise. For a stable filtered optical output, the laser must be simultaneously kept resonant with both cavities. This was enabled by two Pound-Drever-Hall frequency locking feedback loops, which employ radio frequency phase modulation interferometry. The control architecture involves a master-slave active feedback scheme, where the laser is locked to resonance of one cavity, while the second cavity is frequency locked to the laser. The two fiber cavities are designed to have different free spectral ranges: 2 MHz and 13.5 MHz. This is so that besides the resonances locked to the laser, the remaining modes of the two cavities do not coincide.

Using this technique, we demonstrate a fiber laser source at 1550 nm with shot noise limited performance above 1.5 MHz.

7580-28, Session 7

High-energy femtosecond fiber laser at 1.6-µm for corneal surgery

F. Morin, F. Druon, M. Hanna, P. M. Georges, Institut d’Optique Graduate School (France)

In highly pathological corneas, the penetration depth of clinical femtosecond lasers at 1 µm is limited by scattering induced losses and wavefront distortion. It has recently been shown that the penetration depth can be improved by a factor of three by increasing the laser wavelength to 1.6 µm. We propose an alternative compact source operating at 1.6 µm based on chirped-pulse amplification in an erbium-doped large-mode-area fiber.

Recent studies have demonstrated the potential of erbium-doped fiber based systems to achieve sub-picosecond pulses with tens of µJ at 1.55 µm. Yet, transposing those systems to 1.6 µm is very challenging since the erbium-doped fiber gain is about 5 times lower at 1.6 µm than at 1.55 µm. This implies the use of longer fibers for amplification, which increases nonlinear phase accumulation.

Our system is based on a 70 fs erbium-doped fiber oscillator stretched in 100 m of a dispersion compensating fiber. The pre-amplification stage is made of an acousto-optic modulator and a telecom-based all-fiber amplifier. A diode-pumped large-mode-area erbium-doped fiber is used to extract energy and manage nonlinearities. The fiber is 12-m-long, has a 20-µm-diameter core and a numerical aperture of 0.08. The pulses are finally compressed in a dual reflective grating compressor.

Nonlinear compensation of the stretcher/compressor dispersion mismatch results in the generation of 605 fs pulses at 300 kHz with an energy of 1.5 µJ. This is to our knowledge, the first sub-picosecond laser reaching the µJ level at 1.6 µm in erbium-doped fibers.

7580-29, Session 8

Giant-chirp fiber oscillators

W. Renninger, F. W. Wise, Cornell Univ. (United States)

Recent work has shown that stable, highly-chirped pulses can be generated by all-normal-dispersion fiber lasers. Pulses in the ~100-ps range but with bandwidth to support ~0.5-ps pulses are produced, with energies of tens of nanojoules and at repetition rates of 1 MHz and below. The chirped pulses can be compressed to near the transform limit. Lasers that produce pulses with such giant chirp should greatly simplify chirped-pulse fiber amplifiers. After a brief review of fiber lasers based on dissipative solitons, recent developments will be summarized.

7580-30, Session 8

2-GW peak power 71-fs pulses at 50 kHz based on nonlinear compression of a fiber CPA system

S. Hädrich, J. Rothhardt, T. Gottschall, J. Limpert, Friedrich-Schiller-Univ. Jena (Germany); A. Tünnermann, Friedrich-Schiller-Univ. Jena (Germany) and Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

We present a high peak and average power laser system with ultrashort pulses at high repetition rates. Pulse shortening and peak power enhancement of a state-of-the-art fiber laser system is achieved by utilizing nonlinearity, namely self-phase modulation and subsequent compression in a chirped mirror compressor. The nonlinear interaction is achieved by propagation in a noble gas filled hollow core fiber with an

inner diameter of 200 µm and a length of 0.53 m. A total dispersion of -7000 fs^2 is applied by a chirped mirror compressor resulting in ultrashort pulses of 71 fs duration. This is achieved by coupling 400 MW, 800 fs pulses from the CPA system to the Xenon filled hollow fiber. The average power at the output of the compressor is measured to be 10 W at 50 kHz repetition rate resulting in 200 µJ pulse energy. Hence, the compressed pulses have a peak power of more than 2 GW. Consequently, the pulses of the CPA system are shortened by a factor of ten and the peak power is enhanced by a factor of 5. In addition this approach offers further peak and average power scalability.

7580-31, Session 8

The critical role of intracavity dynamics in high-power mode-locked fiber lasers

J. N. Kutz, Univ. of Washington (United States); B. G. Bale, Aston Univ. (United Kingdom)

Although the practical and innovative applications of mode-locked lasers has continued to grow in the past decade, its broader impact has been limited due to restrictions on pulse energies, which is a consequence of the underlying cavity nonlinearities. Recently, however, progress has been made experimentally to achieve mode-locked fiber lasers that produce high-energy, ultrashort pulses in self-similar lasers (SSL), chirped pulse oscillators (CPO), and all-normal dispersion (ANDi) lasers.

In contrast to solitonlike processes that dominate modern mode-locked lasers, these lasers depend strongly on dissipative processes as well as strong phase modulations to shape the pulse.

These new lasers exhibit a variety of pulse shapes and evolutions, which distinguish it from the typical soliton (anomalous) mode-locked lasers. Further, the intracavity dynamics is critical to understanding the stability and operation of the mode-locked state. As a result, modeling the pulsed solution within the context of a theoretical model where all processes are distributed does not characterize the intracavity dynamics or accurately capture the mode-locking behavior. In this presentation, we provide new analytic methods for describing the large intracavity laser dynamics in the SSL, CPO and ANDi lasers. These analytic methods are developed from a variational method of the averaged evolution equations that includes the essential discrete components that are responsible for large intracavity pulse fluctuations. The reduction demonstrates the underlying stable node structure of the mode-locked solution and highlights how phase profiles, which have been experimentally observed, are critical in the mode- locking dynamics. Further, the variational model provides an excellent theoretical framework for optimizing laser cavity performance. Indeed, laser performance optimization and the determination ofpeak power levels can be found at a fraction of the computational expense of standard methods.

7580-32, Session 8

Improved performance of nonlinear CPA-systems by spectral clipping

E. Seise, D. N. Schimpf, J. Limpert, A. Tünnermann, Friedrich-Schiller-Univ. Jena (Germany)

In this work we present a new method for peak-power scaling in nonlinear CPA-systems. There are several methods for compensating the nonlinear spectral phase shift accumulated in such systems due to self-phase modulation. For example, the separation length of the grating pair in a compressor unit can be changed. More sophisticated methods involve spectral amplitude and phase shaping using a spatial light modulator (SLM) or an acousto-optic programmable dispersive filter (AOPDF).

The method presented in this work is completely passive, i.e. no active components like a SLM or AOPDF are required. By cutting the amplitude spectrum, for example in the stretcher unit, we demonstrate pulse quality enhancement and an increase of peak-power at the output of the CPA-system. Using this method the peak-power of an existing nonlinear CPA-system delivering Sech2-pulses can be increased. A theoretical model allows us to determine an optimal ratio between the spectral cutting bandwidth and the pulse bandwidth at a certain B-integral. The important fact is that stretcher units based on dielectric gratings are commonly designed to provide a spectral bandwidth which is, typically, two to five times larger than the pulse bandwidth. A simple redesign of these stretcher units, applying our new spectral clipping technique, would significantly increase the output peak-power of such nonlinear CPA-systems by a factor of two up to five due to the higher stretching ratio. In addition to the simulations, we experimentally verified the theoretical predictions by applying our new technique to a fiber CPA-system.

7580-33, Session 8

200W, 350fs fiber CPA system enabled by chirped-volume-Bragg-gratings and chirally-coupled-core fiber technology

M. Rever, S. Huang, Univ. of Michigan (United States); V. I. Smirnov, E. V. Rotari, I. Cohanoshi, OptiGrate Corp. (United States); S. Mokhov, L. B. Glebov, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); A. Galvanauskas, Univ. of Michigan (United States)

Fiber CPA laser systems are an extremely promising technology for generating ultrashort (fs scale) pulses at high average powers (hundreds of Watts to kW) while still producing diffraction-limited beams and being compact and robust compared to bulk solid-state systems. Two obstacles still must be overcome to realize this potential, however. First, there is a need for stretchers and compressors that can yield long stretched pulse durations (hundreds of ps to nanoseconds) and can handle high energies and average powers, yet are still simple and compact, so as to not offset the benefits of fibers. The second challenge is that large-core fibers are needed for amplifiers and other components that still are robustly single-mode.

In this work, we present an Yb-fiber CPA system based on two novel technologies to overcome the aforementioned problems. Chirped volume Bragg gratings (CVBGs), slabs of photo-thermo-refractive glass of cm-scale with a quasi-periodic longitudinal index of refraction, are used for the stretcher and compressor. Their compactness and simplicity makes them compatible with fiber laser benefits, and their excellent power handling capabilities are demonstrated here. Chirally-coupled-core (CCC) fibers, which have large core diameters (35 µm in this work), yet are robustly single mode and can be coiled and spliced, are used for the power amplifiers. Using these technologies, a system producing a record 200W of power (130W compressed) with 350fs pulse durations is demonstrated, and the potential for scaling towards the kW level is explored.

7580-34, Session 8

Spectral-temporal management of Yb-doped fiber CPA-systems

D. N. Schimpf, F. Röser, T. Eidam, J. Limpert, A. Tünnermann, Friedrich-Schiller-Univ. Jena (Germany)

Fiber-based amplification of ultrashort pulses is usually accomplished employing the technique of chirped pulse amplification (CPA). State-of-the-art fiber CPA-systems deliver pulses with energies of about mJ and duration > 700 fs [1]. A primary aim is further peak-power scaling. In general, a broader spectral bandwidth corresponds to a higher peak power. However, gain narrowing during amplification may impose a limitation on the output bandwidth. In this contribution it is shown that spectral management enables significant peak-power scaling. At first, emphasis is placed on amplification below saturation. Then, we discuss the interplay of saturation-induced pulse-distortion and the spectral behaviour of the gain. Consequently, peak-power scaling requires a spectral-temporal management.

7580-67, Poster Session

A novel DWDM method to design a 100-kW Laser

S. Basu, Sparkle Optics Corp. (United States)

In this paper, we will present the design analysis of a novel concept that can be used to spectrally multiplex 125 1-kW single mode lasers. In a typical spectral combination scheme to generate a high power laser beam with near diffraction limited beam quality, a number of single-mode lasers operating at slightly different wavelengths are combined in a grating [1]. The number of lasers that can be multiplexed is limited by the bandwidth of the laser medium and the angular dispersion of the grating. It has been shown that the number of laser beams that can be multiplexed can be dramatically increased, and the size of the device can be significantly reduced by amplifying the angular dispersion in a set of total internal reflection surfaces operating at near the critical angle [2]. This method has been successfully demonstrated to multiplex and demultiplex 8 channels of a tunable single-mode fiber laser source, which are separated by 0.4 nm in wavelength. We will present analysis of a specific design that spectrally combines 125 single-mode, single-frequency lasers over a 50 nm bandwidth at 0.4 nm wavelength spacing as has been demonstrated in [2]. With a projected 1-kW power per channel [3], 100-kW DWDM laser is expected with near diffraction-limited beam quality for high-power applications.

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7580-68, Poster Session

Monolithic Yb-fiber femtosecond laser with intracavity all-solid PBG fiber and ex-cavity HC-PCF

D. Turchinovich, X. Liu, J. Lægsgaard, Technical Univ. of Denmark (Denmark)

We report on a monolithic, i.e. all-in-fiber femtosecond Yb-fiber laser, operating at around 1030 nm, and delivering approximately 275-fs long pulses with 9 nJ energy at 27 MHz repetition rate, directly from the fiber end. Our laser is a chirped-pulse amplification (CPA) MOPA system, consisting of a linear-cavity oscillator, an amplifier chain, and a hollow-core photonic crystal fiber (HC-PCF) for the final pulse compression. All elements of the MOPA system are fusion-spliced together, i.e. no free space coupling between the elements is used in this laser. The linear-cavity femtosecond oscillator is modelocked with a semiconductor saturable absorber mirror (SESAM) which is glued directly to the fiber on one end of the cavity. A broad-band highly reflective fiber-pigtailed mirror is used as the other end of the cavity. A novel PM all-solid photonic bandgap fiber is spliced into the cavity for dispersion management. The oscillator delivers approximately 40 pJ pulses with 8 nm spectral bandwidth. The oscillator pulses are stretched in a long PM SMF, and then launched into a 2-stage amplifier chain, resulting in approximately 12-ps long pulse with an energy of 15 nJ and a spectral bandwidth of 11 nm. A final pulse compression in a spliced-on low-nonlinearity birefringent HC-PCF results in pulses with approximately 275 fs duration and 9 nJ energy, delivered directly from the end of the HC-PCF, with the spectrum unaffected by the compression. Our laser demonstrates a very good temperature and mechanical stability, and stable Q-switch-free modelocking performance.

7580-69, Poster Session

Relations between phosphorus/aluminum concentration ratio and photodarkening rate and loss in Yb-doped silica fibers

P. Laperle, L. Desbiens, H. Zheng, M. Drolet, A. Proulx, Y. Taillon, INO (Canada)

The relations between dopant concentrations (phosphorus and aluminum) and photodarkening rate, excess loss, and activation energies in ytterbium-doped silica fibers are experimentally investigated. It is shown that increasing the concentration of phosphorus from 0.2 to 2.5 mol% in codoped phosphorus/aluminum fiber cores decreases the photodarkening excess loss by a factor of 7 and the photodarkening rate by a factor of 10. Moreover, the effective number of ytterbium ions involved in photodarkening increases from 4 to more than 6 for tested phosphorus/aluminum concentration ratios from 0.1 to 1, respectively. In contrast, increasing the aluminum concentration from 2 to 5 mol% for a fixed phosphorus concentration of 0.2 mol% has negligible effect on the initial photodarkening rate or the effective number of ytterbium ions involved in the process, but still decreases the photodarkening excess loss by a factor of 4. Those results suggest photodarkening activation energies of 5.2 eV for ytterbium/aluminum-codoped silica fibers and more than 7.8 eV for ytterbium/phosphorus/aluminum-codoped silica fibers. The net improvement in photodegradation of fiber amplifiers based on such phosphorus and aluminum codoping is measured experimentally and numerically simulated. The output power loss of 1064-nm ytterbium-doped LMA fiber amplifiers with phosphorus/aluminum ratios of 0.1 and 0.6 is reduced after 10,000 hours from 17% to less than 2%, respectively. Better understanding of the effects of phosphorus and aluminum on photodarkening will help to design reliable and efficient ytterbium-doped fiber amplifiers.

7580-70, Poster Session

Characterizing the transition dynamics for multi-pulsing in mode-locked lasers

J. N. Kutz, Univ. of Washington (United States); B. G. Bale, Aston Univ. (United Kingdom)

Multi-pulse mode-locking operation has been achieved in a wide variety of laser cavity configurations. Indeed, this multi-pulse per round trip laser operation is a ubiquitous phenomena in mode-locking. A common qualitative understanding of the multi-pulsing mode-locking process can be understood from energy considerations. By increasing the gain, the mode-locked pulses are made narrower in the time-domain, thereby increasing their bandwidth. However, it is energetically unfavorable for the bandwidth to increase significantly beyond that of the gain. Thus a more energetically favorable situation is created in the laser cavity whereby two mode-locked pulses are generated which are broader in the time-domain (narrower in the frequency domain) and therefore can extract a maximal amount of gain. This simple premise serves to qualitatively identify the underlying physical mechanism responsible for the multi-pulse mode-locked dynamics.

We theoretically characterize the instability process responsible for the resulting multi-pulse mode-locking by considering a laser cavity mode-locked with waveguide arrays.

Here, the nonlinear mode-coupling in the waveguide arrays is responsible for the intensity discrimination necessary for the mode-locking. By considering an averaged model for this laser cavity, exact pulse solutions can be constructed and their linear stability examined. Indeed, this is one of the great strengths of this quantitative model: it admits exact solutions for which the stability can be explicitly determined. We show that as the gain increases the pulse solution undergoes a Hopf bifurcation which leads to a stable mode-locked breather solution. Increasing the gain further leads to a chaotic region where the pulse intermittently transitions from one to two pulses. Further increases in gain splits the pulse into two pulses. Further increasing the gain leads to another Hopf bifurcation and eventual splitting. This process, which can be completely characterized,

repeats itself and is the basic mechanism responsible for the multi-pulsing mode-locking phenomenon. Thus the fundamental transition process is chaotic in nature, with the solution dynamically switching back and forth between the breather and the two-pulses over a range of gain parameters, before the two pulse per roundtrip state stabilizes for higher gain parameters. This chaotic transition sequence, which happens for a very narrow range of parameter space, has been recently verified experimentally for the first time in a number of laser cavity configurations.

7580-71, Poster Session

Operating regimes and performance optimization of the mode-locking dynamics of a laser cavity with passive polarizer

E. Ding, J. N. Kutz, Univ. of Washington (United States)

The master mode-locking equation proposed by Haus describes the averaged mode-locking dynamics in a laser cavity where the intensity discrimination results from the interplay of the nonlinear polarization rotation and discrete mode-locking elements that consists of three waveplates and a polarizer. This model is phenomenological and a direct comparison between theory and experiment is not possible. Leblond, Sanchez and co-workers established an iterative procedure to obtain an averaged pulse evolution equation whose coefficients could be directly related to the experimental settings in the laser cavity. In this work we generalize the iterative method to capture four additional physical effects: an arbitrary alignment of the fast- and slow-axes of the fiber with the waveplates and polarizer, the fiber birefringence, chromatic dispersion, and the saturating gain dynamics. Such a generalization results in the cubic-quintic complex Ginzburg-Landau equation (CQGLE) at the leading order and the Swift-Hohenberg at the next order. Extensive comparisons with the full governing model show that the CQGLE is a quantitatively accurate model that can be used to characterize the stability of the mode-locking process and operating regimes of the laser cavity, provided that the intra-cavity fluctuations remain small. A variational reduction reduces the CQGLE to a low-dimensional model for which mode-locked solution of the laser can be obtained. Indeed, the operating regimes of the laser are characterized as a function of the orientations of the waveplates and polarizer, which is done within the context the low-dimensional model that provides tremendously rapid optimization of the laser cavity and performance.

7580-72, Poster Session

Coherent combination of fiber amplifiers with arbitrary optical phase differences

A. P. Napartovich, Troitsk Institute for Innovation and Fusion Research (Russian Federation); N. Elkin, D. Vysotsky, SRC RF TRINITI (Russian Federation)

Coherent laser beam combining is potentially realizable way to increase the combined beam brightness beyond the limits imposed on single-mode lasers by technological problems. The active control of individual laser beam characteristics is more flexible but essentially more complicated in both, necessary equipment and service. Passive phase locking is an attractive alternative, since it does not need external management, which can strongly simplify the system. A specific feature of fiber amplifiers and lasers is that they possess optical path differences of many wavelengths magnitude. Cold-cavity theory predicts in this case fast decline in efficiency of coherent fiber laser beam combining with number of lasers. Experiments, in contrast, demonstrated in such systems that high degree of phasing takes place for laser array of up to 16 lasers. As lasers are strong non-linear systems, explanation of this discrepancy should rely on a role of non-linear effects: gain saturation and intensity-dependent index. Besides, since the gain band width is significantly larger than difference between spectral lines responding to different longitudinal modes, it is a freedom in fitting laser wavelength to any value, which corresponds to best relation between gain and losses. Taking as a unit injection controlled laser, the problem of laser wavelength adjustment can be quantified. Then a relationship between a number of lasers phase-locked and their parameters can be expressed explicitly. Results of numerical simulations of a fiber laser array with Fourier coupling will be presented and their interpretation based on injection-controlled laser operation will be given.

7580-73, Poster Session

Energy enhancement in mode-locked laser cavities using multi-mode fiber lasers

E. Ding, J. N. Kutz, Univ. of Washington (United States)

It has been well established that the Master mode-locking equation, or cubic-quintic complex Ginzburg-Landau equation (CQGLE), can be used to describe the evolution of the electric field envelope in a ring cavity single-mode fiber laser subject to the discrete periodic effects of waveplates and polarizers. The waveplates and polarizer create an effective saturable absorber that generates the intensity discrimination necessary to initiate Kerr-lens mode-locking. In this work, we study a pair of coupled CQGLE which can be used to model the mode-locking dynamics in a multimode fiber that supports two co-propagating fiber modes. The multi-mode structure allows for broader spatial electromagnetic structures and the suppression of deleterious nonlinear effects from self-phase modulation, thus increasing the energy delivered per mode-locked pulse. It is found that mode-locking in multimode fiber can be achieved, but that the pulses are less stable than those in the case of single-mode operation. When the losses of the fiber modes are comparable, initial pulses quickly evolve into non-localized structures that persist over time. In fact, mode-locking can only occur when the attenuation in the second mode is much greater than that of the fundamental mode, the case of experiemental relevance. Approximate mode-locked solutions to the coupled mode equations are obtained, and the corresponding stability is calculated explicitly. It is found that localized pulses in multimode fiber are more prone to undergo multi-pulsing than the case of single-mode operation. It is observed that this phenomenon is a consequence of the build-up of secondary structure rather than pulse-splitting. The results of the present work are in good agreement with experiments.

7580-74, Poster Session

Ultra-wide-tunable fibre source of femto- and picosecond pulses based on intracavity Raman conversion

S. M. Kobtsev, Novosibirsk State Univ. (Russian Federation) and Tekhnoscan JSC (Russian Federation); S. Kukarin, S. Smirnov, Y. Fedotov, Novosibirsk State Univ. (Russian Federation)

This report for the first time presents the results of experimental investigations into femto- and picosecond all-positive dispersion tuneable Yb-doped fibre laser with efficient intra-cavity Raman conversion of radiation in the range of 1070-1300 nm. We demonstrated smooth spectral detuning of radiation Stokes components within ranges 1130-1174, 1190-1235, and 1255-1300 nm generated when the fundamental harmonic of the laser was tuned within the 1075-1120-nm range. A 60-m long stretch of 1060XP fibre was used for Raman conversion inside a linear cavity of the mode-locked Yb fibre laser. The average output power of the laser radiation at different Stokes components reached up to 250 mW. This report also discusses original broad-band loop fibre mirrors used in the course of experiments and particulars of the broad-band continuous detuning of the radiation spectrum generated by the ultrashort-pulse fibre laser. Mode-locked operation of the laser was achieved due to the effect of non-linear rotation of radiation polarisation. Further analysed are different modes of ultra-short pulse generation in relatively long optical resonator (~75 m) occurring at various configurations of the employed polarisation controllers. Two of these modes are the most typical: generation of

isolated picosecond pulses and generation of picosecond packets, each being a train of femtosecond pulses. The auto-correlation function of the latter generation mode has an unusual double-feature shape (femto- and picosecond), which was for the first time experimentally observed with all-positive dispersion mode-locked fibre laser in the presented work.

7580-75, Poster Session

Alleviate photo darkening by single-mode RMO fiber design

K. E. Mattsson, T. Nikolajsen, NKT Photonics A/S (Denmark)

In this work we propose and demonstrate a new single mode fiber design that alleviates photo darkening. The fiber design is based on a reduced signal mode to gain material overlap which is found to reduce the induced losses of PD. For the fiber saturated photo darkening operation is observed after 1500 hours operation with less than 7 % reduction in slope efficiency from 350 W output power in Yb/Al co-doped material. The temporal behavior of the fiber is experimentally investigated and the power scalability is theoretically predicted.

7580-76, Poster Session

Reliable pulsed-operation of 1064-nm wavelength-stabilized diode lasers at high power: boosting fiber lasers from the seed side

M. A. Bettiati, G. Beuchet, P. Pagnod-Rossiaux, P. Garabedian, J. Perinet, S. Fromy, J. Bertreux, J. Hirtz, F. Laruelle, 3S PHOTONICS SA (France)

Most Pulsed Fiber Lasers (FLs) are built on a Master Oscillator - Power Amplifier (MOPA) architecture, as this configuration has the advantage, among others, of exploiting direct modulation of the diode laser seed (the MO) to reach high repetition rates and high peak-power pulsed operation. To enhance the FL global performance and reliability, high power single-lateral-mode 1064 nm diodes with outstanding long-term behavior are needed. The reliability of these devices at high power has been a challenge for years, due to the high built-in strain in the Quantum Well (QW). In this paper, we present excellent reliability results obtained, in both cw and pulsed conditions, on the latest generation of 1064 nm single-lateral-mode diodes developed at 3S PHOTONICS. Aging tests in cw conditions prove the intrinsic robustness of the diode even at very high junction temperatures, while specific tests in pulsed operation at 45 °C heat-sink temperature, and high repetition rates of several hundred kHz, confirm the stability of the devices in accelerated conditions directly derived from real applications. Both free-running and wavelength stabilized (by means of a Fiber Bragg Grating (FBG)) packaged devices show very stable performances under pulsed conditions. Reliable operation at higher average power than currently commercially available diode lasers seeds is demonstrated.

7580-77, Poster Session

Prediction of dynamical instability in ring-geometry passively phased fiber laser array

E. J. Bochove, Air Force Research Lab. (United States); A. Aceves, Southern Methodist Univ. (United States); E. Kazantseva, Y. Braiman, Oak Ridge National Lab. (United States)

We present a framework for studying the first-order dynamical stability of high power passively-phased fiber laser arrays that possesses considerable generality and is free from ab initio physical approximations. Part I of this work presents a formal analysis that yields insight and intuition and leads to a practical procedure. In Part II we show how by application to some examples new predictions arise. The basis of the analysis is (a) space-time dependent nonlinear wave equations for the propagation of pump and signal fields and arbitrary ancillary fields, (b) ordinary differential equations describing the medium dynamics, and (c) a set of relations describing the mutual coherent coupling of the array due to boundary conditions resulting from the array interaction. We then formally solve a set of linearized differential equations describing the system's evolution near a stationary state and calculate the leading Lyapunov exponent that forms the basis of stability analysis in our approach. In addition to stability analysis, we obtain expressions for fluctuations driven by various noise sources, e.g. in signal phases. Except for the formally required linearization, no other approximations were made in the formulation of the analysis. As demonstration, we apply the method to some simple systems for which exact closed-form solutions are possible, and also to a more complex example for which we show that the inclusion of both pump and signal fluctuations leads to a new dynamic instability.

7580-78, Poster Session

The effect of a mutual off-centered launch of a SM fiber into a few modes fiber on the output beam quality

Y. Shamir, Y. Sintov, E. Shafir, Soreq Nuclear Research Ctr. (Israel); M. Shtaif, Tel Aviv Univ. (Israel)

An interesting insight can be obtained while launching an optical radiation of a fundamental mode fiber into a larger few modes fiber core. It is shown that the output beam parameter product (BPP) yields a local minima value, while it is launched at a non-centered position. In certain cases it can even gain global BPP minima, if the mode mixture of the output few-mode fiber is such that the fraction of power embedded within the highest order radial mode (of the LP0m type) is small enough. In order to demonstrate this phenomenon, an experimental setup is established. In this setup, the small size fundamental mode is introduced at different locations across the core of a few-mode fiber. Both far and near field intensity diameters are monitored for each location. The light source used is an unpolarized 1064nm laser source with 660GHz linewidth, which has coherence time as short as 1.5ps, or, alternatively, coherence length of 0.3mm within the fiber. Under these conditions, the group delay differences, after few meters, are large enough so that the various propagating modes are summed incoherently. Therefore, the power weight distribution of the modes determines the output beam quality. This phenomenon is less significant in deep MM fibers, where a continuum of modes is present. In some applications, where the BPP is of crucial importance, and no more than a few modes should be present, this phenomenon is of major importance.

7580-79, Poster Session

Different generation regimes of mode-locked all-positive-dispersion all-fiber Yb laser

S. M. Kobtsev, Novosibirsk State Univ. (Russian Federation) and Tekhnoscan JSC (Russian Federation); S. Kukarin, S. Smirnov, Novosibirsk State Univ. (Russian Federation)

The subject of this work is investigation of different generation modes of all-positive-dispersion all-fibre Yb laser mode-locked due to effect of non-linear polarization evolution. For the first time we realized in the same laser both generation of single picoseconds pulse train and a newly observed lasing regime where generated are picosecond wave-packets, each being a train of femtosecond sub-pulses. The auto-correlation function of the latter generation mode has an unusual double-feature shape (femto- and picosecond). We were able to switch the laser between different generation modes in a short laser cavity by re-adjustment of polarization controllers and could easily distinguish the regime observing changes in output spectrum and auto-correlation traces of generated pulses. When the cavity length is increased up to

dozens of meters and more single-pulse generation regime becomes unstable whereas wave-packets generation can be easily obtained. Using both experimental results and numerical modeling we discuss in detail the mechanisms of laser mode-locking and switching of generation regimes. Also we consider a strong dependence of output laser characteristics such as pulse duration and energy on configuration of polarization controllers. We show good qualitative agreement between experimental results and numerical modeling based on non-linear Schrödinger equation.

7580-80, Poster Session

Modulation instability, Akhmediev breathers, and 'rogue waves' in nonlinear fiber optics

J. M. Dudley, Univ. de Franche-Comté (France); G. Genty, Tampere Univ. of Technology (Finland); F. Dias, ENS Cachan (France); N. Akhmediev, Australian National Univ. (Australia)

There has recently been much interest in the study of extreme "rogue" events in nonlinear fiber optics. Such events are associated with characteristic heavy tailed probability distributions where – in contrast to Gaussian statistics – events much larger than the mean occur with significant probability. Interest in this area began in 2007 with reports of extreme value soliton statistics during supercontinuum generation. These experiments attracted widespread attention because they were carried out in a regime where spectral broadening was seeded by modulation instability (MI), allowing important links to be made with proposed formation mechanisms of oceanic rogue waves. The degree to which MI seeds either high power optical solitons or oceanic rogue waves is a subject of ongoing research, but important insights into both optical and oceanic nonlinear propagation have already been obtained. In optics, perhaps the most significant result has been the "rediscovery" of powerful analytic solutions that rigorously describe the induced MI process, and ultrashort pulse train formation from an initial beat signal. Although previous studies of this process have used numerical simulations or approximate truncated sideband models, we show that the rediscovered 1985 "Akhmediev Breather" (AB) model provides an exact formalism with which to interpret this evolution. Moreover, we show that the AB model provides insight into noise-driven spontaneous MI, allowing the shape of the nonlinear broadened MI spectrum to be estimated analytically. We present theoretical, numerical and experimental results, and we discuss consequences for the design of sources generating supercontinuum and high repetition rate pulse trains.

7580-81, Poster Session

Chirped pulse shaping via fiber dispersion modulation

A. A. Sysoliatin, A.M. Prokhorov General Physics Institute (Russian Federation); M. Yavtushenko, I. Zolotovskii, Ulyanovsk State Univ. (Russian Federation); O. G. Okhotnikov, Tampere Univ. of Technology (Finland)

A method to utilize the nonmutual effects and obtain an efficient compression of high energy pulses in oscillating single-mode fibers is proposed. The periodic modulation of the dispersion along the fiber length could be helpful to control subpicosecond pulses as in time and frequency domains as the pulse chirp. Pulse compression from 600 to 15fs has been achieved. The efficient pulse compression in a fiber with oscillating dispersion takes place and compressed pulse is stable against ASE noise. The experimental results on optical spectral broadening and high power pulse generation using specially designed and fabricated fiber with varying along length dispersion confirm a feasibility of such a technique.

7580-82, Poster Session

Quenching investigation on new erbium doped fibers using MCVD nanoparticle doping process

D. E. Boivin, T. Föhn, E. Burov, A. Pastouret, C. Gonnet, O. Cavani, C. Collet, S. Lempereur, Draka Comteq France (France)

Ever demanding network implementations brought new requirements to be addressed to offer cost effective and power efficient solutions with smaller footprints. This general trend together with the constant need to improve L-band optical amplification efficiency account for the renewed interest on highly doped Erbium fibers.

Erbium doped fiber amplifiers (EDFAs) performance degradation with Er3+ concentration increase has extensively been studied [1] and is attributed to additional losses due to energy transfers between neighbouring ions. Experimental observations have been interpreted by the homogeneous upconversion (HUC) and pair-induced quenching (PIQ) models, which account for pump power penalty and unsaturable absorption respectively. For a given Er3+ concentration, studies have also showed that both fiber manufacturing process and core matrix composition have a strong impact on quenching parameters.

In 2009, we introduced a new doping concept involving Al2O3/Er nanoparticles (NP) in a MCVD-compatible process showing improved performances in terms of erbium homogeneity along the fiber length for standard doping levels [2]. In this paper, we address our most recent work on concentration quenching encountered in both standard and NP Erbium doped fibers. Experimental results are further analysed by numerical simulations making use of genetic algorithms to determine quenching parameters with a better accuracy.

7580-83, Poster Session

Self-starting passive mode-locked ytterbium fiber laser with variable pulse width

S. B. Cho, H. Song, S. Gee, D. Y. Kim, Gwangju Institute of Science and Technology (Korea, Republic of)

We report a robust self-starting mode-locked ytterbium fiber laser using a high-contrast semiconductor saturable absorber mirror (SESAM)that is proposed and fabricated as the hybrid cavity design taking advantage of ring and linear cavity laser. The average output power of single mode-locked-pulse regime is observed from 7.6 to 10.4 mW and the slope efficiency of this mode-locked regime is 5.4 %. The repition rate of the pulse is about 36 MHz. The optical spectrum is centered at 1062 nm. The extinction ratio of the optical spectrum is nearly 40 dB and the laser reveals a good spectral purity. We have verified that the pulse width dependence on fluence and posion changes of saturable absorber in simple simulations. In experiments, we demonstrate that the pulse width in mode-locked laser is adjustable by changing the axial position of the SESAM which are critically related to the absorption of the saturable absorber and the power of cavity owing to changing both the focused fluence on the SESAM and the coupling efficiency of reflected beam. We have obtained few pico-seconds pulse duration and the adjustable range was 2 ps without dispersion compensators in the cavity and provides a high reliability of turn-key operation. we optimized the peak power of the mode-locked pulse laser by obtaining the optimum position of the SESAM based on pulse pulse power change and width reduction with axially moving the SESAM and this method can be commonly applicable to general mode-locked laser which use the SESAM as a mode locker.

Return to Contents

7580-84, Poster Session

Efficient MM to SM conversion in a 61 port photonic lantern

D. Noordegraaf, P. M. W. Skovgaard, M. D. Maack, NKT Photonics A/S (Denmark); J. Bland-Hawthorn, The Univ. of Sydney (Australia); R. Haynes, Anglo-Australian Observatory (Australia); J. Lægsgaard, DTU Fotonik (Denmark)

In astronomy, optical fibers have been used for many years to transport light from the telescope to the optical spectrograph. For collecting a large amount of light, large core multi-mode (MM) fibers are preferred. In the near infrared part of the spectrum from 1000 nm to 1800 nm, high altitude hydroxyl in the Earth's atmosphere radiates hundreds of extremely bright, ultranarrow emission lines that completely dominates the background. In recent years ultrabroadband fiber Bragg gratings have been demonstrated in single-mode (SM) fibers that can reflect the unwanted signal while allowing the desired signal to enter the spectrograph. In order to make use of these gratings in a MM fiber system, an efficient MM to SM conversion is needed. This is possible with the photonic lantern that features a bundle of SM fibers that is adiabatically tapered to form a MM waveguide. In this work we demonstrate, to the best of our knowledge, the first high port count low loss photonic lantern. The coupling loss going from a MM section having a core diameter of 100 µm and 0.09 NA to an ensemble of 61 individual SM fibers was measured to be as low as 1.06 dB. This demonstration proves the feasibility of using the photonic lantern within the field of astrophotonics for coupling MM star-light into an ensemble of SM fibers in order to perform fiber Bragg grating based spectral filtering.

7580-85, Poster Session

Advantage of circularly polarized light in nonlinear fiber-amplifiers

D. N. Schimpf, E. Seise, T. Eidam, S. Hädrich, J. Limpert, A. Tünnermann, Friedrich-Schiller-Univ. Jena (Germany)

It is experimentally demonstrated that circularly polarized light is advantageous if the Kerr-nonlinearity has to be minimized during laser-amplification. This method permits peak-power scaling of fiber amplifiers since the self focussing threshold is increased. Furthermore, the pulse-quality of ultrashort fiber lasers is improved.

In a fiber-based chirped pulse amplification system, we experimentally show that the use of circularly result in lowered impact of Kerr-nonlinearity compared to linearly polarized light.

7580-86, Poster Session

Monolithic all-glass device combining pump coupling and end cap scheme for high-power fiber lasers

J. K. Kim, C. Hagemann, T. Schreiber, T. Peschel, R. Eberhardt, A. Tünnermann, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

We report on a novel concept for monolithic pump combining technology to integrate efficiently multi pump fiber channel into an double clad ytterbium doped fiber. The proposed structure consists of a dichromatically coated planar convex lens spliced to an Ytterbium-doped double-clad photonic crystal fiber surrounded by multiple pump fibers. The lens is also used as an protecting end cap where the laser beam expands before exiting the surface. The pump fibers are also attached in this lens ciurcularly surrounding fibers. The lens images these pump fibers end facets into the pump core, where the lens surface is coated by a dichroic mirror (reflective for 980 nm, transmittive for >1030 nm). The all-glass structure, assembled by laser splicing, makes the system stable, efficient and suitable for high power operation. We selected 5 channels as testing channels among 14 pump channels (200 µm, NA=0.12) in the first ring to confirm reliability of the system. The coupled pump power efficiency into the 500 µm core with NA=0.5 was over 80% up to a total power of 90 W. Currently this setup shows slightly more coupling efficiency compare to the conventional bulk curved metalic mirror, which have been fabricated by single diamond turning. We also extended the configuration to a 2nd layer of the pump fibers and got the same coupling efficiency of over 80%. With the monolithic pump combining technologies, we confirmed that the proposed device has a potential application not only in kW range high power fiber lasers but also compact photonic devices.

7580-87, Poster Session

All-fiber higher order mode module with anomalous dispersion below 800 nm

K. G. Jespersen, M. K. Garmund, D. P. Jakobsen, B. Palsdottir, L. Grüner-Nielsen, OFS (Denmark)

We demonstrate an all-silica fiber-based module with anomalous dispersion below 800nm. The fiber module is based on propagation in a higher order mode, and mode conversion is achieved using UV inscribed broadband long-period gratings. The large normal material dispersion in silica in the near infrared is compensated by anomalous waveguide dispersion of the higher order mode resulting in a total higher order mode dispersion of +131.1ps/(nm km) (Beta2 = -0.0407ps2/m) at 765nm. The operation bandwidth is ~20nm with a maximum insertion loss of 2.5dB. The multipath interference noise is shown to be <-26.7dB in the operation bandwidth. The effective area in the higher order mode is 16.2um2, which is large, compared to microstructured fibers with anomalous dispersion in the same wavelength regime. Nearly dispersive or linear pulse propagation can be obtained for pulse energies up to 100pJ with 100fs pulse width. This power regime is interesting for e.g. medical endoscopic two-photon fluorescence imaging. The proposed anomalous dispersion module is a promising candidate for dispersion management in femtosecond fiber deliveries at wavelengths compatible with the Ti:Sapphire gain spectrum.

7580-88, Poster Session

All-fiber regenerative amplification of low energy 40-ps seed pulses from a gain-switched laser diode at low repetition rates

S. Kanzelmeyer, M. Hildebrandt, T. Theeg, M. Frede, D. Kracht, J. Neumann, Laser Zentrum Hannover e.V. (Germany)

Regenerative amplification of low energy 40 ps pulses in an all-fiber setup is demonstrated for the first time to our knowledge. The 20 pJ seed pulses are generated in a gain-switched laser diode at variable repetition rates and pass an Yb-doped single-clad fiber amplifier several times. The amount of round trips is controlled by an acousto-optic modulator. Due to the corresponding depletion of the population inversion unwanted amplified spontaneous emission (ASE) is effectively suppressed even at very low average seed power levels of only a several ten nano watts. Gain values of more than 27 dB could be achieved. The demonstrated concept opens up new power scaling opportunities for low average power and low energy seed sources.

7580-90, Poster Session

Suppression of stimulated Raman scattering in high-power fiber laser systems by lumped spectral filters

F. Jansen, D. Nodop, C. Jauregui-Misas, J. Limpert, Friedrich-Schiller-Univ. Jena (Germany); A. Tünnermann, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany) and Friedrich-Schiller-Univ. Jena. (Germany)

We present a systematic study on the inhibition of stimulated Raman scattering by lumped spectral filters both in passive optical transport fibers and in fiber amplifiers. This study reveals the parameters that have the strongest influence on the suppression of the Raman scattering (such as the attenuation at the Raman wavelength and the insertion losses at the signal wavelength). These parameters have to be optimized in order to achieve the desired Raman inhibition and/or to minimize the loss in amplifier efficiency. The study is concluded with realistic predictions on the use of spectral filtering elements for Raman scattering inhibition in real-world high power fiber amplifiers. Thus, using for example 10 lumped spectral filters with 20dB effective Raman attenuation and less than 0.25dB insertion losses, a maximum Raman threshold increase by a factor of 3 is expected. In this context, long period gratings are proposed as promising filtering elements for Raman inhibition in high power fiber amplifiers. In order to experimentally verify the theoretical predictions and the suitability of long period gratings, a fiber amplifier consisting of 2m active Ytterbium doped fiber was built. Three long period gratings were consecutively inserted at different positions along the fiber, and the Raman threshold was determined for each situation. It is shown that, with three long period gratings, the Raman threshold (defined as the 20 dB ratio of Raman to signal output power) was increased by about 60%, which offers a good agreement with the theoretical predictions.

7580-91, Poster Session

Transform-limited pulses from a mJ-class nonlinear fiber CPA-system by phase shaping

E. Seise, T. Eidam, D. N. Schimpf, J. Limpert, A. Tünnermann, Friedrich-Schiller-Univ. Jena (Germany)

The interaction of dispersion and nonlinearity typically affects the pulse-quality at the output of ultrafast laser-amplifiers. The effect of dispersion can be well compensated; however, the influence of nonlinearity generally causes degradation of the pulse-quality. One dominant effect is the optical Kerr-effect in form of self-phase modulation (SPM), where a nonlinear phase is accumulated during the amplification process. When working in the CPA-regime this nonlinear phase can be partly compensated by changing the separation length of the grating compressor. More promising techniques are active amplitude and phase shaping. Applying amplitude shaping by a modification of the pulse-shape cannot significantly reduce the magnitude of SPM, but it can control and form the generally uncompressible phase. With phase-shaping nearly arbitrary spectral phases, e.g. produced due to SPM, can be compensated.

In this contribution we demonstrate actively pulse-shaping for peak-power and pulse quality improvements in high repetition-rate, mJ pulse energy, fiber CPA systems. At B-integrals up to 10 rad, nearly transform-limited pulses could be achieved. We could extract 1mJ pulse energy at a repetition-rate of 50kHz and 780fs pulse duration after compression.

The applied phase-shaping method is based on an analytical model describing the impact of SPM in CPA-systems. By using this method the spectrum was measured and then used to calculate the phase that needs to be applied. This spectral phase was used to compensate the nonlinear phase, accumulated in the main amplifier. The compensation has been done with a spatial-light modulator (SLM) situated in the fourier plane of a 4f-stretcher-setup.

7580-92, Poster Session

Distributed side pumping using high brightness pumps: an architecture for power scaling beyond 1 kW

R. J. Horley, L. Cooper, SPI Lasers UK Ltd. (United Kingdom); T. Gabler, JT Optical Engine GmbH + Co. KG (Germany); F. Ghiringhelli, A. T. Harker, S. Norman, M. N. Zervas, SPI Lasers UK Ltd. (United Kingdom); H. Zimer, JT Optical Engine GmbH + Co. KG (Germany)

As the output power of fibre lasers increases, doubling about every 18 months, the stresses on components within the laser have undergone corresponding increases. While there are areas of high stress in the signal path recent advances in pump laser technology have further increased the stresses on areas of the pump path. These high brightness pump modules will enable the power trend to continue, but require renewed attention to power handling in the pump path.

We review recent advances in GTWave distributed side pumping technology and high brightness pump technology and show that together they provide an architecture for power scaling beyond 1kW while keeping nonlinear effects at an acceptable level. In distributed side pumping the pump power is launched into a passive fibre and evanescently coupled into the active fibre, with which it is in contact, along its entire length. The simple splice to the passive fibre reduced power loss and associated heating at this point and the distributed injection into the active fibre limits the rise in the core and coating temperature to within acceptable limits. In high brightness pump technology the outputs from several diode emitters are coupled into a single fibre, increasing the power in the fibre several fold over the previous technology while maintaining the same core area and numerical aperture.

We present recent developments in fibre laser technology and conclude with the latest high power results using high brightness pumps and GTWave fibre technology demonstrating power scaling to kW class power levels.

7580-93, Poster Session

SBS suppression through seeding with narrow-linewidth and broadband signals: experimental results

C. A. Lu, I. A. Dajani, C. Zeringue, C. L. Vergien, A. Lobad, Air Force Research Lab. (United States)

We present experimental verification of a novel technique [1] to suppress stimulated Brillouin scattering (SBS) in narrow linewidth fiber amplifiers. This technique relies on seeding with a combination of broad- and narrow-linewidth laser beams that are separated sufficiently enough to suppress four-wave mixing and to allow for efficient laser gain competition between the two signals. In the experiment, a monolithic fiber configuration was used. Broadband 1045 nm light and single frequency 1064 nm light were combined in a wavelength-division multiplexer and then coupled into a 10 m long 10/125 Yb-doped gain fiber. With appropriate selection of seed power ratio, we were able to generate an output signal predominantly comprised of 1064 nm light while simultaneously suppressing the back-scattered Stokes light. The slope efficiency for the two-tone amplifier was approximately 78%, slightly below that of a single-tone amplifier. The SBS threshold for the former, on the other hand, was appreciably higher than that of the latter which is in excellent agreement with the theory. The effect of seed power ratio on SBS supression was also invetigated and the results were in accordance with the theory and simulations. Finally, we discuss implementation of this technique at very high powers.

References

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7580-96, Poster Session

High-power fiber amplifier using a PM Yb-doped photodarkening-resistant LMA fiber with depressed-clad index profile design

M. Drolet, C. Paré, H. Zheng, P. Laperle, A. Proulx, Y. Taillon, INO (Canada)

Based on a depressed-clad index profile design, a PM Yb-doped large mode area (LMA) fiber with an effective mode area of 450 µm2 was designed and fabricated. The fiber was used to amplify 10-ns pulses at 1064 nm with a repetition rate of 100 kHz, and an output energy higher than 200 µJ was obtained, within a bandwidth of 0.5 nm. The fiber was coiled on a 12-cm diameter mandrel and the output beam M2 value was measured at 1.05, suggesting a single-mode output. The output polarization extinction ratio was higher than 20 dB. The photodarkening excess loss of the aluminium/phosphorus co-doped fiber core was measured to be a factor 5 lower than what is typically observed with a standard Yb-doped fiber. It is shown how a depressed-clad index profile design can improve higher-order mode filtering while keeping the coiling diameter practical for compact fiber amplifier packaging.

7580-97, Poster Session

Photodarkening-induced increase of temperature in ytterbium-doped fibers

J. J. Montiel i Ponsoda, M. J. Söderlund, Helsinki Univ. of Technology (Finland); J. P. Koplow, Sandia National Labs. (United States); J. J. Koponen, nLIGHT Corp. (Finland); S. K. Honkanen, Helsinki Univ. of Technology (Finland)

We observe significant increase of uncooled ytterbium-doped fiber temperature when cladding pumped. The studied commercial fiber sample is held in air uncoated and its temperature is measured by a thermal camera. Simultaneously to the 915 nm pumping, photodarkening is characterized by monitoring the absorption coefficient change at 600 nm. The observed temperature increase is much higher than what is expected from quantum defect between the pump and emission wavelength. Further, the time dependence of the fiber temperature increase correlates with progressive photodarkening. Pump power lost in photodarkening-induced absorption losses is therefore hypothesized to cause the temperature increase. In effort to explain this phenomenon, we measure the temperature dependent absorption at 915 nm which exhibits the two opposite effects of spectral broadening of the photodarkening losses and the reduction of ytterbium absorption due to temperature-induced ground state depopulation. The latter effect is excluded by a pristine fiber absorption change measurement, leaving the 915 nm photodarkening-induced absorption. We use this data in a thermal model to explain the sample fiber temperature. The presented heat generating mechanism is also hypothesized to play a role in determining photodarkening dynamics.

7580-98, Poster Session

Fine adjustment of cavity loss by fiber optical loop mirror for dual-wavelength laser

M. Durán-Sánchez, Benemérita Univ. Autónoma de Puebla (Mexico) and Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); E. A. Kuzin, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); R. I. Alvarez-Tamayo, Benemérita Univ. Autónoma de Puebla (Mexico); B. Ibarra-Escamilla, A. Flores-Rosas, M. A. Bello-Jiménez, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

Experimental demonstration of dual wavelength operation of a fiber laser through fine adjustment of cavity loss, using a Fiber Optical Loop Mirror (FOLM) with a high-birefringence fiber in the loop. The reflection and transmission of the FOLM presents a sinusoidal wavelength dependence which can be shifted by controlling the temperature of the hi-bi fiber. A temperature change of the hi-bi fiber by 0.1oC causes a measurable change in the ratio between the reflectance for the wavelengths R(l1)/R(l2). Using this adjustment be able to change the generation mode from single wavelength to stable dual wavelength generation with equal powers for l1 and l2 or to stable dual wavelength generation with unequal powers at l1 and l2. The change of the ratio between the FOLM reflection R(l1)/R(l2) allows the investigation of tolerance of dual wavelength generation on the ratio between cavity loss. Was found that for the switch from a single wavelength emission at l1 to single wavelength emission at l2 the ratio R(l1)/R(l2) has to be changed by the order of magnitude of 10-2. This value shows the tolerance of the dual wavelength laser to the cavity loss adjustment.

7580-99, Poster Session

Laser process control for high-power fiber laser applications

S. Kaierle, Fraunhofer-Institut für Lasertechnik (Germany)

The emerging use of highly focused lasers in the range of 1µ wavelength such as fiber and disc lasers poses new challenges on process development as well as on the supervision of these processes. Smaller diameters in laser beams at increased power density result in different processing conditions compared to conventional lasers. As a result also the monitoring and control of these processes have to be adapted to these changed conditions. In laser beam welding for example the keyhole gets much smaller in diameter resulting in higher aspect ratios. Similar in laser cutting with fiber or disc lasers the cutting kerf turns out to be smaller as well. Thus the observation of these processes require more sophisticated monitoring strategies and sensor equipment. The paper describes the latest state-of-research on laser process monitoring for 1µ laser materials processing. Based on the Fraunhofer patented CPC system today's available approaches will be discussed.

7580-100, Poster Session

Hybrid Fourier domain modelocked laser (FDML) utilizing an optical parametric amplifier (OPA) and an erbium doped fiber amplifier (EDFA)

H. Y. K. Cheng, The Univ. of Hong Kong (Hong Kong, China); B. A. Standish, Ryerson Univ. (Canada); X. D. V. Yang, Ryerson Univ. (Canada) and Univ. of Toronton (Canada) and Sunnybrook Health Sciences Ctr. (Canada); X. J. Gu, Ryerson Univ. (Canada); Y. M. E. Lam, K. K. Wong, The Univ. of Hong Kong (Hong Kong, China)

We report the first Fourier Domain Modelocked Laser (FDML) constructed using two distinct optical amplifiers, namely the Optical Parameter Amplifier (OPA) and the Erbium Doped Fiber Amplifier (EDFA), centered at ~1556nm. FDML is a swept source laser technique that matches the round trip time of light waves so as to amplify and maximize the optical power within the laser cavity. The FDML effect generated by OPA or EDFA alone in a laser cavity does not yield both high power and bandwidth, which are optimized for potential imaging applications. Therefore, in this study, we utilized a one-pump OPA and a C-band EDFA in a series configuration within the cavity and employed a polygon filter to generate a hybrid FDML effect. Results demonstrate that the generated spectrum benefits from both the OPA and EDFA, as a substantially higher optical power and significantly wider bandwidth have been achieved when compared to the individual configurations. The FDML arrangement generated at least 10dB more power at each wavelength within the spectrum. We have demonstrated that FDML is possible even when different optical amplifiers were employed in the same cavity. We believe

this technique can enable different amplifiers, not limited to OPA and EDFA, to complement the deficiencies of each other to result in optimal spectral shapes and higher lasing powers for imaging applications such as Optical Coherence Tomography.

7580-101, Poster Session

Cascaded Raman fiber laser in Fourier domain mode lock operation

B. Vuong, M. K. Harduar, Ryerson Univ. (Canada); H. Y. K. Cheng, The Univ. of Hong Kong (Hong Kong, China); X. J. Gu, Ryerson Univ. (Canada); L. R. Chen, McGill Univ. (Canada); B. A. Standish, Ryerson Univ. (Canada); X. D. V. Yang, Ryerson Univ. (Canada) and Univ. of Toronto (Canada) and Sunnybrook Health Sciences Ctr. (Canada)

In this study, a cascaded Raman fiber laser in Fourier domain mode lock (FDML) operation is presented. This laser utilizes a Ytterbium doped twin fiber pump laser source at 1109 nm. The pump light is directed to a cascaded Raman cavity, which consists of multiple cascaded fiber Bragg grating pairs and 3.86 km of dispersion compensation fiber, which provides Raman gain. The output wavelength of a cascaded Raman laser is determined by the Stokes shift (~440 cm^-1 in optical fiber) and the pump laser wavelength. The power builds up in the cascaded Raman cavity and shift to higher Stokes orders produce multiple spectral peaks. At higher Stokes orders, the overlapping Raman peaks create broad bandwidth gain with relatively large gain ripples. FDML operation using a polygon-based tunable filter helps to suppress the ripples. The overall laser has an output power of (> 30 mW). Broadband tunable lasers are important in applications such as swept-source optical coherence tomography.

7580-102, Poster Session

Developing dual core ytterbium doped fiber ring laser in Fourier domain mode locked operation for swept-source optical coherence tomography

M. K. Harduar, B. Vuong, Ryerson Univ. (Canada); H. Y. K. Cheng, The Univ. of Hong Kong (Canada); A. Mariampillia, Univ. of Toronto (Canada); X. J. Gu, Ryerson Univ. (Canada); L. R. Chen, McGill Univ. (Canada); B. A. Standish, X. D. V. Yang, Ryerson Univ. (Canada)

Currently available lasers for swept-source optical coherence tomography (OCT) typically have output power below 100 mW. For multi-channel simultaneous operations, higher output power is desired. We present a novel dual core Ytterbium (Yb) doped fiber ring laser with broadband rapid tunability in Fourier Domain Mode Locked (FDML) operation. The short (~10cm) segment of dual core Yb fiber gain structure allows bi-directional pumping at 915nm, and provides broadband gain (~ 100nm) centered around 1060nm. The asymmetrical core diameters of the dual core fiber has high damage threshold and can receive > 3W of pump power, which allows higher output power tunable around 1060nm. Using a polygon-based unidirectional wavelength filter, high speed FDML operation is demonstrated at sweeping rate > 50kHz with average output power > 100mW at low pump current. This laser source is suitable for swept source OCT, especially aimed at applications requiring multichannel simultaneous operation.

7580-103, Poster Session

Ultra-low absorption and laser-induced heating of volume Bragg combiners recorded in photo-thermo-refractive glass

J. Lumeau, K. Chamma, L. Glebova, L. B. Glebov, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

Volume Bragg gratings in photo-thermo-refractive glass find large interest in many high power applications. Among them, spectral beam combining based on reflecting Bragg gratings is one of the most promising. Achieving 100+ kW combined laser beam requires the use of reflecting Bragg gratings with extremely low absorption. In this paper we present a new method based on the interferometric measurement of the change of optical thickness of plane parallel windows when exposed to high power radiations and implement it to the measurement of small absorption in PTR glass and PTR Bragg gratings. Absorption as low as 5 10-5 cm-1 is measured in virgin PTR glass while absorption below 3 10-4 cm-1 is measured in high efficiency reflecting Bragg gratings. Finally, we demonstrate that actual level of absorption in PTR glass allows spectral beam combining of laser with 10 kW level while 100 kW level without cooling would require decreasing absorption in PTR Bragg gratings to value similar to the one in virgin glasses. The approaches for the further decrease of absorption in both original PTR glass and volume Bragg gratings for beam combiners are discussed.

7580-104, Poster Session

High-energy pulses at a very low repetition rate from a self-mode-locked all-fiber erbium laser with large normal cavity dispersion

V. I. Denisov, B. N. Nyushkov, V. S. Pivtsov, Institute of Laser Physics (Russian Federation)

For the first time, the self-mode-locking regime was obtained in an all-fiber erbium laser with a cavity length of more than 1 km and a normal net cavity dispersion as large as 217 ps2. To construct this laser, only a commercial telecommunication fiber and typical fiber-optic elements were used. An original linear-ring cavity design with polarization instability compensation provides high reliability of the self-mode-locking regime and good frequency stability. The laser emits short (5 ns) pulses at a very low repetition rate (82.4 kHz) and record high energy (564.3 nJ) at a pump power of 450 mW. Since no output saturation and no wave-breaking effects were observed at the available pump power, the pulse energy can be further augmented by increasing the pump power or (and) by lengthening the cavity. Such a laser can be used in LIDAR systems, telecommunications, and industry.

7580-105, Poster Session

Remote FBGs sensor interrogation based on 1.3 μm Fourier domain mode-locked wavelength swept laser

B. C. Lee, M. H. Oh, M. Y. Jeon, Chungnam National Univ. (Korea, Republic of)

Fiber Bragg gratings (FBGs) have been widely used in optical fiber sensors and optical fiber communications because the FBG has many advantages over conventional techniques, such as electro-magnetic immunity, compactness, remote sensing, ease of fabrication, and wavelength selectivity. In this manuscript, we demonstrate a high speed remote fiber Bragg gratings (FBGs) sensor interrogation using 1.3 um Fourier-domain mode-locked (FDML) wavelength-swept laser. The laser cavity consists of an SOA, two isolators, a polarization controller, a scanning fiber Fabry-Perot tunable filter, a 3 km-long SMF-28e dispersion

managed fiber, a 30 % output coupler, an optical circulator, and four channel FBG sensors. The FDML laser could be operated if the scanning frequency of the Fabry-Perot tunable filter matches with the fundamental frequency of the laser cavity. Each reflected signal from three FBGs provides an individual laser to operate with FDML wavelength swept laser. The scanning frequencies of the each laser cavity are 30.5314 kHz, 31.5393 kHz, 32.7108 KHz, and 33.8023 kHz. When the scanning frequency is chosen by 33.8023 kHz, the lasing wavelength of the FDML laser is 1296.824 nm. We obtained typical response as a function of strain when an FBG is tuned under static strain. The slope coefficient for measured relative wavelength difference is 0.005 pm/ustrain. We also demonstrate the dynamic response of the FBG remote sensor array with 100 Hz modulation strain.

7580-106, Poster Session

Pulsed single-mode Yb-doped fibre amplifier around 976 nm: numerical modelling and experimental study

A. Bouchier, Lab. d'Analyse et d'Architecture des Systèmes (France); M. Myara, Univ. Montpellier 2 (France); G. Lucas-Leclin, P. M. Georges, Lab. Charles Fabry de l'Institut d'Optique (France)

High power diffraction-limited sources around 976 nm are attractive to build new sources around 488 nm, or to pump rare-earth-doped materials. In silica, ytterbium ions present high emission cross-section around 976 nm, and continuous wave efficient lasers have been obtained for example with single-mode fibres pumped with a 914nm-Nd:YVO4 laser. We demonstrate that amplification of gain-switched laser diode in such fibres lead to gains higher than 30 dB. To reach high gains, the criteria of pulses amplification optimisation are the input signal average power and the time domain shape of the input pulses. A theoretical study is an interesting tool to predict the amplifier performances, and to choose the input pulses characteristics in terms of duration and repetition rates to optimize the peak power gain. However, traditional time-domain only models rely on fitting-parameters and do not allow the prediction of the amplifier behaviour. That's why we used a classical time-space two-level model that we solved thanks to a Finite-Difference Time-Domain method, leading to the excited-atom population, the pump, signal and amplified spontaneous emission propagations. These simulations allow to observe the pulse width influence on the excited state population and to predict the gain and the time shape of the amplified pulse depending only on physical parameters. Pulsed signal amplification simulations taking into account both time and space evolutions and a parasitic laser effect describe correctly the experimental results.

7580-107, Poster Session

Development, manufacturing and lasing behavior of Yb-doped ultra large mode area fibers based on Yb-doped fused bulk silica

A. Langner, M. Such, G. Schötz, Heraeus Quarzglas GmbH & Co. KG (Germany); V. Reichel, S. Grimm, F. Just, M. Leich, J. Kirchhof, Institut für Photonische Technologien e.V. (Germany); B. Wedel, G. Köhler, O. Strauch, HIGHYAG Lasertechnologie GmbH (Germany); V. K. Krause, G. Rehmann, Laserline GmbH (Germany)

At the Photonics West 2008 (presentation 6873-36) we introduced our rare earth doped fused bulk silica which overcame the typical geometrical limitations of other well known techniques such as the MCVD solution doping process. Our unique production technique is based on the sintering of Yb-doped granulates of high-purity SiO_2 particles.

Using production techniques such as mechanical drilling, grinding, fire polishing, gas phase etching, plasma outside deposition of fluorine doped fused silica and overcladding, we have processed our Yb-doped silica rods into different laser active double cladding fiber preforms with very smooth and flawless interfaces between core and cladding. These preforms possess an un-doped pump cladding with a round or the so called 2D and 4D pump cladding shape and a fluorine doped outer cladding. The preforms have been successfully drawn into multimode fibers with an outer diameter of 1000 µm and an active core diameter typically about 100 µm.

The fiber cross section design, the quality of the interfaces between active core, un-doped pump cladding and F-doped outer cladding and the core material composition are all important factors for the laser performance of these fibers. We have investigated the refractive index profiles and the intrinsic stress profiles of different preforms to visualize these interface effects. Detailed studies of the laser performance of these fibers will be presented.

7580-108, Poster Session

High power erbium doped fiber laser generating switchable radially and azimuthally polarized beams at 1.6 µm wavelength

Q. Zhan, R. Zhou, P. E. Powers, J. W. Haus, Univ. of Dayton (United States); B. Ibarra-Escamilla, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

Radially and azimuthally polarized beams have attracted continuous interests owing to their potential applications in broad areas, including high resolution imaging, particle trapping, microfabrication and laser processing of metals, etc. Efficient, stable and flexible sources that can produce these beams are highly desirable. Fiber lasers are very attractive owing to their relatively high gain, compactness and flexibility. Recently, various kinds of methods have been explored to produce radial or azimuthal polarizations. However, these methods require the use of elements that are either difficult to fabricate or not suitable to support high power. In most of the cases, the beam polarization quality was relatively poor.

We report a 1.6 µm Erbium doped fiber laser design that is capable of producing switchable high quality radially and azimuthally polarized beams. A c-cut calcite crystal within a three-lens telescope is inserted in the cavity design. Due to the axially symmetric birefringence of the calcite crystal, radially and azimuthally polarized modes have spatially separated foci in the cavity. Switching between the radially and azimuthally polarized outputs can be achieved by simply translating one of the lenses of the telescope. The design is highly efficient and maximum power much higher than the previously reported output power of fiber laser generating radially polarized outputs has been obtained. Switching between the radial and azimuthal polarization outputs through translating an intracavity lens has been successfully demonstrated. Such a high power fiber laser at eye-safe wavelength may find interesting applications in free space optical communication and remote sensing.

7580-35, Session 9

Microstructured fibres for high power laser applications

D. J. Richardson, J. R. Hayes, M. N. Petrovich, F. Poletti, S. Dasgupta, P. Horak, S. Alam, K. Chen, Univ. of Southampton (United Kingdom); J. H. V. Price, Univ. of Southampton (United States); N. G. R. Broderick, Univ. of Southampton (United Kingdom)

We review recent advances in the development of microstructured fibers for high power laser applications including direct laser signal generation and amplification, fibers for high power beam delivery (both pulsed and CW) as well as fibers for external-cavity frequency conversion and pulse manipulation.

7580-36, Session 9

Photonic crystal fiber with resonant-coupling higher-order-mode suppression

B. G. Ward, C. G. Carlson, D. Wright, C. Eickholt, U.S. Air Force Academy (United States)

Abstract: The attainment of the maximum possible mode field area in optical fibers sustaining a single transverse mode has long been a goal of fiber designers seeking to increase non-linear thresholds in fiber lasers and amplifiers. Traditional step index fibers suffer from excessive bend losses in the fundamental mode when fabricated with numerical apertures small enough to suppress higher order modes. This occurs when the effective index of the fundamental mode becomes near enough to that of cladding modes such that unavoidable irregularities in the fiber cause efficient coupling between them. Non-axially symmetric micro-structured fibers including photonic crystal fibers and leakage channel fibers have been investigated as possible means to mitigate this process and enable further mode field area scaling while retaining low-loss fundamental mode propagation. Resonant and chiral selective coupling of higher order modes out of the core have also been pursued to this aim.

In this paper we report on the theoretical and experimental investigation of a photonic crystal fiber, depicted in Fig. 1, designed for single-polarization operation in a coiled configuration incorporating a resonant higher-order mode suppressing structure within the cladding. In order for this design to be effective, the fiber must be configured with a constant coiling direction relative to the axis of the resonant structure. A finite-element model predicts that the mode field area is 2312 μm2 straight and 2014 μm2 in a 63.5 cm diameter coil at a wavelength of 1.59 μm. The effective index separation between the fundamental mode (Fig 2) and highest-index cladding mode (Fig 3) is 1.4E-4 while the effective index separation between the LP11 mode (Fig 4) and its associated resonant cladding mode is 1.1E-5 for a perfectly aligned coil. This means that the effective numerical aperture guiding the fundamental mode is 0.02 while that guiding the LP11 mode is 0.006 while the fiber is coiled. Thus the LP11 mode should be much more susceptible to scattering into cladding modes than the fundamental mode resulting in highly-suppressed higher-order mode content at the output of the fiber.

To test the ability of the fiber to produce single-transverse mode output, we performed spatially and spectrally resolved (S2) imaging of the output of a 16.8 meter length of fiber when seeded with a broadband ASE source. We observed no trace of any localized or distributed scattering to higher order modes in the spatially resolved Fourier transformed output spectra indicating robust single-transverse-mode output (Fig 5). In order to attempt to induce measurable discrete scattering we introduced sharp bends in the fiber at the seeded end. Under these conditions we still did not observe any trace of scattering. The mode field intensity profile obtained during the S2 measurement did not perfectly match the predicted mode field profile. We believe that this is due to modes propagating in the air-clad pump cladding which contribute to the overall output intensity profile but not the modal content of the core. These measurements indicate that this type of fiber is promising for use in high-power fiber lasers and amplifiers, a possibility that will be explored in future work.

7580-37, Session 9

Single-mode large-mode area fiber amplifier with higher-order mode suppression and distributed passband filtering of ASE and SRS

T. T. Alkeskjold, NKT Photonics A/S (Denmark)

A Large-Mode Area (LMA) single-mode Yb-doped fiber amplifier with distributed narrow passband filtering is demonstrated. The fiber passband is ~40nm wide and centered at 1070nm for efficient filtering of both short- and long-wavelength Amplified Spontaneous Emission (ASE) as well as Stimulated Raman Scattering (SRS). The fiber also provides Higher-Order Mode (HOM) suppression and is polarization maintaining. It has a mode field diameter of 27um and exhibits a slope efficiency of >60%.

7580-38, Session 9

Power-scalable long-wavelength Yb-doped photonic bandgap fiber sources

A. Shirakawa, H. Maruyama, K. Ueda, The Univ. of Electro-Communications (Japan); C. B. Olausson, J. K. Lyngsø, J. Broeng, NKT Photonics A/S (Denmark)

Yb-doped fiber laser operating at the long-wavelength wing of the Yb emission (1150-1200 nm) has been extensively investigated. Its frequency doubling promises fiber-laser based yellow-orange (570-600 nm) sources required for many applications. In conventional Yb fiber lasers/amplifiers, the huge gain at a 1030-1100 nm range creates strong amplified spontaneous emission (ASE) and can lead to parasitic lasing, limiting the available gain and thereby the power scaling.

In order to overcome this problem, we are investigating air-clad Yb-doped photonic bandgap fiber (Yb-PBGF) laser/amplifier. The Yb gain profile is engineered by forming the PBG transmission window around the signal wavelength (here 1178nm). The confinement loss outside the PBG (stop band) is too high to be measurable (at least >1300 dB/m), realizing perfect elimination of the undesired gain at <1150nm. The net small-signal gain at 1178nm is as high as 21dB. A fiber-Raman laser was amplified by the Yb-PBGF to a record-high power of 67W at 1178nm with a 12dB saturated gain. The ultralow attenuation property (<0.02dB/m at 1178nm) enables the high efficiency operation even at the low-gain wavelength (<0.6dB/m). Polarization-maintaining amplification of a linearly-polarized narrow linewidth Yb fiber oscillator is also being investigated for high-power 589nm generation required by laser guide star adaptive optics.

7580-39, Session 9

Efficient bi-doped fiber lasers and amplifiers for the spectral region 1300-1500 nm

E. M. Dianov, M. A. Melkumov, S. V. Firstov, A. V. Shubin, O. M. Medvedkov, I. A. Bufetov, Fiber Optics Research Ctr. (Russian Federation)

We report on the first 10 W-level Bi-doped lasers operating in 1300-1500 nm region. As an active medium for these lasers Bi-doped phosphogermanosilicate fibers (PGSB) were used. We have investigated the influence of the PGSB fiber core composition on optical and lasing fiber properties. Comparison of the luminescence and absorption spectra shows that PGSB fiber core contains at least two types of bismuth active centers: Bi active centers associated with Ge and Bi active centers associated with P. It was demonstrated that the slope efficiency of PGSB fiber lasers strongly depends on the pump and lasing wavelengths and on the fiber core composition. The slope efficiencies of PGSB fiber lasers operating at 1280, 1330, 1480 and 1500 nm amounted to 14-50%. The maximal output power from fiber lasers emitting at 1330 nm and 1480 nm was 10W and 2W, respectively and was determined by available pumping power.

Optical amplifiers based on PGSB fibers were also investigated. The results obtained enable to estimate the potentialities of bismuth fiber amplifiers: 21.5 dB optical net gain at the pump power 200 mW (pump wavelength 1318 nm). The optical gain was registered in a wavelength band with lambda/max=1446 nm and spectral width of 30 nm at the 3 dB level.

7580-40, Session 10

Multiwavelength optical fiber refractive index profiling

A. D. Yablon, Interfiber Analysis (United States)

Fourier transform spectroscopy and interference microscopy are combined to provide the world's first multi-wavelength optical fiber refractive index profile (RIP) measurements. The RIP and its spectral dependence are obtained with sub-micron spatial resolution across an octave stretching from about 500 nm to the 1 micron operating band of Yb-doped fiber lasers and amplifiers. Since critical optical fiber performance features, including the modal effective area, group-velocity dispersion, grating spectra, and polarization properties, directly depend upon the RIP and its spectral dependence, the new technique represents an important advance over previous RIP measurement technologies, which measure the RIP at only one single wavelength that is typically far outside the operating band of the fiber. Furthermore, optical fibers are doped with a proprietary mix of multiple species that may contribute to the refractive index in a non-additive way so a method for analyzing the RIP's spectral dependence for an arbitrary fiber composition is desirable. In contrast to commercial Refracted Near Field (RNF) technology, which measures at a cleave, the technique described here measures transversely through the side of an uncleaved fiber, enabling measurements of axial fiber RIP variations found in fiber gratings, physical tapers, and fusion splices. This unique capability permits intelligent optimization of fusion splices between dissimilar high-power optical fibers. Since the new technique is a phase measurement, rather than an amplitude measurement like RNF, it does not require calibration to mitigate measurement drift. Finally, this technique is applicable to silica glass, non-silica glass, and polymer optical fibers.

7580-41, Session 10

Fiber amplifier utilizing an Yb-doped large-mode-area fiber with confined doping and tailored refractive index profile

T. Kokki, M. Laurila, J. J. Koponen, C. Ye, nLIGHT Corp. (Finland)

Most methods to achieve good beam quality from fiber amplifiers with double-clad LMA fibers have been based on inducing losses for the higher-order modes by coiling the fiber, using a non step-index refractive index profile, or a combination of these approaches. Novel fiber structures which reduce coupling between transverse modes have also been designed. Recently, confining the active ion doping area has been suggested as a method to favor the fundamental mode through preferential gain. Using the Direct Nanoparticle Deposition (DND) technology, large-core fibers with radially and independently varying active ion concentration and refractive index profiles can be realized. We report on the design, development and manufacture of a double-clad LMA fiber in which the core has a central Yb-doped area with a flat refractive index, surrounded by a passive area with a radially decreasing refractive index. Due to the confined doping, this hybrid design offers preferential gain for the fundamental mode. Simultaneously, the tailored refractive index lowers mode coupling (through increased modal separation) and increases higher-order mode losses. The fiber was characterized in a fiber amplifier setup. Very large effective mode area with robust near-single-mode operation and low bend sensitivity were demonstrated.

7580-42, Session 10

750-W double-clad ytterbium tapered fiber laser with nearly theoretically limited efficiency

V. N. Filippov, Tampere Univ. of Technology (Finland); Y. Chamorovskii, Institute of Radio Engineering and Electronics (Russian Federation); J. Kerttula, Tampere Univ. of Technology (Finland); K. Golant, Institute of Radio Engineering and Electronics (Russian Federation); O. G. Okhotnikov, Tampere Univ. of Technology (Finland)

Recently, we have proposed and experimentally demonstrated an active tapered double clad fiber (T-DCF) for high power fiber lasers and amplifiers [1-3]. Having a large clad diameter (1 mm) at one end, these fibers allow the use high-power, low-brightness laser diodes as pump sources. The narrow part of T-DCF acts as a transversal fundamental mode filter preserving a single-mode regime of T-DCF based laser/amplifier. Although early demonstrations show promising performance [1, 2] they established that T-DCFs could suffer from so-called vignetting effect when fraction of pump power leaks out of the cladding due to violation of total internal reflection condition. This effect results in reduced laser efficiency observed earlier, 30 % in [4], 54.1 % in [5] and 63 % in [3].

This study aims to improve T-DCF laser efficiency by optimization longitudinal shape, tapering ratio, core/clad ratio and Yb-ion concentration. Using a theoretical model developed earlier [3]; we have derived an optimal trade-off between the angular pump power distribution and the longitudinal shape of the active tapered fiber. Different kinds of T-DCF shapes have been analyzed to diminish the vignetting effect. It was found both numerically and experimentally that the parabolic shape of T-DCF has assured advantages over other profiles in terms of pump absorption and slope efficiency. The core/clad ratio, tapering ratio and dopant concentration were also thoroughly engineered taking into account the stimulated Brillouin scattering and optical fuse effect.

Numerous T-DCFs with different parameters have been fabricated and tested in laser geometry. 750 W ytterbium fiber laser pumped by 915 nm diode laser bars has been built using a parabolic T-DCF demonstrating a nearly theoretically-limited slope efficiency of 80%.

In conclusion, the double clad tapered fiber technology has been refined to develop high power lasers and amplifier with superb efficiency. Optimally engineered structure of tapered fiber prevents pump power losses and allowed 750 W output with a nearly diffraction-limited (M2~1.7) beam to be demonstrated with slope efficiency of 80%.

7580-43, Session 10

LMA fibers based on two-dimensional solid-core photonic bandgap fiber design

S. L. Semjonov, O. N. Egorova, A. F. Kosolapov, A. E. Levchenko, V. V. Velmiskin, A. D. Pryamikov, Fiber Optics Research Ctr. (Russian Federation); M. Y. Salganskiy, V. F. Khopin, M. V. Yashkov, A. N. Guryanov, Institute of Chemistry of High Purity Substances (Russian Federation); E. M. Dianov, Fiber Optics Research Ctr. (Russian Federation)

Prospects of fabrication of all-solid band-gap (ASBG) fibers with large mode area (LMA) will be discussed. ASBG fiber is photonic crystal fiber without holes. Cladding is two dimensional photonic crystal and consists of cylindrical high index inclusions of germanium oxide doped silica glass arranged periodically in silica glass around the core. Light confine in the fiber core due to coherent scattering. Specific properties of ASBG fibers with small diameter of high-index cylinders d in comparison with pitch between them in hexagonal structure of the cladding (d/ <0.2) are studied. Reduction of d/ resulted in reduction of numerical aperture (NA) of the fiber core, so single-mode LMA propagation could be achieved. Additionally, small diameter to pitch ratio permits cladding pumping through fiber end without capturing large part of pump radiation to high index inclusions. Theoretical and experimental study of single-mode propagation in these fibers will be presented.

Problems related with incorporation of an active core material into LMA ASBG fiber will be considered too. In such a case, very high optical homogeneity of this material is required. Stack-and-draw technique was used to fabricate uniform core material from the cores of MCVD preforms. Results of testing LMA ASBG fiber samples with active core made of this material will be presented.

7580-44, Session 11

Novel designs for pump and signal fiber combiners

F. Gonthier, FG2 Tech (Canada)

The availability of fiber combiners has been essential to the wide deployment of robust fiber laser in the market. Some standard parts have emerged in larger volume, but new designs, involving both different processes and different fiber configurations are being proposed to the market, offering novel or improved specifications. We will present some of those new designs involving true signal fiber feedthroughs and better return loss and isolations properties. The new fabrication process also allows more latitude in selecting the number of input pump fibers and is independent of the signal fiber internal structure.

7580-45, Session 11

7+1 to 1 pump/signal combiner for air-clad fiber with 15 µm MFD PM single-mode signal feed-through

D. Noordegraaf, M. D. Maack, P. M. W. Skovgaard, S. Agger, T. T. Alkeskjold, NKT Photonics A/S (Denmark); J. Lægsgaard, Risø National Lab. (Denmark)

A 7+1 to 1 pump/signal combiner with single-mode (SM) polarization maintaining 15 µm mode-field-diameter (MFD) signal feed-through is demonstrated. It is designed for pulse amplification in an active Yb-doped air-clad fiber operated in backward pumped configuration.
The combiner utilizes a microstructured taper element that maintains both a 15 µm MFD and SM guidance throughout the taper section at a taper ratio of 3.4. The taper element consists of a concentric dual-core structure, with a SM step-index core surrounded by two rings of air-holes. In the untapered end of the taper element light will be guided in the SM step-index core. In the tapered end light will be guided in a core defined by an air-hole microstructure. In the tapered region light is coupled adiabatically between the two cores, thereby remaining guided in a SM waveguide throughout the taper. The combiner is spliced to a 5 m Yb-doped double-clad fiber with a 16 µm signal MFD. The amplifier system was seeded with 10 ps pulses at a repetition rate of 80 MHz. An average amplified signal power of 18 W and a peak power of 23 kW was achieved, with a signal to Raman noise level of -35 dB. The system features a strictly SM signal output with an M2<1.1.

7580-46, Session 11

Simple and monolithic picosecond pulse shaper based on fiber Bragg gratings

J. Rothhardt, S. Hädrich, T. Gotschall, J. Limpert, A. Tünnermann, Friedrich-Schiller-Univ. Jena (Germany); M. Rothhardt, M. Becker, S. Brückner, H. Bartelt, IPHT Jena (Germany)

Many applications of short laser pulses require precise control of the temporal pulse shape. In this contribution we present a simple and robust pulse shaping device based on coherent pulse stacking. The device is based on fiber Bragg gratings written in a polarisation maintaining step index fiber and a fiber optical circulator. Up to four pulse replicas are reflected by fiber Bragg gratings and interfere at the output of the device. Temperature control allows tuning of the relative pulse amplitudes and phases of the pulse replicas. We experimentally demonstrated 235 ps and 416 ps long flattop pulses with rising and falling edges shorter than 100 ps. In contrast to other pulse shaping techniques the presented setup is robust, alignment free, provides excellent beam quality and is also suitable for pulse durations up to several nanoseconds.

7580-47, Session 11

A monolithic pump signal multiplexer for air-clad photonic crystal fiber amplifiers

B. G. Ward, U.S. Air Force Academy (United States); J. D. Tafoya, D. L. Sipes, Jr., Optical Engines, Inc. (United States)

We report on the performance of a monolithic 6+1X1 fiber pump signal multiplexer for use in a fiber amplifier. Such combiners are highly sought after because they eliminate losses and alignment problems inherent in free-space fiber amplifier architectures. The main engineering challenge lies in the requirement to convert pump delivery fiber output with a typical numerical aperture of 0.22 to a smaller area active fiber pump cladding with a numerical aperture as large as 0.6 while simultaneously achieving efficient coupling of the signal input through the combiner into the active fiber which typically has a larger mode field diameter than the signal input fiber. In order to taper down the pump cladding while maintaining a constant signal core diameter, we fabricate a taper using a process wherein a fiber is lowered into an etching bath and then removed with a velocity profile that achieves and adiabatic pump cladding taper. This taper is then fused onto the 6+1 fiber bundle at the large end and to the air-clad large mode area polarization maintaining photonic crystal fiber at the small end. Currently we employ 6 pump delivery fibers in a 200/220/0.22 core/clad/NA format and a 25/250 polarization maintaining step index signal delivery fiber for the bundle. The large end of the taper has a cladding diameter of 650 µm while the small end has a cladding diameter of 300 µm to match the pump cladding diameter of the PCF which is 314 µm. The core within the taper has a constant diameter of 40 µm and NA of 0.06 achieved through a step index profile. The mode field diameter of the PCF is 54 µm. Employing a constant core diameter within the taper intermediate between the input and output fiber core diameters significantly reduces coupling loss although with such a significant expansion of the core diameter the loss is several dB. In the co-pumped amplifier configuration however, this may be compensated for by increasing the seed power. Signal lost due to mode mismatch propagates harmlessly in the pump cladding. Each splice is actively aligned and the orientations of the stress rods in the signal input fiber and PCF are manually aligned. One important aspect of this coupler design is that no polymer coatings are used to confine the pump radiation resulting in an all-glass design that should have a high power handling capability. The pump injection loss was found to be less than 0.2 dB resulting in a pump launch efficiency of approximately 95%. We report the signal coupling efficiency and power handling capability as well.

7580-48, Session 11

Electrically tunable liquid crystal photonic bandgap fiber laser

C. B. Olausson, NKT Photonics A/S (Denmark) and Technical Univ. of Denmark (Denmark); L. Scolari, L. Wei, Technical Univ. of Denmark (Denmark); D. Noordegraaf, NKT Photonics A/S (Denmark) and Technical Univ. of Denmark (Denmark); J. Weirich, Technical Univ. of Denmark (Denmark); T. T. Alkeskjold, K. P. Hansen, NKT Photonics A/S (Denmark); A. O. Bjarklev, Technical Univ. of Denmark (Denmark)

In this work we merge the PBG fiber laser concept with the tunability offered by liquid crystals to create an all-spliced fiber laser with electrical tunability in the range 1040-1065nm.

The design structure of photonic crystal fibers offers the unique possibility of infiltrating the airholes with liquid crystals which will raise the overall cladding index and give rise to guidance by the photonic bandgap effect. Liquid crystals exhibit large electro-optic effects and by applying an electric field to a liquid crystal photonic bandgap fiber, the bandgap can be shifted. Tunable lasing is achieved by combining a liquid crystal photonic bandgap device with an ytterbium-doped photonic crystal fiber. We fabricate an all-spliced laser cavity based on a liquid crystal photonic bandgap fiber mounted on a silicon assembly, a pump/

signal combiner with single-mode signal feed-through and an ytterbium-doped photonic crystal fiber.

Lasing occurs at the wavelengths that experience the least loss due to the bandgap combined with the highest gain due to their emission cross section. These wavelengths are near the short wavelength edge of the bandgap. By applying a voltage of 130-155Vrms to the silicon assembly the bandgap edge and thereby the laser wavelength is shifted towards longer wavelengths. The laser cavity produces a single-mode output which is tunable by 25nm. This is to our knowledge the first liquid crystal based electrically tunable fiber laser. With a few improvements to the system, the device holds potential as a low cost, easily tunable, single-mode seed source for fiber amplifiers.

7580-49, Session 11

All-fiber side pump combiner for high-power fiber lasers and amplifiers

C. Jauregui-Misas, Friedrich-Schiller-Univ. Jena (Germany); S. Böhme, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); J. Limpert, Friedrich-Schiller-Univ. Jena (Germany); A. Tünnermann, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

We present an all-fiber side pump for high power fiber lasers and amplifiers. This pump combiner consists of a capillary with decreasing wall thickness fused around the active fiber in a way that it becomes an additional cladding layer of it. The pump fibers are then spliced to the side of the capillary with the thickest wall. This provides enough room to allocate around 12 pump fibers (100um diameter) in a standard 400um double-clad fiber.

This side pump combiner offers several advantages such as the fact that it does not interrupt the active fiber core at any point, thus allowing for truly monolithic all fiber lasers and amplifiers. Simultaneously the insertion losses of this pump combiner are negligible. Additionally, since no material is removed from the optical fiber, but added instead, there is no loss of mechanical robustness at the pump coupling points. Finally, the pump light is coupled into the active double-clad fiber all along the combiner's body (~ 1cm long), which avoids the concentration of heat in a very small area, resulting in high pump power handling capabilities.

If the taper angle of the capillary wall is low enough a high coupling efficiency (< 95%) is possible. Using this structure we have achieved a maximum combined pump power of 86 Watt from 7 pump diodes. This, we believe, is the highest combined pump power reported so far from a single lumped side pump combiner.

7580-50, Session 11

High-power tunable thulium fiber laser with volume Bragg grating spectral control

T. S. McComb, L. Shah, R. A. Sims, V. Sudesh, M. C. Richardson, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

A volume Bragg grating is used in two different configurations to control the output spectrum of a thulium doped silica fiber laser. When used in a direct feedback configuration on the end of a bidirectionally pumped resonator, a power of up to 159 W with 54% slope efficiency is produced with a narrow output spectrum centered at 2052.5 nm with <1.5 nm full-width at 10 dB down from spectral peak. Maximum laser linewidth is limited by the VBG reflectivity width. The VBG based laser is compared to a laser resonator based on a standard HR mirror and is able to maintain stable spectrally narrow operation while the HR mirror laser has a wide and varied spectral output over 20-30 nm. Both lasers have similar slope efficiency, threshold and power performance with any difference attributed to lack of AR coatings on the VBG. In a second cavity, the VBG is used in a tunable configuration by rotating the VBG away from normal incidence. Tuning range was found to be >100 nm from 1947 nm to 2052.5 nm with output powers as high as 48 W and up to 52% slope efficiency. Tuning range is only limited by VBG center wavelength and on the short wavelength end by the VBG aperture size. In system configurations, M-squared is maintained at less than 1.2 at all power levels and long term operating stability at full power is demonstrated.

7580-51, Session 12

SBS suppression and acoustic management for high power narrow linewidth fiber lasers and amplifiers

M. D. Mermelstein, M. J. Andrejco, J. M. Fini, C. Headley III, D. J. DiGiovanni, OFS Labs. (United States)

This paper discusses the transverse acoustic design of active large mode area LP01 optical fibers that provide ~ 10 dB of SBS threshold suppression. The fundamentals of the SBS process and its mitigation are briefly reviewed. Optical fibers capable of kilowatt performance levels are presented and characterized. The potential for further increases in single frequency output powers are discussed.

7580-52, Session 12

High-power linear-polarized narrow linewidth photonic crystal fiber amplifier

C. Wirth, Friedrich-Schiller-Univ. (Germany); T. Schreiber, I. Tsybin, M. Rekas, R. Eberhardt, A. Tünnermann, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

We report on the amplification of narrow linewidth laser radiation from 27 W to an average power of 1.2 kW in close to diffraction limited beam quality using a photonic crystal fiber amplifier. The seed source is an external cavity diode laser (EDCL). Its linewidth is controlled by a radio frequency noise generator modulating the pump current, which allows controlling and suppressing the Brillouin gain in the fiber amplifiers. After preamplification 27 W of average power are used to seed the main amplifier employing a double clad photonic crystal fiber with an air-clad pump core design with NA>0.5 and a step index core with a fundamental mode field diameter of 27 µm. The detailed characterizations include measurement of beam quality and degree of polarization evolution with power as well as the control of Brillouin scattering by the laser linewidth. Additionally, the observation of a threshold-like higher order mode amplification by a kind of transversal mode hole burning at the highest power level is reported. The beam quality and degree of polarization are stable up to this critical power level. The measured M^2 stays below 1.3 (4-sigma method) but increases at this critical power level, where the fundamental mode turns into the next higher order mode. The critical power is controlled by the seed power and therefore the gain in the fiber. At a minimum gain of 16.4 dB we obtained 1.2 kW average power and a linewidth of <80 pm limited by self-phase modulation of the amplitude modulated signal.

7580-53, Session 12

Experimental and theoretical studies of a single frequency PCF amplifier with pump-limited output of 260 W

C. A. Robin, I. A. Dajani, C. L. Vergien, C. Zeringue, T. M. Shay, Air Force Research Lab. (United States)

We report on experimental and theoretical investigations of a polarization-maintaining narrow-linewidth high power Yb-doped photonic crystal fiber amplifier. In the experiment, a slope efficiency of approximately 74% was obtained with a maximum output power of 260 W. Measurements of the beam quality yielded M2 values in the range of 1.2-1.3. The linewidth was measured at different output powers and yielded values that were less than 30 KHz. Our maximum output power was pump limited and measurements of the reflected light indicated that we operated well below the SBS threshold. The measured PER was approximately 18 dB while ASE suppression exceeded 30 dB. An elaborate and self-consistent model describing the interplay among laser gain, thermal effects, and stimulated Brillouin scattering (SBS) in high power fiber amplifiers is used to study the power limitations of this amplifier configuration. The heat equation incorporates quantum defect heating and accounts for both radiative and convective cooling at the surface of the fiber. Laser gain is included in pump, signal, and Stokes evolution equations. For the SBS process, a distributed noise source spanning multi-frequency channels is used as we show that the use of localized noise to describe amplifiers with thermal gradient and laser gain is problematic. Our simulations reveal that an output power approaching 1 KW can be achieved and we identify the conditions where our amplifier can be thermally or SBS limited.

7580-54, Session 12

kW level narrow linewidth Yb fiber amplifiers for beam combining

V. Khitrov, Nufern (United States)

Beam combining of fiber lasers has attracted much interest as a practical means to power scale fiber laser/amplifiers beyond the limitations of a single mode output from an individual fiber. Almost all of the high power demonstrations to date that deliver good beam quality after the combing process (coherent and spectral) require some linewidth control for efficient combining, typically less than 10GHz. The current generation of single mode, Yb-doped LMA fiber amplifiers can operate with 7GHz linewidth at 1kW output power, as summarized in Figure 1. However, the next generation of these amplifiers, based on the latest developments in LMA Yb-doped fiber technology with higher SBS threshold, will be required to either operate with less than 10GHz linewidth at higher power levels (2-3kW) or operate with narrower linewidth (say 2-3GHz) at the 1kW level. We will present the latest data on optical properties of these new Yb-doped amplifiers and the SBS threshold as a function of input seed laser linewidth, including examples of several delivered systems, along with a discussion on future developments/limitations in higher power narrow linewdith fiber amplifiers.

7580-55, Session 13

Passively stabilized 215-W monolithic CW LMA-fiber laser with innovative transversal mode filter

F. Stutzki, C. Jauregui, C. Voigtländer, J. U. Thomas, J. Limpert, S. Nolte, A. Tünnermann, Friedrich-Schiller-Univ. Jena (Germany)

We report on the development of a high power monolithic CW fiber oscillator with an output power of 215 W in a 20µm core diameter Large Mode Area fiber (LMA). This fiber laser is passively stabilized with an in-fiber transversal mode filter. The root mean square of the output power fluctuations is less than 0.5 % on a timescale of 20 s, which represents an improvement of more than a factor 5 over a non-stabilized fiber laser using a fiber Bragg grating (FBG) as reflector.

Due to the few-mode nature of LMA fibers, a FBG written in them exhibits a multi-peak reflexion spectrum in which each resonance corresponds to a different transversal mode. This reflectivity spectrum stimulates multimode laser operation, which results in temporal and spatial power instabilities due to gain competition between the different transversal modes.

To stabilize the temporal and spatial behavior of the laser output, we have developed an innovative passive in-fiber transversal mode filter. This filter can be completely written into the active fiber using fs-Laser pluses. Furthermore, this concept is scalable with the fiber core diameter, which implies that there is no performance loss in fibers with even larger cores. In consequence this structure is inherently power scalable and can, therefore, be used in kW-level fiber laser systems.

7580-56, Session 13

Brightness enhancement limits in pulsed cladding-pumped fiber Raman amplifiers

J. Ji, C. A. Codemard, J. Nilsson, Univ. of Southampton (United Kingdom)

We analyze theoretically limitations on the brightness enhancement of a multimode pump beam, to be efficiently converted into a diffraction-limited Stokes beam in a cladding-pumped fiber Raman amplifier. For a given minimum Raman pump absorption, parasitic 2nd Stokes generation limits the cladding-to-core area ratio, and thus the brightness enhancement. A W-type fiber acting as a spectral waveguide filter allows for nearly five times larger inner-cladding areas by suppressing the 2nd Stokes. We further analyze limits set by glass damage and indirectly propagation loss, as well as pulse walk-off. A well-designed fiber with 3.5 dB/km propagation loss allows for a pump-to-signal brightness improvement of up to 3600 times both in the pulsed and the cw regime.

7580-57, Session 13

Preferential gain ROD-type fiber for stable fundamental mode extraction at ultrahigh-power levels

T. Eidam, Friedrich-Schiller-Univ. Jena (Germany); T. V. Andersen, NKT Photonics A/S (Denmark); E. Seise, S. Hanf, C. Jauregui-Misas, J. Limpert, Friedrich-Schiller-Univ. Jena (Germany); A. Tünnermann, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany) and Friedrich-Schiller-Univ. Jena (Germany)

We report on the development of a low-nonlinearity fiber design capable of producing fundamental mode radiation at ultra high average powers from short length (range of 1m) and large mode field diameter (>50µm) fibers.

In conventional large mode area fiber most of the core is typically uniformly doped. As a consequence gain factors for the fundamental mode and the next higher order modes are comparable. Furthermore, the fundamental mode extracts inversion only in the central part of the core according to its intensity profile, leading at high pump and signal power levels to high and unused inversion density with a strong overlap with higher order transversal modes. In experiments this leads to a threshold-like onset of mode instability, originating from mode competition. Finally, this effect avoids further power scaling.

The presented fiber features an optimized doping profile to prefer the amplification of the fundamental mode. In addition non-extracted inversion is minimized avoiding the issue of transversal spatial hole burning. As a consequence ultrafast fiber laser systems with novel performance are in reach, i.e. systems delivering simultaneously >1GW peak power and >1kW average power. In a first iteration a ROD-type fiber with 60µm MFD and 1.7m length was used in a CPA system to produce pump power limited 330 W of average power at 37MHz. The pulses are compressible to femtosecond duration.

7580-58, Session 13

100 W CW cladding-pumped fiber Raman laser at 1120 nm

C. A. Codemard, J. Ji, J. K. Sahu, J. Nilsson, Univ. of Southampton (United Kingdom)

We report a 100 W continuous-wave cladding-pumped fiber Raman laser operating at 1120 nm. We believe this is the highest power reported from any fiber Raman laser. The fiber Raman laser consists of an 85 m long germanium-doped double-clad fiber in a 4% - 100% linear cavity, which is end-pumped by a multimode ytterbium-doped fiber laser source at 1064 nm. The Raman laser has a slope efficiency of 71% with respect to launched pump power. The laser output M2 is measured to be ~ 1.6 at 80 W of output power.

7580-59, Session 14

Optical phased array beam control for APPLE

T. A. Dorschner, P. L. Hoover, Raytheon Co. (United States)

No abstract available

7580-60, Session 14

Creating discrete cylindrical vector beams using coherently combined fiber arrays

R. S. Kurti, Jr., K. Halterman, R. K. Shori, C. Arian, Naval Air Warfare Ctr. (United States); M. Wardlaw, Office of Naval Research (United States)

A novel method is presented for beam shaping far field intensity distributions using coherently combined fiber arrays. Traditionally, coherent arrays have been composed of linearly polarized elements having their polarization vector along a common axis. In this novel method, the fibers are arranged uniformly on the perimeter of a circle, and the linearly polarized beams are oriented with their polarization vectors arranged in a cylindrical fashion such that each subsequent vector is rotated by 2*pi/N where N is the number of elements on the circle. The elements each have the same Gaussian intensity distribution and power. The ensemble yields a far field intensity pattern that is a good approximation to a cylindrical vector (CV) beam which is characterized by a nonuniform polarization distribution and a null in the center of the beam. These synthetically created CV beams, or discrete cylindrical vector (DCV) beams, can be represented in a closed form solution to predict the far field intensity distributions. This solution is shown to agree with experimental results where several values of N, the number of elements, were tested. In addition, some more complex geometries such as nested geometries, fractal geometries, and some nonuniform geometries have been simulated, all of which also have a central null in the beam and have a nonuniform polarization distribution. These results are in contrast to linearly polarized beams, where the intensity peaks on axis, and from traditional cylindrical vector beams, which are generated by a single laser cavity.

7580-61, Session 14

Spectral beam combining of thulium fiber laser systems

R. A. Sims, C. C. Willis, P. Kadwani, T. S. McComb, L. Shah, V. Sudesh, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); Z. A. Roth, M. K. Poutous, E. G. Johnson, The Univ. of North Carolina at Charlotte (United States); M. C. Richardson, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

Beams from three frequency stabilized master oscillator power amplifier (MOPA) lasers were spectrally combined using a metal diffraction grating. Two of the laser oscillators were stabilized with guided mode resonances filters while the third was stabilized using a gold-coated diffraction grating. GMRFs are thin film structures composed of a waveguide and a sub-wavelength diffractive array allowing particular an evanescent diffracted order to couple into the waveguide then leak back on itself. This mode feeds back into the laser resonator with a stabilized narrow spectrum.

Each MOPA system was capable of producing a minimum of 40 W output powers with slope efficiencies between 50-60 %. The three lasers being combined were operating at wavelengths of 1984.3, 2002.1, and 2011.9 nm with spectral linewidths between 250-400 pm. Beam combining was accomplished by spatially overlapping the spectrally separated beams on a water-cooled gold-coated diffraction grating with 600 lines/mm. Beam quality (M2) measurements were made at multiple power levels of the combined beams. Power levels of 49 W were achieved before heating and thus thermal deformation of the metal diffraction grating caused degradation in beam quality. Efficiencies of the unpolarized combining grating were ~ 67% which produced combined beams with 32 % efficiencies with respect to launched diode pump power.

7580-62, Session 14

Incoherent beam combining of multiple single-mode fiber lasers, utilizing fused tapered bundling

Y. Shamir, Y. Sintov, Soreq Nuclear Research Ctr. (Israel); M. Shtaif, Tel Aviv Univ. (Israel)

Fiber lasers have well entered into the KW regime, delivering close to diffraction-limited beam quality (BQ). Power up-scaling with minimum brightness deterioration is a highly desirable goal. However, some limitations are usually observed: core thermal durability, nonlinear scattering, availability of high brightness pump sources and output surface damage. Previous works report coherent phased-locked or spectral combining. However, these mostly are free space based rather than all-fiber solutions. Until recently, some of these works yielded nearly diffraction limit beams, but reached to power levels of tens to few hundreds of Watts only. Incoherent all-fiber combining is an additional approach for scaling the output power, with a potentially mild beam deterioration. An intensity addition of the combined incoherent entries is achieved, while the overall brightness can be closely conserved. The lowest BPP can approach the square root of the number of sources times the BPP of a strongly guided HE11 mode. The combining mechanism is based on waveguide evanescent coupling, as in common communication couplers, with an exception that the radiation is launched from a cut section at the end of the structure. Three and seven port combiners were implemented, delivering a total power of 18.5Watt. The experimental results show a good match with theory. The presented combining configuration is scalable in power and number of ports, and can be advantageous where multiple fiber sources should be combined with good beam quality. Among all beam combining methods, the power to BPP ratio of the incoherent all-fiber approach can be the highest available. Therefore, it is potentially the optimal solution for combining multiple high-brightness fiber coupled sources.

7580-63, Session 15

Passive coherent locking of fiber lasers using volume Bragg gratings

A. Jain, O. G. Andrusyak, G. B. Venus, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); V. I. Smirnov, OptiGrate Corp. (United States); L. B. Glebov, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

Compact narrow-linewidth high-power lasers with good beam quality are desired for a great number of applications. Even kW level output powers achievable from single large mode area (LMA) fiber lasers are not sufficient for many applications, making beam combining techniques a promising tool.

We introduce a novel technique of coherently locking fiber lasers that uses volume Bragg gratings (VBGs) recorded in photo-thermo-refractive

(PTR) glass as a passive multiplexer. A two-channel coherently-locked Yb-doped fiber laser system with narrow linewidth (<5 pm) and near diffraction-limited beam quality is demonstrated at a level of ~ 10 W (limited by pump). In the presented experiment we used a VBG with peak diffraction efficiency ~ 50% and FWHM of ~ 90 pm at an incidence angle ~ 4 degrees. Output from each laser is partially diffracted by the VBG and coupled into the other laser, effectively locking the two channels.

The output transverse modes, polarization, and slope efficiency are directly influenced by the coiling diameter of the polarization maintaining (PM) LMA fiber used and the rotational orientation of its facets. This paper will discuss the coiling and orientation mechanisms used and analyze its effects on the stability of coherent operation of the fiber laser system, with and without external polarization control. New geometries will be proposed that allow coherent locking of a larger number of channels using a single VBG and several VBGs multiplexed into a single PTR-glass plate.

7580-64, Session 15

208-W average power and 6.3-mJ pulse energy from four spectrally combined fiber amplified Q-switched nanosecond laser sources using low-cost interference filter

O. Schmidt, D. Nodop, J. Limpert, A. Tünnermann, Friedrich-Schiller-Univ. Jena (Germany)

In this contribution we introduce a simple scheme to spectrally combine four single beams using three low-cost dielectric interference filters as combining elements. 25 ns pulses from four independent and actively Q-switched fiber seed-sources are amplified in a single stage fiber-amplifier. Temporally and spatially combined 208 W of average power and 6.3 mJ of pulse energy are obtained out of a fiber-based laser system. A detailed observation of beam quality as well as the thermal behavior of the combining elements is carried out and reveals mutual dependency. The deterioration of beam quality can be led back to thermal induced wave-front distortions on the part of the interference filters. This effect as well as other influences on M2 will be discussed and compared to the competing combining approach with dielectric gratings.

7580-65, Session 15

Thermal tuning of volume Bragg gratings for high power spectral beam combining

D. R. Drachenberg, O. G. Andrusyak, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); I. Cohanoschi, OptiGrate Corp. (United States); O. Mokhun, V. I. Smirnov, OptiGrate Corp. (United States) and CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); G. B. Venus, L. Glebov, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States) and Optigrate Corp. (United States)

A tabletop kW-level spectral beam combining (SBC) system using volume Bragg gratings (VBGs) recorded in photo-thermo-refractive (PTR) glass was presented at the last meeting. Diffraction efficiency of VBGs can approach 100% for the Bragg wavelength. However, when using VBGs for spectral beam combining, it is important to ensure high diffraction efficiency for the diffracted beam and low diffraction efficiency for the transmitted beams simultaneously. The unique, unmatched properties of VBGs allow achieving this condition at wavelengths with less than 0.25 nm separation. We present modeling of reflecting VBGs for high power SBC that takes into account laser spectral bandwidth, beam divergence, PTR-glass scattering losses, and grating non-uniformity. A method for optimization of VBG parameters for high-efficiency SBC with an arbitrary number of channels is developed. Another important aspect of spectral beam combiner design is maintaining high diffraction efficiency as the temperature of beam-combining VBGs changes during operation due to absorption of high power radiation. A new technique of thermal tuning of large aperture VBGs, designed to maintain high efficiency of beam combining without mechanical adjustment over a wide range of laser power, is developed. This technique also allows quick fine-tuning of a beam combiner if it is misaligned during transportation. Finally, these tools are used to demonstrate a robust and portable 5-channel kW-level SBC system with near diffraction limited spectrally-combined output beam.

7580-66, Session 15

A multi-channel phase locked fibre bundle laser

D. C. Jones, A. J. Turner, A. M. Scott, S. M. Stone, QinetiQ Ltd. (United Kingdom); R. G. Clarke, C. Stace, C. D. Stacey, BAE Systems (United Kingdom)

We report on the phase locking of a fibre bundle based on a single frequency oscillator coupled into four fibre amplifiers to provide a coherent beam of over 600W. The oscillator was phase modulated to a width of up to 1GHz to increase the threshold for stimulated Brillouin scattering and then a fraction split off and frequency shifted to form a reference beam. The oscillator output was amplified by end-pumped fibre amplifiers based on 20 micron core Yb doped fibre to provide a power of up to 259W per channel. The beams combined to form a coherent output with phase errors of a twentieth of a wave, unaffected by the spectral broadening.

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High Energy/Average Power Lasers and Intense Beam Applications IV

7581-01, Session 1

Enhanced performance of an electric oxygen-iodine laser

D. L. Carroll, G. F. Benavides, CU Aerospace LLC (United States); J. W. Zimmerman, B. S. Woodard, Univ. of Iliinois at Urbana-Champaign (United States); A. D. Palla, J. T. Verdeyen, CU Aerospace LLC (United States); W. L. Solomon, Univ. of Iliinois at Urbana-Champaign (United States)

Ongoing experiments have led to continued improvements in the Electric Oxygen-Iodine Laser (ElectricOIL) system that significantly increased the discharge performance, supersonic cavity gain, and laser power output. The cw laser operating at 1315 nm is pumped by the production of O2(a) in a radio-frequency (RF) discharge in an O2/He/NO gas mixture. The gain has improved from the initial demonstration of 0.002% cm-1 to >0.21% cm-1, by more than a factor of 100-fold, and similarly the outcoupled laser power has risen from 0.16 W to >27 W (with a 5 cm gain length cavity). New discharge geometries have led to improvements in O2(a) production. Modeling with the BLAZE-IV model is in good agreement with data and helps to guide our understanding of this complex hybrid laser system.

7581-02, Session 1

Singlet oxygen production in transverse gas flow slab RF discharge for electric discharge oxygen-iodine laser

A. A. Ionin, Y. M. Klimachev, P.N. Lebedev Physical Institute (Russian Federation); I. V. Kochetov, A. P. Napartovich, TRINITI (Russian Federation); O. A. Rulev, L. V. Seleznev, D. V. Sinitsyn, P.N. Lebedev Physical Institute (Russian Federation)

Results of experimental and theoretical study of singlet delta oxygen (SDO) production in transverse gas flow RF slab discharge for an electric discharge oxygen-iodine laser are presented. The electric discharge facility operating in both pulse-periodic and CW mode was manufactured: gas flow duct including multi-path cryogenic heat exchanger, dielectric slab channel, and slab electrode system incorporated in the channel for RF discharge ignition. Experiments on SDO production in transverse gas flow RF discharge were carried out. SDO production depending on gas mixture content, gas mixture, gas flow velocity, low-frequency modulation of RF power and RF discharge power was experimentally studied. It was shown that SDO yield increased with gas pressure decrease, gas flow deceleration and helium dilution of oxygen at the same input power. CW RF discharge was demonstrated to be the most efficient for SDO production at the same averaged input power of RF discharge. SDO yield was demonstrated to be not less than 10%.

7581-03, Session 1

Kinetics and scaling of gain and lasing in a 1-5 kW microwave discharge oxygen-iodine laser

W. T. Rawlins, S. Lee, D. B. Oakes, S. J. Davis, Physical Sciences Inc. (United States)

Scaling of Electric Oxygen-Iodine Laser (EOIL) systems to higher powers requires extension of electric discharge powers into the kW range and beyond, with high efficiency and singlet oxygen yield. This paper describes the implementation of a moderate-power (1 to 5 kW) microwave discharge at 30 to 70 Torr pressure in a supersonic flow reactor designed for systematic investigations of the scaling of gain and lasing with power and flow conditions. The 2450 MHz microwave discharge is confined near the flow axis by a swirl flow. The discharge effluent, containing active species including O2(a1 g), O(3P), and O3, passes through a 2-D flow duct equipped with a supersonic nozzle and cavity. I2 is injected upstream of the supersonic nozzle. The apparatus is water-cooled, and is modular to permit a variety of inlet, nozzle, and optical configurations. A comprehensive suite of optical emission and absorption diagnostics monitors the absolute concentrations of O2(a), O(3P), O3, I2, I(2P3/2), I(2P1/2), small-signal gain, and temperature in both the subsonic and supersonic flow streams. The experimental results include numerous observations of positive gain and lasing in supersonic flow, and the scaling of gain with a variety of flow and reaction rate conditions. The results are compared with kinetics modeling predictions to highlight key discrepancies as well as areas of agreement. The observed gains are generally lower than the predicted values, due in part to chemical kinetics effects and also due to mixing limitations specific to the reagent injection design. We discuss in detail the observed effects related to O-atom chemistry, and their import for scaling the gain to higher levels.

7581-04, Session 1

Iodine dissociation in the photochemistry of iodine/nitrous oxide mixtures

M. C. Heaven, Emory Univ. (United States); V. N. Azyazov, P.N. Lebedev Physical Institute (Russian Federation); D. Postell, Emory Univ. (United States)

The 193 nm laser photolysis of N2O/I2 mixture was employed to study the kinetics of the dissociation of iodine dissociation by O2(a1Δ) at the chain stage. Singlet oxygen was produced by the secondary photochemical reactions:

N2O + h (193 nm) O(1D) + N2

O(1D) + N2O O2(a1Δ) + N2.

Photolysis of N2O/I2 mixtures at 193 nm resulted in formation of electronically excited iodine atoms:

I2 + h (193 nm) I(2P1/2) + I(2P3/2)

with a quantum yield about 0.25. The secondary photochemistry of the N2O/I2 system was characterized by monitoring the time histories of I(2P1/2) and I2. Temporal profiles of I2 were detected via LIF of the I2(B-X) transition. I(2P1/2) was monitored by observing emission at the transition I(2P1/2-2P3/2) at =1315 nm.

The 193 nm laser pulse resulted in the formation of both O2(a1Δ) and I(2P1/2), thereby providing conditions equivalent to the I2 dissociation process at the chain stage. Experiments were carried out with pre-photolysis partial pressures in the ranges 25-100 Torr for N2O and 7-30 mTorr for I2. Each laser pulse photodissociated about 50 % of I2 and

about 0.1 % of N2O. Regardless of the fact that I2, O2(a1Δ) and I(2P1/2) were present in the system, the chain reaction of I2 dissociation was not observed. It was found that under such experimental conditions that quenching of the I2 intermediate by N2O prevails above the rate of the reaction I2 + O2(a1Δ) 2I +O2(X3). Kinetic modeling was used to test the multi-pathway I2 dissociation model.

7581-05, Session 1

An all gas-phase iodine laser based on NCl3 reaction system

T. Masuda, Keio Univ. (Japan); T. Nakamura, M. Endo, Tokai Univ. (Japan); T. Uchiyama, Keio Univ. (Japan)

Chemical Oxygen-Iodine Laser (COIL) is expected for various applications because it has many attractive characteristics. However, the requirements of liquid fuel place some limits on the COIL device because it is heavy and unsuitable to long preservation. Consequently, there has been considerable interest in developing alternate system that uses different energy transfer partners that is produced by all gas-phase chemical reaction. Although successful lasing has been reported for azide-based reaction system, we paid great attention to amine-based reaction system. In this system, iodine atom is pumped by NCl(1Δ), that is produced by decomposition of nitrogen trichloride, NCl3. Amine-based system has several advantages over the azide-based system, such as simpler reaction scheme and capability of condensed storage of laser fuel, NCl3.

Recently, we reported the detailed conditions required to achieve laser oscillation of amine-based all gas-phase iodine laser (AGIL) system which were established by numerical simulation. It was seen that the order of the injection nozzle is crucial to suppress undesirable reactions. The proposed injection nozzle order is that NCl3 is injected as main flow and HI and H2/H are injected at the same point as the secondary and tertiary flows. Following the calculations, we have fabricated a flow reactor whose mixing nozzles were optimized based on the simulation.

As a result, continuous-wave laser output of 50 mW with 40% duty factor was obtained from a stable optical resonator consisting of two 99.99% reflective mirrors. The observed laser characteristics were reasonably explained by numerical model calculations. To our knowledge, this is the first achievement of amine-based, all gas-phase iodine laser oscillation.

7581-06, Session 1

Catalytic enhancement of singlet oxygen for hybrid electric discharge oxygen-iodine laser systems

S. Lee, W. T. Rawlins, S. J. Davis, Physical Sciences Inc. (United States)

We have observed enhanced production of singlet oxygen, O2(a1Δg), in the reaction of the effluent of O2/He discharges on an iodine oxide film surface in a microwave discharge flow reactor at 320 K. We observe as much as a two-fold increase in the O2(a) yields in excess of discharge-generated amounts for non-catalytic conditions. The iodine oxide surface appears to catalyze a heterogeneous reaction of discharge effluent species such as atomic oxygen to form O2(a) with high collision efficiency. Injection of molecular iodine into the catalytically enriched active-oxygen flow results in excitation of the I(2P1/2) state approaching optical transparency at 1315 nm. Addition of NO2 results in positive small-signal gain in the 320 K subsonic flow. The observed catalytic effect could significantly benefit the development of hybrid electrically driven oxygen-iodine laser systems.

7581-07, Session 1

O2(a1Delta) quenching in O/O2/O3/CO2/He/Ar mixtures

M. C. Heaven, Emory Univ. (United States); P. A. Mikheyev, V. N. Azyazov, P.N. Lebedev Physical Institute (Russian Federation); D. Postell, Emory Univ. (United States)

In the present study we have investigated the quenching of O2(a1Δ) in O/O2/O3/CO2/He/Ar mixtures. Oxygen atoms and singlet oxygen O2(a1Δ) molecules were produced by the 248 nm laser photolysis of ozone. O2(a1Δ) quenching was followed by observing the 1268 nm fluorescence of O2. The temporal profiles of oxygen atoms O(3P) were monitored by means of the O+NO chemiluminescent reaction. O2(a1Δ) decay profiles were recorded with variations of the Ar, He, N2 and CO2 partial pressures and gas temperature in the range 295-370 K.

Fast and slow decays of O2(a1Δ) were observed. The fast decay occurred when O atoms were present in the system. An attempt was made to model the fast decay using the three body quenching process O(3P) + O2(a1Δ) + O2 O(3P) + O2 + O2. An effective rate constant for this process was estimated to be 1.1×10-31 cm6/s.

It was found that O2(a1Δ) decay profiles were unchanged with variation of Ar and N2 partial pressures and gas temperature in the range 295-370 K. Dilution of the gas mixture by CO2 and He resulted in a decrease of the quenching rate. These observation are in conflict with the kinetic model proposed by Braginskiy at al. (J. Phys. D: Appl. Phys., 2005, 38, p. 3609) and may suggest quenching of O2(a1Δ) by vibrationally excited ozone O3(v). Kinetic modeling was used to search for the role of three body quenching and O3(v) in O2(a1Δ) quenching process.

7581-08, Session 2

Ultrashort pulses exceeding 18-megawatt peak intensity directly produced by a Ti:sapphire chirped-pulse oscillator

W. Koehler, C. Bartylla, B. Luerss, FEMTOLASERS Produktions GmbH (Austria)

We demonstrate the latest result in the development of long-cavity Chirped Pulse Oscillators (CPOs). In these ultrafast Ti:Sapphire Oscillators a prolongation of the Cavity-length is used to increase the energy per pulse circulating in the cavity. An appropriate dispersion management in the positive dispersion regime leads to chirped intracavity pulse avoiding the pulse destruction by non-linearities in the Ti:Sapphire crystal (Fernandez et all. Optics Letters 2004).

The latest results in developing such Lasers is the use of two Herriot-cells ending up in an allover cavity length of 55m delivering a repetition rate of 2.7MHz. A novel cooling method was developed to avoid disturbing thermal lenses and improve efficiency by avoiding thermal population of the lower laser level. With an average output-power of 2.75W we could reach a pulse energy of 840nJ and an efficiency of >20%. With a spectrum of >35nm we could compress the pulses down to 46fs. To our knowledge this is the first time that a peak power of more then 18MW was demonstrated produced directly from an oscillator.

7581-09, Session 2

Femtosecond vacuum ultraviolet pulse generation at 126 nm by using a femtosecond infrared laser

S. Kubodera, M. Kaku, M. Katto, Univ. of Miyazaki (Japan)

The progress of an ultrashort-pulse high-intensity laser is mainly based on the solid-state laser technology. The lasing wavelengths are thus limited to the near infrared and visible spectral regions. Development of subpicosecond vacuum ultraviolet (VUV) lasers could induce new application fields that have not been realized by existing long wavelength femtosecond lasers. We have been developing an optical-field-induced-ionization (OFI) rare-gas excimer amplifier to amplify femtosecond VUV seed pulses produced by harmonic generation of a femtosecond infrared laser. We have observed femtosecond VUV pulses at 126 nm as a result of the seventh harmonic of a Ti:Sapphire laser at 882 nm. The femtosecond VUV pulse was optimized in Xe at a pressure of 2.2 Torr. The harmonic intensity observed in Kr and Ar compared to that in Xe was qualitatively explained by phase matching. Theoretical calculations show that neutral Xe has a negative Δk at 126 nm, which is a contrast to positive Δk values observed in neutral Kr and Ar at 126 nm. The phase matching may be fulfilled until dielectric breakdown of the media caused by OFI. The increase of the harmonic emission in Xe was thus limited by OFI, in which generation of free electrons deteriorated the phase matching and depleted the neutral Xe atoms. We are currently characterizing the temporal and spatial properties of the VUV pulse at 126 nm. Measurement of the VUV pulse widths by using autocorrelation or cross-correlation of multiphoton ionization of rare-gases or multiphoton absorption in a MgF2 crystal is in progress.

7581-10, Session 3

Study on Nd:YAG laser emitting with high power and high efficiency at 1123 nm

S. Zhang, Q. Wang, X. Zhang, Z. Liu, W. Sun, Shandong Univ. (China)

A diode-end-pumped continuous-wave (cw) Nd:YAG laser emitting at 1123 nm is realized efficiently in a 25-mm-long cavity. A composite Nd:YAG crystal was used as the gain medium and an diode-end-pumped configuration was adopted. With an incident diode power of 26.1 W, an output power of up to 9.3 W is obtained, corresponding to an optical-to-optical conversion efficiency of 35.6%. The laser performances at 1123 nm are compared between composite Nd:YAG and common Nd:YAG crystals. We have reported an efficient continuous wave Nd:YAG laser emitting at 1123 nm. The highest conversion efficiency from 808-nm diode laser to 1123-nm laser was obtained within a 25-mm-long cavity. The laser performances at 1123 nm were compared between composite Nd:YAG and common Nd:YAG crystals in the 25- and 35-mm-long cavities, respectively. The results show that composite Nd:YAG is a better choice and more appropriate for 1123-nm laser generations.

7581-11, Session 3

Excimer laser deposition of super-hard coatings

R. F. Delmdahl, Coherent GmbH (Germany)

Super-hard functional coatings are obtained by high power excimer laser based PLD. Diamond-like, tetrahedral amorphous carbon (ta-C) is grown on substrates moderately heated to below 90°C inside a vacuum chamber upon ablating a graphite target by means of a high pulse energy excimer laser at a wavelength of 248 nm. The fast evaporation of the target material induced by the high photon energy of 5 eV, the short temporal width of 30 ns and the high fluence of the excimer laser pulses generates plume species with a high degree of ionisation and high kinetic energies.

As a consequence, the kinetic energies resulting from excimer based PLD are significantly higher than those associated with the thermal evaporation and the ion sputtering deposition methods. In fact, the mean kinetic energy of the atoms and ions in the plume are in the range of 30 eV to 80 eV for fluencies of 5 J/cm2 to 20 J/cm2.

Such large on-target UV fluences are easily provided by high energy excimer lasers such as the Coherent LPXpro and LSX laser models which can operate at output energies up to 1 J and average output powers up to 540 W.

The large kinetic energies achieved with excimer based PLD are the key to the high fraction of sp3-bonds in the ta-C films and, hence, to an exceptional hardness which is of special interest for industrial applications.

7581-12, Session 3

Time-resolved imaging of material response following laser-induced breakdown in the bulk and surface of fused silica

R. N. Raman, R. A. Negres, P. P. DeMange, S. G. Demos, Lawrence Livermore National Lab. (United States)

Optical components within high energy laser systems are susceptible to material modification when the breakdown threshold is exceeded or damage is initiated by pre-existing impurities. These material modifications are the result of exposure to extreme conditions involving the generation of high temperatures and pressures occurring at a scale on the order of a few microns. The response of the material following localized energy deposition, including the timeline of events and the individual processes involved during this timeline, is still largely unknown.

In this work, we investigate the events taking place during the entire timeline in both bulk and surface damage in fused silica using a set of time-resolved microscopy systems. These microscope systems offer about 1 micron spatial resolution when imaging static or dynamic effects allowing for imaging of the entire process with adequate temporal and spatial resolution. These systems incorporate various pump-probe geometries designed to optimize the sensitivity for detecting individual aspects of the process such as near-surface material motion, the speed of the ejecta, the propagation of shock waves, and the material transformations. The experimental results indicate that the material response can be separated into individual steps, some terminating within a few tens of nanoseconds but some extending up to about 100 microseconds. Overall the results demonstrate that the final characteristics of the modified region depend on the material response to the energy deposition and not on the laser parameters.

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7581-13, Session 3

Improved spatial beam quality for chirped volume holographic gratings (CVHG)

C. Moser, F. Havermeyer, Ondax, Inc. (United States)

We have developed a novel method to correct the spatial distortion resulting from temporally stretching/compressing pulses with a chirped volume holographic grating (CVHG) in glass. We fabricated a chirped volume holographic grating with 10 nm bandwidth, 300 ps delay (30 mm long grating) at 1031nm exhibiting a smooth spatial Gaussian profile after diffraction. Coupling efficiencies for the stretched pulse exceeding 75% into a single mode fiber were demonstrated. The spatial profile is maintained over a wide temperature range from 10 to 40 degrees Celsius.

The use of CVHG for compressing and stretching pulses is attractive over other technologies based on dispersive grating technologies. The compactness of the CVHG solution provides higher beam pointing stability and enables self-contained, compact, turn-key pico and femtolaser solutions.

Up to now, a common drawback of the CVHG was the poor spatial quality of the diffracted beam. This effect is more pronounced with increasing time delay i.e grating length. The diffracted beam shows an oblong shape combining spatial and spectral chirp. We discuss the origin of the distortion effect and present a package method which corrects the distortion by providing a controlled mechanical stress to the CVHG. We show that, by adjusting the amount of stress, the spatial beam shape can be fine tuned to obtain the optimal beam quality.

This development provides a reliable solution for CVHG in current fast laser applications and provides a path for stretching/compressing pulses in the nanosecond range to provide short pulses with higher optical power.

7581-14, Session 4

Scaling of diode-pumped Cs laser: transverse pump, unstable cavity, MOPA

B. V. Zhdanov, M. K. Shaffer, R. J. Knize, U.S. Air Force Academy (United States)

There has been recent interest in Diode Pumped Alkali Lasers (DPALs) and their scaling to higher powers. Scaling of DPALs to high powers requires using multiple pump sources such as laser diode arrays or stacks of arrays. Coupling of multiple pump beams into the laser gain medium can be realized using a transverse pumping scheme that is most efficient for the laser operating with large mode volume. We have demonstrated Cs laser with unstable resonator transversely pumped by 15 narrowband diode laser arrays. This laser operates on lowest transverse mode with a diameter of 7 mm with an optical-to-optical efficiency higher than 30%. Successful operation of this laser has also been demonstrated using transverse pumping by high power narrowband diode laser stacks. An alternative power scaling approach: MOPA system with transversely pumped by multiple diode lasers Cs amplifier was studied experimentally and demonstrated high optical efficiency.

7581-15, Session 4

Transverse-pumped alkali-vapor lasers

J. S. Zweiback, A. M. Komashko, General Atomics Aeronautical Systems, Inc. (United States); W. F. Krupke, WFK Lasers, LLC (United States); T. Ogul, General Atomics Aeronautical Systems, Inc. (United States)

Alkali vapor laser performance has been steadily improving since the first demonstration in 2003. Slope efficiencies over 80% and average powers over 100W have been demonstrated. Most previous experiments have used an end-pumped geometry. While this is a straightforward analog to end-pumped DPSSLs, there are many benefits to a transverse pump geometry, including automatic separation of pump and laser beams, decrease in required diode brightness, reduced laser flux on optical windows, and reduced transport losses. General Atomics Aeronautical Systems, Inc. recently has been studying transverse pumped alkali laser systems. We will discuss our current theoretical and experimental studies.

7581-16, Session 4

Modeling laser performance of scalable side-pumped alkali laser

A. M. Komashko, J. S. Zweiback, T. Ogul, General Atomics Aeronautical Systems, Inc. (United States)

Diode pumped alkali lasers (DPALs) are a good candidate for efficient, high-power lasers. The extremely low quantum defect of the alkali system alleviates thermal management problems. Pumping with spectrally matched diode lasers allows for high efficiency operation, while at the same time, DPALs keep advantages of a gas laser (no thermal stresses, high intrinsic beam quality). Side pumped geometry simplifies system design, separating laser and pump light and providing physical space for a large number of diode stacks needed for power scaling. However, DPALs are three-level lasers and the interaction of pump and laser fluxes make numerical modeling the only viable option for system studies in this geometry. General Atomics Aeronautical Systems, Inc. has built a simplified numerical code for simulation of laser performance in different side pumped geometries. Pump and laser fluxes are modeled as plane waves traversing a rectangular laser cell. Alkali laser level population densities are calculated in the CW approximation. Cell temperature and density of alkali and buffer gasses are fixed as a function of cell coordinates.

With this code, we have studied performance of a rubidium DPAL with helium and methane buffer gas at high peak pump power. We observed dramatic differences in pump absorption with the laser turned off, compared to an operating laser. Cell temperature is a key parameter that controls effective absorption length. If pump density is sufficiently high, we can find an operating point with optical to optical efficiency above 60% with reasonably homogenous spatial laser output profile even for a single side pumped laser cell.

7581-17, Session 4

Potential energy surfaces and line broadening in optically pumped alkali lasers

L. Blank, D. E. Weeks, Air Force Institute of Technology (United States)

Optically pumped alkali lasers rely on the interaction between alkali atoms and a buffer gas to pressure broaden the pumping transition. The molecular dynamics that give rise to pressure broadened lines are governed by the potential energy surfaces between colliding species. The 2S1/2 2P1/2 and 2P3/2 potential energy surfaces for the interaction between a variety of alkali atom (Li, Na, K, Rb, Cs) rare gas (He, Ne, Ar, Kr) pairs are computed at the MSCSF CI level. A relativistic effective core potential is used to model the inner electrons, while up to 9 electrons for the alkali atoms and up to 8 electrons for the rare gas atoms are included in the calculation. Preliminary results for Rb + Ar include a 21 cm-1 well at an equilibrium distance of 7 angstroms in the ground state surface and a 96 cm-1 well for the at 4.5 angstroms for the first excited state surface. Line broadening calculations are performed and compared with experiment.

7581-18, Session 4

Extended saturation and lineshape analysis and computational model of diode-pumped alkali lasers

S. W. Hackett, J. Holtgrave, G. P. Perram, Air Force Institute of Technology (United States)

The saturation characteristics of an optically pumped atomic alkali laser including a full hyperfine spectroscopic description is developed and compared to experimental results. Modeling of pressure broadened, saturated lineshapes yields broadening rates with errors of less than 0.5%. Dicke narrowing has been observed and rates for velocity changing collision quantified. Bleaching of the vapor by a broadband source at low pressures allows for a description of the threshold and slope efficiency, including their dependence on alkali concentration and cavity optical properties (losses and output coupling.) A pulsed Ti:Sapphire laser pumped a 795-nm rubidium laser as much as 24 times its threshold intensity while maintaining linear slope efficiencies, nearly doubling the previous high of 12.8 and increasing confidence that this type of system will effectively scale in power for tactical military applications. Extension of the quasi-two level model using a full rate analysis predicts output power pulse shapes and illustrates the effects of spin-orbit relaxation rate. Effects of pump beam mode overlap with cavity mode on slope efficiency are explored. A temperature and output coupling dependence of the slope efficiency not attributable to the Rigrod equation which includes both variations in output coupling and temperature dependent gain was observed.

7581-19, Session 4

Excimer-pumped alkali vapor lasers: a new class of photoassociation lasers

J. D. Readle, C. J. Wagner, Univ. of Illinois at Urbana-Champaign (United States); J. T. Verdeyen, CU Aerospace LLC (United States); T. M. Spinka, Univ. of Illinois at Urbana-Champaign (United States); D. L. Carroll, CU Aerospace LLC (United States); J. G. Eden, Univ. of Illinois at Urbana-Champaign (United States)

Excimer-pumped alkali vapor lasers (XPALs) are a new class of photoassociation lasers which take advantage of the spectrally broad absorption profiles of alkali-rare gas collision pairs. In these systems, transient alkali-rare gas molecules are photopumped from the thermal continuum to a dissociative ^2 ^+_{1/2} interaction potential, subsequently populating the n^2P_{3/2} state of the alkali. The FWHM of the excimer absorption profile is observed to be >=5 nm in oscillator experiments, indicating XPAL compatibility with conventional high power laser diode arrays.

An alternative technique for populating the n^2P_{3/2} state is direct photoexcitation on the n^2P_{3/2} n^2S_{1/2} transition. However, because the XPAL scheme employs an off-resonant optical pump, the strengths of resonantly-enhanced nonlinear processes are minimized. Additionally, the absorption coefficient may be adjusted by altering the number densities of the lasing species and/or perturbers, a valuable asset in the design of large volume lasers.

We present an overview of XPAL lasers and their operation, including the characteristics of recently demonstrated systems photopumped with a pulsed dye laser. Lasing has been observed in Cs at both 894 nm and 852 nm by pumping CsAr/CsKr as well as in Rb at 795 nm by pumping RbKr. These results highlight the role of the perturbing species in determining the strength and position of the excimer absorption profile. It is expected that similar results may be obtained in other gas mixtures as similar collision pair characteristics have historically been observed in a wide variety of transient diatomic species.

7581-20, Session 4

Modeling of the XPAL system

A. D. Palla, D. L. Carroll, J. T. Verdeyen, CU Aerospace LLC (United States); J. D. Readle, T. M. Spinka, C. J. Wagner, J. G. Eden, Univ. of Illinois at Urbana-Champaign (United States)

The XPAL system was recently demonstrated in mixtures of Cs vapor, Ar, and ethane, by the pumping the ground state of Cs-Ar van der Waals complexes and subsequent dissociation of diatomic, electronically-excited CsAr molecules (exciplexes or excimers). Because of the addition of van der Waals complexes and exciplex states, modeling of the XPAL system is far more complicated than classic DPAL modeling. In this paper we discuss BLAZE-V modeling of this new laser system and compare with experiments.

7581-21, Session 4

Spectroscopic studies of alkali atom-rare gas systems

K. L. Galbally-Kinney, W. J. Kessler, W. T. Rawlins, S. J. Davis, Physical Sciences Inc. (United States)

The diode pumped alkali laser (DPAL) technology has progressed rapidly since the first demonstration of laser oscillation in 2003. Subsequent to that observation, many papers have appeared in the literature, and laser oscillation has been reported in Cs, Rb, and K vapors, many by diode laser excitation. These lasers offer attractive features such as high conversion efficiency and have the potential for transforming the poor beam quality of high power diode lasers to beams with excellent far field profiles. However, there are some important scaling issues including how the spectrally broad diode lasers can be efficiently coupled to the much narrower alkali D lines. Several approaches are being pursued including pressure broadening of the alkali D lines and development of spectrally narrowed, high power diode lasers. In this paper we discuss an alternate approach based on observations of alkali atom-rare gas excimer molecules first observed in the 1970s. These alkali-rare gas molecules offer a spectrally broad absorption feature ideal for coupling diode lasers. Eden and co-workers have recently demonstrated laser oscillation based on pumping the Cs-Kr molecule. In this presentation we will discuss the spectroscopy and kinetics of this approach and present data on several Rb- and Cs- rare gas species. We will also present small signal gain measurements on these species.

7581-22, Poster Session

Fiber-based drive laser systems for the Cornell ERL electron photoinjector

D. G. Ouzounov, H. Li, B. M. Dunham, C. K. Sinclair, F. W. Wise, Cornell Univ. (United States)

Cornell University is developing a high brightness, high average current electron source for the injector of an Energy Recovery Linac (ERL) based synchrotron radiation source. The source is a very high voltage DC electron gun with a negative electron affinity photoemission cathode. A master oscillator-power amplifier (MOPA) laser system has been developed to satisfy the requirements of the Cornell ERL high brightness electron photoinjector. The system operates at 1.3 GHz repetition rate and generates 3-ps pulses tightly synchronized to the master clock of the accelerator. Currently, the system provides 45 watts infrared power (1040 nm) in near diffraction-limited beam. A BBO Pockels cell is used to generate macropulse trains at varies repletion rates. The infrared pulses are frequency-doubled to produce green beam average power of 15 watts which is required for the photocathode. The pulses are shaped transversely and longitudinally to optimize the electron beam parameters and to reduce nonlinear space charge effects. The green pulses (Gaussian shape, 2 ps) are efficiently shaped to flat-top pulses with sharp rise and fall times through differential delay in a set of birefringent crystals (YVO4). The transverse shaping is implemented with commercial refractive beam shaper (Newport). The laser systems design and characterization will be presented, along with initial experiments on the electron beam. Future work will address achieving of even larger average power.

7581-23, Poster Session

A 20fs synchronization system for lasers and cavities in accelerators and FELs

R. B. Wilcox, J. M. Byrd, L. R. Doolittle, G. Huang, J. W. Staples, Lawrence Berkeley National Lab. (United States)

A fiber-optic RF distribution system has been developed for synchronizing lasers and RF plants in short pulse FELs. It is designed to synchronize lasers in the LCLS (four channels) and to synchronize accelerating cavities in the FERMI@Elletra FEL (16 channels). Typical requirements are 50-100fs rms over time periods from 1ms to several hours. Our system amplitude modulates ~3GHz RF onto a CW laser signal and senses fiber length using an interferometer operating on the same signal. The laser wavelength is stabilized to 5x10^-10 by being locked to an absorption line in Rb. A photodiode detects the RF at the receiver, where an FPGA signal processor feed-forward corrects the phase digitally, based on information from the interferometer. This interferometer was tested on a 2km installed fiber in LCLS, showing less than one fringe of drift per day. No mechanical delays are used, so the delay correction range is limited only by numerical range. With all functionality in the receiver, adding channels is simplified. We have demonstrated a dual-channel transmitter/receiver set with a fiber path length difference of 2.2km and 18fs rms differential error over 60 hours. Using two independent receivers with a fiber path length difference of

200m (typical of our actual requirements) we demonstrated less than 15fs rms differential error over 12 hours. A VCXO and frequency multiplier were included in this loop. The system is constructed from standard telecommunications components, and uses regular telecom fiber.

7581-24, Poster Session

KC Space Pirates and NASA Power Beaming Challenge

B. Turner, M. Lades, KC Space Pirates (United States)

Using an 8Kw disk laser from TRUMP we beamed power to a PV receiver array attached to a robotic climber. The goal was to climb straight up at a speed in excess of 5 m/s and achieve the best power to weight based on payload lifted. Solutions ranged from manual laser aiming to military class tracking systems. From silicone solar cells to custom indium based laser power converter photovoltaics. Only 3 teams made it to the finial round. I will give a rundown of their solutions with analyses of the advantages and disadvantages of each.

Conference 7582: Nonlinear Frequency Generation and Conversion: Materials, Devices, and Applications IX

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Nonlinear Frequency Generation and Conversion: Materials, Devices, and Applications IX

7582-01, Session 1

Highly efficient and compact microchip green laser source for mobile projectors

J. Khaydarov, S. Essaian, G. Nemet, A. V. Shchegrov, N. Simanovskaia, Spectralus Corp. (United States); H. Danielyan, G. Gabrielyan, A. R. Poghosyan, S. Soghomonyan, Spectralus CJSC (Armenia)

Compact and efficient green lasers are of high interest to consumer electronics applications such as handheld and pocket projectors. First-generation, LED-based mobile projectors have just appeared in 2008. While RGB lasers offer many advantages in brightness and system design, a viable efficient and low cost green laser platform has been difficult to realize. Since direct green laser sources are not available, a number of nonlinear second-harmonic-based approaches have been proposed recently. In this work, we demonstrate a novel green laser source, based on a monolithic cavity microchip laser platform - monolithic assembly of Nd:YVO4 crystal and PPMgOLN crystal. The use of our highly efficient, periodically poled MgO-doped Lithium Niobate (PPMgOLN) as the nonlinear frequency doubler allows obtaining a significant increase in the overall efficiency of the green microchip laser. The microchip laser platform also offers cost efficient solution for the cost-sensitive market. The laser performs efficiently in both cw and pulsed regimes with repetition rates from 60Hz to 2KHz. We demonstrate 50-150mW green output with wall-plug efficiency exceeding 10% in the temperature range over 40°C. We discuss a compact package for this laser with volume less than 0.4cm3.

7582-02, Session 1

High-power green light generation by second harmonic generation of single-frequency tapered diode lasers

O. B. Jensen, P. E. Andersen, Technical Univ. of Denmark (Denmark); B. Sumpf, K. Hasler, G. Erbert, Ferdinand-Braun-Institut für Höchstfrequenztechnik (Germany); P. M. Petersen, Technical Univ. of Denmark (Denmark)

Green light is useful for a number of applications including display and biomedical applications. Traditionally frequency doubled diode pumped solid state lasers are used, when the power exceeds a few hundred mW's, as suitable high power laser diodes have not been available.

In this work, we demonstrate the use of a newly developed high power tapered diode laser with good spectral and spatial properties in frequency doubling. The tapered diode laser consists of a DBR section for wavelength selectivity, a single-mode ridge section to provide the good beam quality and a tapered amplifier section for increasing the output power. The laser is equipped with two electrodes in order to be able to control the current to the ridge and tapered section individually. The laser is capable of emitting more than 10 W of output power in a single-frequency, near-diffraction-limited beam.

The output of this laser is frequency doubled using periodically poled MgO:LiNbO3 to generate in excess of 1.5 W of output power at 531 nm in a single-frequency, near-diffraction-limited beam.

We investigate different configurations for generation of the green light and will present the use of the green light source for different applications.

7582-15, Session 1

RGB laser generation from fiber MOPAs coupled to external enhancement cavities

J. P. Anderegg, T. A. Chernysheva, D. F. Elkins, C. L. Simmons, R. C. Bishop, C. L. Pedersen, M. L. Murphy, F. L. Williams, Evans & Sutherland (United States)

Red (631 nm), green (532 nm), and blue (448 nm) continuous-wave (CW) lasers have been developed by Evans & Sutherland (E&S). These multi-watt RGB lasers are used as light sources in E&S' laser projector (ESLP), which delivers ultrahigh-resolution content (8192 × 4096 pixels) to large-surface-area venues (e.g., planetariums, simulators, visualization centers, etc.). Efficient visible wavelength generation is obtained by coupling single-frequency near-infrared (NIR) beams into free-space enhancement cavities containing critically phase-matched lithium triborate (LBO) crystals. The NIR energy is produced by a master-oscillator-power-amplifier (MOPA) system which is fiber-based, thus yielding Gaussian beams which are near-ideal for efficient fundamental-to-harmonic conversion. Both polarization-maintaining (PM) fibers and non-PM fibers have been employed with non-PM fiber systems requiring polarization sensing and control. Green laser light is produced by a second-harmonic generation (SHG) process with a 1064 nm fundamental. Red laser light is produced by a sum-frequency mixing (SFM) process with 1064 nm and 1550 nm as fundamentals. Blue laser light is produced by an SFM process with 1064 nm and 775 nm as fundamentals, where 775 nm is first produced by an SHG process with a 1550 nm fundamental. All resulting visible lasers are single-axial-frequency with FWHM bandwidths less than 200 kHz, and are spatially pure with M^2 values less than 1.05. At least 18 W of CW optical power has been generated at all three visible wavelengths, with available NIR amplifier power as the primary limiting factor.

7582-16, Session 1

Highly reliable 198 nm light source for semiconductor inspection based on dual fiber lasers

S. Imai, K. Matsuki, N. Kikuiri, Advanced Mask Inspection Technology, Inc. (Japan); K. Takayama, O. Iwase, NuFlare Technology Inc. (Japan); Y. Urata, T. Shinozaki, Y. Wada, S. Wada, Megaopto Co., Ltd. (Japan)

Highly reliable DUV light sources are required for semiconductor applications such as a photomask inspection. The mask inspection for the advanced devices requires the UV lightning wavelength beyond 200 nm. By use of dual fiber lasers as fundamental light sources and the multi-wavelength conversion we have constructed a light source of 198nm with more than 100 mW. The first laser is an Yb doped fiber laser with the wavelength of 1064 nm; the second is an Er doped fiber laser with 1560 nm. To obtain the robustness and to simplify the configuration, the fundamental lights are run in the pulsed operation and all wavelength conversions are made in single-pass scheme. The PRFs of more than 2 MHz are chosen as an alternative of a CW; such high-PRF light is equivalent to CW light for inspection cameras. We use reliable devices in the wavelength conversion stages; especially a new CLBO device which is developed in another project is used for doubling the SHG output from the Yb doped fiber laser. Then we can obtain automatic operation for 6 months, which is described as follows. Free running operation gives rise to no power interruptions for a week; weekly maintenance within an hour is automatically done if it is required; monthly maintenance within 4 hours is automatically done on fixed date per month; manufacturer's maintenance is done every 6 month. Now this unique 198 nm light source is equipped in the leading edge photomask inspection machine.

7582-17, Session 1

High average and peak power pulsed fiber lasers at 1030 nm and 515nm

B. Cocquelin, J. Saby, F. L. Salin, A. Meunier, Eolite Systems (France)

Although many applications require high power pulses in the visible, fiber lasers have mostly restricted their range to the near infrared. We will present new results obtained with rod type fiber lasers leading to record high performances. Starting we newly designed large mode area photonic crystal fibers in a very simple architecture, we produced over 110W at 1030 nm with Q-switched pulse duration below 10 ns and M2<1.3. These very high peak and average powers lead to over 60W at 515 nm. We have also obtained diffraction limited beams with an output power exceeding 210 W at 1030 nm and 130 W at 515 nm in a very simple MOPA configuration. Due to the very high gain in these fibers, we can keep pulse durations below 20 ns up to 500 kHz in a purely Q-switched system. We will then present results on very high average power picosecond pulse amplification using the same technology as well as route to the kW average power with 10ns, diffraction limited beams.

7582-24, Session 1

Efficient, green laser based on a blue-diode pumped rare-earth-doped fluoride crystal in an extremely short resonator

M. Strotkamp, T. Schwarz, B. Jungbluth, Fraunhofer-Institut für Lasertechnik (Germany)

Intended for use in mobile projectors, the green cw-laser presented in this work utilises a rare-earth-doped fluoride crystal laser pumped by a blue laser diode. The absorption wavelength of Pr:YLF fits the emission wavelength of GaN laser diodes commercially available, and Pr:YLF emits at 523nm.

The laser consists of a blue laser diode, beamshaping optics, a focussing lens and the hemispherical resonator. Since the aim was to build a compact laser system, the resonator comprises a coated Pr:YLF crystal and a concave outcoupling mirror with an extremely small radius. The resonator is only 10mm long and exhibits high stability against misalignment compared to longer resonator designs.

Available from Nichia the blue pump diodes have an output power of 500mW and 1W. For the lower power diode with a M2 of 1 and 3 in the fast and slow axis, a good overlap with the laser mode can be achieved in the 5mm long crystal. The output of the laser with the higher power diode does not increase as desired due to a M2 of 3 and 6.

With the 500mW diode a laser with M2=1 and an output power of 140mW for an absorbed pump power of 410mW has been achieved. With a threshold of 70mW the laser exhibits a slope of 40% and an electro-optical efficiency of 6.5%.

Despite the reduced overlap with the 1W diode, an output power of 290mW for an absorbed pump power of 850mW and slightly increased M2 has been shown.

7582-25, Session 1

Frequency doubling of fiber laser radiation of large spectral bandwidths

S. Nyga, J. Geiger, B. Jungbluth, Fraunhofer-Institut für Lasertechnik (Germany)

In this work the reduction of conversion efficiency due to the spectral bandwidth of the fiber laser radiation is investigated. Subsequently, compensation optics to correct the spectral phase mismatch inside the nonlinear crystal are dimensioned and tested. For the experimental investigations a laboratory fiber laser setup was used consisting of a seed diode and a three stage fiber amplifier. The laser delivers an average output power of up to 100 W at 1 MHz. Even below the Raman threshold the output is far away from Fourier limit, providing a nearly Lorentz-shaped spectrum with a bandwidth of up to 5.8 nm and a temporal pulse width of 800 ps. As the bandwidth increases nearly linearly with the pump power of the third amplifier stage, this parameter could be easily controlled for the experiments. For a better comparison of measurements with different bandwidths, the input power at the nonlinear converter stage could be kept constant by means of an external attenuator.

All conversion experiments were conducted with a moderate load of the nonlinear crystals, i.e. intensity less than 150 MW/cm2. Without compensation for the spectral phase mismatch, a conversion efficiency of 19% is attained for a Type I configuration with a 20 mm long LBO crystal. The conversion efficiency drops with rising bandwidth and lies at less than 10% at 5.8 nm. With compensation optics to correct the spectral phase mismatch 27 W green are obtained from 60 W infrared with 4.4 nm bandwidth at the same load.

7582-03, Session 2

Compact module of a frequency-doubled CW diode laser with an output power of more than 500 mW at 531 nm and a beam quality of less than 1.3

J. Wueppen, M. Traub, E. Pawlowski, Fraunhofer-Institut für Lasertechnik (Germany); K. Hasler, B. Sumpf, G. Erbert, Ferdinand-Braun-Institut für Höchstfrequenztechnik (Germany)

We present a compact module, emitting nearly diffraction limited green laser light at 531 nm at an average output power of more than 500 mW. As pump source for the second harmonic generation a DBR tapered laser with a total length of 6 mm was used. The RW section had a length of 2 mm including a 1 mm long passive DBR section. The devices were mounted p-side up on a copper block. For this mounting scheme, the device reaches up to 7 W maximal output power. At the power level of about 3.8 W used in the presented experiment, a wavelength of 1062.6 nm with a line-width below 0.02 nm (FWHM) was determined. More than 80% of the emitted power is originated within the central lobe of the beam waist profile illustrating the nearly diffraction limited beam quality. Using a 30mm long MgO-doped periodically poled LiNbO3 bulk crystal, the second harmonic wave is generated in a single-pass setup. Due to precise alignment and beam shaping based on the results of numerical simulations and a properly temperature control of the PPLN crystal, a maximum optical conversion efficiency of more than 14% (3,7%/W) was achieved. The fluctuation of the output power is far below 1%.

The characteristics of the fundamental and the SHG beam are presented. Additionally, the results of the simulations of the conversion process as well as the packaging aspects are shown.

7582-04, Session 2

Efficient green lasers for high resolution scanning micro-projector displays

V. Bhatia, A. S. Bauco, H. M. Oubei, D. A. S. Loeber, Corning Inc. (United States)

Laser-based projectors are gaining increased acceptance in mobile device market due to their low power consumption, superior image quality and small size. The basic configuration of such micro-projectors is a miniature mirror that creates an image by raster scanning the collinear red, blue and green laser beams that are individually modulated on a pixel-by-pixel basis. The image resolution of these displays can be limited by the modulation bandwidth of the laser sources, and the modulation speed of the green laser has been one of the key limitations in the development of these displays. We will discuss how this limitation is fundamental to the architecture of many laser designs and then present a green laser configuration which overcomes these difficulties. In this green laser architecture infrared light from a distributed Bragg-reflector (DBR) laser diode undergoes conversion to green light in a waveguided second harmonic generator (SHG) crystal. The direct doubling in a single pass through the SHG crystal allows the device to operate at the large modulation bandwidth of the DBR laser that is only limited by the parasitic reactance of the packaging configuration. This architecture overcomes the inherent limitation of the more common intra-cavity design that typically results in a tradeoff between the modulation speed and conversion efficiency. We demonstrate that the resultant product has a small footprint (<0.6 cc envelope volume), high efficiency (>8% electrical-to-optical conversion) and large modulation bandwidth (>100 MHz) that form key characteristics for application to high resolution scanning micro-projector displays.

7582-05, Session 2

Simultaneous blue and red light generation with birefringent phase matching

K. Miyata, N. Umemura, K. Kato, Chitose Institute of Science and Technology (Japan)

Several nonlinear crystals have been found to be simultaneously birefringent phase-matchable for two different upconversions in the blue and red ranges by using the outputs of a green pumped parametric oscillator and the fundamental beam at 1.0642 um with collinear and noncollinear geometries. We have identified the possible combination of the two involved nonlinear processes and obtained tuning of the wavelengths and relative powers for RGB applications. For the monoclinic BIBO, sum-frequency generation (SFG) at 0.4627 and 0.6260 um was simultaneously phase-matched at 20°C with the collinear geometry. Also, simultaneous collinear phase-matching for second-harmonic generation at 0.4385 um and SFG at 0.5957 um was obtained in the same experimental setup. The wavelength and relative powers of these two configurations were found to be widely tunable thorough the noncollinear and azimuth angles, respectively. The simultaneous phase-matching configurations with other nonlinear materials such as BBO, YCOB, GdCOB, CLBO, and KTP are discussed in detail for comparison.

7582-06, Session 2

High-performance at low cost: manufacturing frequency doubled green semiconductor lasers for mass markets

T. Hoefer, OSRAM Opto Semiconductors GmbH (Germany); U. Steegmueller, OSRAM Opto Semiconductors Inc. (United States); M. Kuehnelt, U. Strauss, T. Schwarz, H. Unold, M. Schmitt, K. Auen, R. Schulz, C. Walter, I. Pietzonka, H. Lindberg, OSRAM Opto Semiconductors GmbH (Germany)

External cavity semiconductor lasers and diode pumped solid state lasers have been widely adapted to serve a wide range of applications in science and industry. Although being in the market for ten or twenty years now, prices are still high and there does not seem to be a trend to real low cost solutions. On the other hand, there have been laser diodes in applications as CD, DVD, and Blue Ray players, where dedicated technologies were developed to make these devices available at low costs. Laser projection is arising as a new high volume application in the consumer market. The lack of green laser diodes is the driving force for OSRAM Opto Semiconductors to develop a frequency doubled green semiconductor laser and the production technology necessary to make the complexity of this advanced laser system affordable.

Optically pumped frequency doubled semiconductor lasers provide an ideal platform to serve the laser projection application. Based on this scalable technology, we developed a 50 mW green laser comprising all the properties that can be expected from a high performance laser: Excellent beam quality and low noise, high speed modulation and good efficiency. More than that, the package is very compact and may be operated passively cooled at up to 60°C. We will describe the key characteristics of the green laser and will present results from reliability testing and production monitoring.

7582-07, Session 2

Coupled ring resonators for efficient second harmonic generation

D. Skoczowsky, A. Jechow, R. Menzel, Univ. Potsdam (Germany); K. Paschke, G. Erbert, Ferdinand-Braun-Institut für Höchstfrequenztechnik (Germany)

We present a new approach of second harmonic generation of diode lasers based on two passively coupled ring resonators. A driving ring resonator with tapered amplifier as gain medium is coupled to a second ring resonator for power enhancement and, thus, efficient second harmonic generation. An all-optical locking of both resonators is realized.

The SHG resonator with PPLN crystal is set up as a miniaturized device [1] having a circumference of 3 cm, only. The driving resonator contains a diffraction grating for tuning the wavelength of emission. Both rings are matched and only one longitudinal mode can oscillate in the coupled laser system. By tilting the grating one can tune the laser emission in steps of 10 GHz for the infrared and 5 GHz for the blue, respectively.

Stable, single frequency operation of the laser was achieved. From 1.7 W tapered amplifier emission a blue output power of more than 300 mW at 488 nm is generated. The blue light is near diffraction limited with M2 < 1.1 for both axes. This scheme of coupled resonators can be adapted to other diode lasers to generate its second harmonic in an efficient way.

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7582-08, Session 3

Limitation of optical frequency comb generation in whispering gallery mode resonators

Y. K. Chembo, N. Yu, Jet Propulsion Lab. (United States)

Optical combs find important applications in frequency metrology, microwave and terahertz generation, and communication. An attractive way to generate optical frequency combs is through nonlinear interactions in small dielectric whispering gallery mode (WGM) resonators. In micro WGM resonators, available high optical Q factors and small mode volumes help to enhance the nonlinear effects, such as four-wave mixing, which are responsible for the comb generation. However experimental results to date also show that the frequency span of the comb generation in a WGM resonator is very limited. In this paper, we present a detailed study on various mechanisms that limit the comb frequency span in WGM resonators. We show that, although the walk-off between the dispersive WGM eigenfrequency distribution and the equidistance comb frequency is the main limiting factor, other phenomena such as modal confinement, material absorption, and modal overlap may also play an important role in pushing optical combs to a wider span in WGM resonators.

7582-09, Session 3

Optical frequency comb generation using dispersion-optimized nonlinear fiber arrangement

J. M. Chavez Boggio, S. Moro, N. Alic, K. Balch, Univ. of California, San Diego (United States); M. Karlsson, Chalmers Univ. of Technology (Sweden); J. Bland-Hawthorn, The Univ. of Sydney (Australia); S. Radic, Univ. of California, San Diego

(United States)

Efficient generation of cascaded four-wave mixing processes using a concatenation of dispersion-optimized nonlinear optical fibers is reported. Two tunable lasers (with frequency spacing ranging from 100GHz to 1THz) are combined to create a sinusoidal beat note, which is subsequently adiabatically compressed to generate a train of pulses with a width of several tens of femtoseconds and exhibiting high peak power (>1kW). Adiabatic compression is optimized by adjusting the fiber dispersion and input power. Subsequent propagation of the generated pulses through a dispersion flattened fiber results in broadband and equalized optical frequency comb generation. The measured optical frequency comb (with 300 GHz spacing) spans over 900 nm centered at 1560 nm. We analyze linewidth broadening as a function of several parameters: comb mode spacing, power, and dispersion. The nonlinear Schrodinger equation was numerically solved using a split Step algorithm and considering the experimental parameters, and we found very good agreement with the experimental results. Numerical simulations give guidelines to optimize the bandwidth, the flatness and the noise performance of the generated optical frequency comb as a function of the mode spacing, power, and fiber dispersion. In summary, we investigated in detail octave spanning optical frequency combs with an essentially arbitrary mode spacing that are generated by a cascade of four-wave mixing processes in dispersion optimized fibers. The mode spacings accessible with the proposed approach (>100GHz) are not accessible with state-of-the-art comb technology (based on mode-locked lasers) that are limited to separations < 5GHz.

7582-10, Session 3

Two-stage bulk compressor for the generation of 10-MW few-cycle pulses at MHz repetition rates

W. Koehler, G. Tempea, FEMTOLASERS Produktions GmbH (Austria)

220-nJ, 42-fs, 5.25-MHz pulses from a long-cavity Ti:Sapphire chirped pulse oscillator were spectrally broadened by nonlinear propagation in a Sapphire plate. The dispersion was subsequently compensated with dispersive mirrors. After far-field spatial filtering the compressor delivered 80-nJ, sub-15-fs pulses at 5.25 MHz.

A novel 500-nJ Oscillator has been developed to demonstrate the energy-scaling potential of this compression scheme, calculations indicating the feasibility of 200-nJ, sub 15-fs pulse generation. A second compression stage has been designed in order to reduce the pulse duration down to <10fs.

7582-11, Session 3

Modal coupling of supercontinuum generation in a tapered fiber

K. Hsu, National Central Univ. (Taiwan); S. Chou, J. Lin, National Chiao Tung Univ. (Taiwan); N. Chen, National United Univ. (Taiwan); S. Liaw, National Taiwan Univ. of Science and Technology (Taiwan); Y. Lai, S. Chi, National Chiao Tung Univ. (Taiwan)

Generation of broadband supercontinuum has many practical applications, and a certain length of submicrometer-diameter wires are needed to generate a wideband spectra from tapered fiber in the literature. However, long submicrometer wires are impossible to produce by use of simple tapering techniques, and these longer tapered fibers are fragile for high-power laser experiment. In this work, by properly tuning the center wavelength of femtosecond Ti:sapphire laser, relatively wide spectra from above 400 nm to below 1200 nm can be generated. The excited tapered fiber is 1 micrometer in diameter and only 1-cm long. After connecting two optical fiber tapers by fusing standard fibers on either side, we can lower down the exciting wavelength for supercontinuum generation. Additionally, numerical simulation is performed to study the nonlinear effects and fiber loss inside the tapered fiber. Spatial modal coupling effect is investigated numerically in order to analyze the spectral response of supercontinuum generation phenomenon.

7582-12, Session 3

Tunable broadband optical generation via giant Rabi shifting in micro-plasmas

R. Compton, A. Filin, D. A. Romanov, R. J. Levis, Temple Univ. (United States)

Broadband, tunable radiation in optical frequency range is generated in atmospheric gases. Giant, self-induced Rabi-shifted radiation is observed when a probe laser interacts with a weakly ionized, cooling atomic or molecular micro-plasma. A micro-plasma is created in a gas at atmospheric pressure by an intense femtosecond laser pulse. A picosecond probe pulse then interacts with this plasma channel, producing red- and blue-shifted sidebands. These coherent sidebands arise from the self-action of the probe beam via induced Rabi oscillation between coupled of excited states populated in the process of the plasma cooling evolution. Maximum shifting of side bands > 90 meV from the carrier frequency is observed resulting in an effective bandwidth of 200 meV. The sidebands are controlled by the intensity and shape of the probe pulse with amplitude and shift predicted by a generalized Rabi-shifting model. Moreover, the characteristic fringe pattern exhibited in the sidebands indicates a high degree of coherence. The coherent broadband light can be shaped and manipulated for applications such as control experiments and short pulse generation.

7582-13, Session 4

LiInSe2 nanosecond optical parametric oscillator tunable from 4.7 to 8.7 µm

A. Tyazhev, G. Marchev, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany); V. Vedenyapin, Institute of Mineralogy and Petrography (Russian Federation); D. B. Kolker, Novosibirsk State Technical Univ. (Russian Federation); A. P. Yelisseyev, S. Lobanov, L. I. Isaenko, Institute of Mineralogy and Petrography (Russian Federation); J. Zondy, Conservatoire National des Arts et Métiers (France); V. P. Petrov, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany)

Although room temperature lasing has been reported up to ~5 µm, practical solid-state-lasers have an upper limit of ~3 µm. The spectral range above 3 µm in the mid-IR can be continuously covered by nonlinear frequency down-conversion using powerful (femtosecond to nanosecond) laser sources in the near-IR. While oxide crystals start to absorb above 4 µm, at practical pump intensities, most of the chalcogenide mid-IR nonlinear crystals will suffer two-photon absorption (TPA) at 1064 nm because of their low band-gap. Being free of limitations related to spectral acceptance or higher order dispersion and nonlinear effects, nanosecond optical parametric oscillators (OPOs) possess the best potential for achieving high power / energy. Operation of such OPOs, pumped near 1 µm, at idler wavelengths exceeding 4.4 µm, apart from the archive Ag3AsS3, has been demonstrated only with AgGaS2 (AGS). The interest in LiInSe2 (LISe) whose band-gap is large enough (2.86 eV), is motivated by its superior thermo-mechanical properties: isotropic expansion, thermal conductivity ~5 Wm-1K-1 (~3 times higher than in AGS), and smaller thermo-optic coefficients as well as higher damage threshold than AGS. In this work we report broadband operation of a 1064 nm pumped LISe OPO, tunable from 4.7 to 8.7 µm. Pumping at a repetition rate of 100 Hz and the absence of thermal effects allowed to increase the average power by more than an order of magnitude at wavelengths much longer than in the initial demonstration (3.3-3.78 µm). We report also extensive damage studies of LISe with the same pump source.

7582-14, Session 4

3.2-watt single-frequency CW source at 790 nm based on frequency conversion of a fiber laser

A. J. Henderson, P. Esquinasi, Lockheed Martin Aculight (United States)

Many promising demonstrations of single pass frequency doubling of fiber lasers have recently been performed, providing a simple, robust method to generate multi-Watt power output in the green and near-infrared. However such sources are limited to operating wavelengths within the relatively narrow gain bandwidths defined by the fiber dopants. For many applications in spectroscopy and atomic physics, a fiber-laser based source with similar output providing continuous tunability in the 700 nm to 1000nm range would be highly attractive to provide a source of comparable capability to single frequency Ti: Sapphire lasers. We have demonstrated 3.2 Watts of single frequency output by single-pass frequency-doubling of a fiber-laser-pumped CW OPO. 25% efficient frequency doubling was demonstrated by focusing 13 Watts of 1580nm input into a 50mm length MgO:PPLN crystal. The single frequency 1580nm input was generated as the resonant signal wavelength in a CW OPO based on MgO:PPLN. The OPO was pumped by a 30 Watt Ytterbium-doped fiber laser operating at 1064nm, with a spectral bandwidth of ~0.6nm. 300mW of output at 980nm was also generated by the same technique using MgO:PPLN crystals of different poling periods.

7582-15, Session 4

Synchronously pumped at 1064 nm OPO based on CdSiP2 for generation of high-power picosecond pulses in the mid-infrared near 6.4 µm

A. Peremans, D. Lis, F. Cechet, Facultes Univ. Notre Dame de la Paix (Belgium); P. G. Schunemann, K. T. Zawilski, BAE Systems (United States); V. P. Petrov, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany)

Synchronously pumped optical parametric oscillators (SPOPOs) are potentially efficient sources of high repetition rate (~100 MHz) ultrashort pulses at wavelengths not available from conventional mode-locked lasers. The use of chalcogenide crystals, transparent in the mid-IR, has been reported only in a few cases but preserving the high repetition rate was possible only by cascaded operation of two SPOPOs.

The only chalcogenide crystal directly pumped at 1064 nm, remains AgGaS2 (AGS), but it exhibits poor thermo-mechanical characteristics like thermal conductivity, anisotropy of thermal expansion and damage threshold. In all cases the pump systems were pulsed (either by using a modulator, Q-switching or pulsed excitation).

The recently discovered CdSiP2 (CSP), is a negative uniaxial chalcopyrite that allows 1064 nm pumping without two-photon-absorption and possesses a useful transparency up to 6.5 µm. It outperforms all other mid-IR nonlinear materials that can be pumped near 1 µm in almost every aspect and is the only material which allows non-critical phase-matching, with a maximum effective nonlinearity of 84.5 pm/V.

In the present work CSP is employed in a picosecond SPOPO pumped at 1064 nm, to produce quasi-steady-state idler pulses near 6.4 µm with an energy as high as 2.8 µJ at 100 MHz. The train of 2 µs long macropulses, each consisting of 200 (picosecond) pulses, follows at a repetition rate of 25 Hz. This corresponds to an average power of 14 mW. The pump depletion (conversion efficiency) exceeds 40%. Without intracavity etalon, the 12.6 ps long mid-IR micropulses have a spectral width of 240 GHz.

7582-16, Session 4

A high peak power compact eye-safe optical parametric oscillator system

F. F. Wu, MetroLaser, Inc. (United States); J. W. Pierce, JP Innovations LLC (United States)

We report the operation of an optical parametric oscillator (OPO) at 1574 nm using KTP, with output peak power of more than 5 megawatts, output pulse energy of up to 30 mJ per pulse, and pulse width of less than 6 nanoseconds at full width half maximum (FWHM). The OPO was pumped by a diode pumped Nd:YAG Q-switched laser, with pump energy of about 95 mJ and pulse width of approximately 7 ns. The conversion efficiency from 1064 nm Nd:YAG laser to OPO output at 1574 nm is more than 30%. The whole system including the Nd:YAG laser was compactly packed inside a case measuring 15” x 9” x 5.3”. The complete Nd:YAG / OPO system was tested over an operating temperature range of -20 C to +35 C and a storage temperature range of -40 C to +50 C without significant power or performance variations, which makes it suitable for field operation.

7582-17, Session 4

Excitation of individual Raman Stokes lines of up-to 10th order using rectangular shaped optical pulses at 530nm

K. Chen, S. Alam, C. A. Codemard, A. Malinowski, D. J. Richardson, Univ. of Southampton (United Kingdom)

We demonstrated the selective excitation of individual Raman Stokes lines of up-to 10th order pumped by 100ns, rectangular-shaped optical pulses at 530nm. The rectangular shaped optical pulses were generated through frequency-doubling of an adaptively pulse shaped fiber MOPA operating at 1060nm. This form of pulse shape is optimal for Raman conversion processes since all parts of the pulse experience the same Raman gain. As a result, it is possible for a single pulse to transfer all of its energy through sequential Raman frequency shifts to successive order Stokes lines along a length of fiber - yielding a pulse at a single selected Raman-order at the fiber output. A high extinction ratio between the selected line and all other Raman-orders can be achieved by an appropriate choice of the input peak power. We have achieved extinction ratios as high as 15 dB between primary and adjacent Stokes lines using this approach in a 1 km long SMF-28 fiber and launched pump powers of up to 5 W at 100 kHz repetition frequency, obtaining wavelength tuneable output at discrete wavelengths in the range 530-780 nm. Sources based on such an approach have potential applications in the areas of material processing and bio-medical science amongst others.

7582-18, Session 5

Tunable nonlinear-optical devices for laser-spectroscopic sensing

B. J. Orr, Y. He, Macquarie Univ. (Australia)

Generating coherent light via nonlinear optics drives many of our laser-spectroscopic sensing applications [1]. For instance, narrowband tunable pulsed optical parametric oscillators (OPOs) controlled by injection seeding are used extensively for cavity-ringdown and coherent-Raman spectroscopies [1-4]. In a high-precision OPO-based spectroscopic system [5-7], we employ a long-pulse (>25 ns) pump laser with optical-heterodyne diagnostics to log instantaneous frequency and chirp on a pulse-by-pulse basis. In other work, we use photorefractive media for narrowband wavelength control of tunable diode lasers and pulsed OPOs [8-10]. Prospective applications of pulsed OPOs include mid-infrared sensing of explosives or post-blast residues and coherent-Raman micro-spectroscopic screening, e.g., of pathogens.

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7582-19, Session 5

Seeded nanosecond optical parametric generator for trace gases measurement

K. Numata, Univ. of Maryland, College Park (United States); S. T. Wu, S. X. Li, H. Riris, A. W. Yu, M. A. Krainak, J. B. Abshire, NASA Goddard Space Flight Ctr. (United States)

Laser remote sensing measurements of trace gases from orbit can provide unprecedented information about important planetary science and answers to critical questions on planetary atmospheres. Remotely measuring methane (CH_4) and other biogenic molecules (such as ethane and formaldehyde) on Mars has important implications on the existence of life on Mars. We report on the development effort of a seeded nanosecond optical parametric generator (OPG) of MgO:PPLN for remote trace gases measurement. This work is supported by the NASA Astrobiology Program's Astrobiology Science and Technology Instrument Development (ASTID) Program. The OPG is pumped by a passively q-switched single frequency laser (3ns, 5KHz, 50uJ) and seed by a DFB laser. The spectrum width of both signal and idler of seeded OPG is Fourier transform limited. The laser can be smoothly tunable through a wide range without mode hop.

7582-20, Session 5

Optical parametric oscillator-based spectroscopy for sensitive chemical sensing

F. Harren, Radboud Univ. Nijmegen (Netherlands)

Over the past years reliable continuously tunable, continuous wave Optical Parametric Oscillators (OPOs) have been developed for the mid-infrared wavelength region. They provide continuous wave laser output at relatively high power (several hundreds of milliWatts up to Watts) and emit any desired wavelength within the infrared wavelength range between 2.5 and 5 micrometer. Accurate detection of specific gases becomes into reach thanks to the infrared fingerprint absorption spectrum of molecular gases in this wavelength region, the high laser powers and the exact tuning capabilities of lasers. When the lasers are combined with sensitive spectroscopic techniques, such as Photoacoustic Spectroscopy, Off Axis Integrated Cavity Output Spectroscopy, Cavity Ring Down Spectroscopy or Wavelength Modulation Spectocopy, gases can be determined extremely sensitive under atmospheric conditions.

The laser based gas sensors typically reach detection limits around 1 part per billion volume for molecules and possess a time resolution of only a few seconds. This has made lasers applicable for a wide variety of applications. Examples will be given on atmospheric detection and biological/medical research.

7582-21, Session 5

Filament-based spectroscopy self-compression to 8 fs for impulsive stimulated Raman spectroscopic sensing

J. Odhner, D. A. Romanov, R. J. Levis, Temple Univ. (United States)

An impulsive, femtosecond-filament-based Raman technique is presented for single-shot, time-resolved measurement of vibrational spectra from 100 cm-1- 4200 cm-1. The method can determine the temperature of a gas phase system by temporally resolving the dispersion of an impulsively excited vibrational wavepacket. Application to a laser-induced filament in air reveals that the initial ro-vibrational temperature is 300 K for both N_2 and O_2. A femtosecond filament is generated in air using 45 fs, 1.8 mJ pulses from a Ti:sapphire laser. Pulse-compression to ~8 fs due to highly nonlinear propagation results in the coherent excitation of all possible vibrational modes in any medium. The resulting ro-vibrational coherence is subsequently probed using a narrowband, 0.6 ps pulse, producing background-free spectra. This temperature is in excellent agreement with the predictions of a new analytic anharmonic oscillator model. The simultaneous measurement of rotational and vibrational Raman spectra of hydrogen using impulsive, filament-based stimulated Raman spectroscopy demonstrates the ability to measure a very broad (>3800 cm-1) range of rotational/vibrational features. Broadband detection, combined with high spectral resolution (25 cm-1) and high signal-to-noise ratio make this an attractive technique for sensing applications. We have used this technique to measure the vapors of several organic and inorganic molecules (toluene, ammonia, pentane, ethanol, methylene chloride, and others).

7582-22, Session 5

Generation of quasi-continuous wave 389-nm coherent light by frequency doubling of a Ti:sapphire laser for nuclear spin polarization of 3He atoms

S. Maeda, H. Morioka, T. Ohira, H. Kumagai, A. Kobayashi, Osaka City Univ. (Japan)

Magnetic Resonance Imaging based on the hyperpolarized helium-3 (^{3}He) gas has been attracted as a non-destructive testing technique for the porous media and the medical field. In order to produce nuclear spin polarization of ^{3}He, optical pumping is the efficient way using a resonant line. However, there is no resonant light source to the line from the ground state of ^{3}He. Then, we have been focusing on the nuclear spin polarization in a discharge cell using the metastability exchange optical pumping (MEOP) technique. We aim at the optical transition 23S1 23P0 at 389nm that has never been investigated for the polarization. Therefore, at first, we developed a single-frequency 389-nm coherent light source based on the second harmonic generation of a single-frequency 778-nm continuous-wave Ti:sapphire laser light with a BiB_3O_6 (BiBO) nonlinear crystal in an external cavity for the enhancement. As a result, we obtained the very efficient output radiation with the conversion efficiency of 56%. Additionally, we examined frequency-doubling of a quasi-continuous wave Ti:sapphire laser for the optical pumping of multi optical transitions. In this presentation, we will show that single frequency experimental results with the quasi-cw 389-nm picosecond light pulse for polarizing.

7582-60, Session 5

Continuous-wave optical parametric oscillators on their way to the terahertz range

R. Sowade, I. Breunig, K. Buse, Univ. Bonn (Germany)

Continuous-wave (cw) optical parametric oscillators (OPOs) are known to be working horses for spectroscopy in the near- and mid-infrared. However, strong absorption in nonlinear media like lithium niobate complicates the generation of far-infrared light. This absorption leads to pump thresholds vastly exceeding the power of normal cw pump lasers. Here, we demonstrate an approach to overcome this hurdle and extend the tuning range of cw OPOs to the terahertz range. We use cascaded nonlinear processes: the resonantly enhanced signal field, generated in the primary parametric process, is intense enough to act as the pump for a secondary process, creating idler waves with frequencies in the terahertz regime. The latter ones are monochromatic and tunable from 1.2 to 1.7 THz with detected powers in the microwatt range. Thus, continuous-wave optical parametric oscillators have entered the field of terahertz photonics.

7582-49, Poster Session

Characterization of palladium thin film deposited by pulsed-laser deposition

U. Singh, N. Jha, T. P. Singh, A. Kapoor, Univ. of Delhi (India)

In this paper the crystalline and morphological properties of Pd thin films deposited on glass substrate by pulsed laser deposition (PLD) technique at different substrate temperatures have been investigated. These films were deposited with an excimer (XeCl) laser source (= 308 nm, pulse duration of 30 ns, repetition rate of 10 Hz).The fabricated films were characterized by various methods such as X-ray diffraction (XRD) and atomic force microscopy (AFM). The thickness and refractive index of samples were measured using ellipsometry. There was influence of substrate temperature on the surface roughness of thin film. The rms roughness increases with increasing temperature. As the temperature increase the crystallinity of the film also increases.

7582-50, Poster Session

Practical aspects of applying triple correlations to the characterization of high-frequency repetition trains of picosecond optical pulses

A. S. Shcherbakov, P. P. Moreno Zarate, A. L. Muñoz Zurita, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); S. A. Nemov, St. Petersburg State Polytechnical Univ. (Russian Federation); J. Campos Acosta, Consejo Superior de Investigaciones Científicas (Spain)

Practical feasibility of measuring the train-average parameters of picosecond optical pulses with asymmetric envelopes being arranged in high-frequency repetition trains is investigated. For this purpose one can use the temporal triple auto-correlation, whose Fourier transformation gives the bispectrum of pulse train. The advantages of similar auto-correlation function in comparison with the second-order one consist in the capability of recovering signals almost unambiguously and in the possibility of revealing asymmetry of train-average pulse envelope as well as the phase. In picosecond optics, the temporal triple auto-correlation can be shaped by a three-beam scanning interferometer together with the following stage of a triple harmonic generation. A three-beam interferometer assumes exploiting three identical mirrors, one of which is fixed, while two another are scanning with the frequencies being significantly dissimilar to each other. There are at least two options of arranging optical schemes for a triple harmonic generation. One of them gives the triple optical harmonic directly within impinging a triplet of light beams leaving that interferometer on nonlinear crystal. The other scheme implies a two-cascade arrangement when firstly two beams generate the second harmonic and then this second harmonic is mixed with the third beam of an initial frequency. The efficiencies of these options are analyzed and compared in various crystalline materials. We consider the key features of experimental technique related to accurate and reliable measurements of the train-average parameters of pulses with possible frequency chirp. For this purpose, the technique for recognizing the width as well as the magnitude of the frequency chirp is progressed.

7582-51, Poster Session

Upconversion fluorescence spectroscopy in rare earth doped sol-gel nano-glass ceramics

L. A. Bueno, A. S. Gouveia-Neto, E. da Costa, A. da Silva, Univ. Federal Rural de Pernambuco (Brazil)

UPCONVERSION FLUORESCENCE SPECTROSCOPY IN RARE EARTH DOPED SOL-GEL NANO-GLASS CERAMICS

L.A. Bueno, A.S. Gouveia-Neto, E.B. da Costa, A.F. da Silva

Universidade Federal Rural de Pernambuco, UFRPE, Recife, Brazil

There has recently been a great deal of interest in searching for new materials for application as hosts in infrared-to-visible light upconverters or optical amplifiers based upon rare-earth doped systems. Some of their many applications include: color displays, high density optical recording, biomedical diagnostics, infrared laser viewers and indicators, fiber lasers and amplifiers. Fluorosilicate based sol gel glass ceramics have recently emerged as auspicious candidates for such photonic devices applications. These glasses are advantageous because they present low temperature of preparation, better mechanical strength, chemical durability, and thermal stability than fluoride-based glasses. The present work involves the investigation of optical transitions and upconversion fluorescence spectroscopy of trivalent lanthanide ions Er^{3+}, Ho^{3+} and Tm^{3+} codoped with Yb^{3+} in -PbF_2 nanocrystals dispersed in silica glassy matrix, excited with near-infrared diode lasers. The dependence of the upconversion luminescence upon diode laser power, and the upconversion excitation mechanisms involved are also investigated. The viability of using these glasses as host for practical applications in optical temperature sensors will also be presented.

7582-52, Poster Session

Numerical analysis for optimum output of idler wave in nanosecond optical parametric oscillators of PPMgSLT

B. K. Rhee, W. Ahn, Sogang Univ. (Korea, Republic of); M. Cha, Pusan National Univ. (Korea, Republic of)

If only a singly resonant optical-parametric oscillator (OPO) is considered, the idler radiation can be generated either from the signal-resonant cavity or the idler-resonant cavity which is characterized by the condition of the reflectivity for the signal and idler waves of the input and output mirrors. In order to understand which type of cavity produces more efficient idler radiation, we investigated the output efficiency of idler wave numerically as a function of the reflectivity of the input and output mirrors in a singly resonant pulsed nanosecond-OPO which consists of a 30 mm long, quasi phase-matched periodically poled Mg-doped stoichiometric $LiTaO_3$ (PPMgSLT) in a 40 mm long cavity with two plane mirrors. OPO is pumped by a Q-switched diode-pumped Nd:YAG laser which has a duration of ~ 90 ns and operates at 10 kHz repetition rate. The wavelengths of the signal and idler waves are 1980 and 2300 nm, respectively. In the numerical analysis, we consider three coupled wave equations for the OPO pumped by a single-mode pump laser source and the spatial variation of the signal output by dividing the pump beam into many rings with equidistant radii, but do not include diffraction and fluctuation of vacuum field. It is found that the optimum output energy of the idler wave can be obtained through the idler-resonant cavity with output mirror of ~ 60% of reflectivity at the idler wave with ~ 25% efficiency. The prediction will be compared to that obtained by the corresponding experiment.

7582-53, Poster Session

A high Brillouin amplification using liquid fluorocarbon

F. F. Wu, A. Khizhnyak, V. B. Markov, MetroLaser, Inc. (United States)

Although fluorocarbon liquid C8F18 is very low gain coefficient of Stimulated Brillouin Scattering (SBS) in which can be several times or an order of magnitude lower than some nonlinear media, a highly purified C8F18 is very safe, stable and with high optical breakdown threshold that makes it an attractive medium. We have utilized it as phase conjugate mirror (PCM) and the PCM reflectivity better than 90% has been achieved at optimized focusing conditions of an incoming beam. The phase conjugated pulse output energy linearly followed the input pulse energy after reaching the threshold level at about 3.3 mJ. The slope efficiency was estimated about 95% without taking into account components' losses. Brillouin amplification through SBS has been realized in highly purified fluorocarbon liquid C8F18. We have designed and performed an experimental test in which amplification is up to 105 or 50 dB at an input signal of 37 nJ. Further lowering of the signal's intensity should result in a higher amplification but it was limited by the tested equipment and other factors.

7582-54, Poster Session

Performance investigation on a quantum dots DFB laser by one- and two-photon pumping

F. Todescato, I. Fortunati, S. Gardin, R. Signorini, Univ. degli Studi di Padova (Italy); J. Jasieniak, Commonwealth Scientific and Industrial Research Organisation (Australia); R. Bozio, A. Martucci, G. Della Giustina, G. Brusatin, M. Guglielmi, Univ. degli Studi di Padova (Italy); M. Prasciolu, Istituto Nazionale per la Fisica della Materia (Italy); F. Romanato, Univ. degli Studi di Padova (Italy)

A distributed-feedback (DFB) laser is a laser where the whole resonator consists of a periodic structure, acting as distributed reflector in the wavelength range of the laser action. The gain medium can range from organic dyes to inorganic semiconductor materials.

In the last years quantum dots (QDs) have been intensively studied because of their important optical properties such as: the tunability of the emission wavelength with their dimension, the high fluorescence quantum efficiency and the photostability. These features are maintained when QDs are dispersed in the suitable sol-gel matrices.

In this work we study the influence on the performance of DFB devices realized by imprinting, with a 1D master, and by electron beam lithography, with 1D and 2D patterns. We will investigate the effect of such parameters: active medium matrix thickness, QDs concentration, pumping incident angle, ecc... The gain medium consists of a CdSe-ZnS core-shell QDs dispersed in a GPTMS/Germanium tetraethoxide hybrid matrix.

Particularly, we focused on the investigation of the laser peak position, threshold and stability for DFB laser excited by one- and two-photon, in a femtosecond regime.

Finally, we present a preliminary study finalized to couple the DFB system with a plasmonic structure to improve the emitting performance of the final device.

7582-55, Poster Session

Sellmeier and thermo-optic dispersion formulas for Beta-BaB2O4

K. Kato, N. Umemura, Chitose Institute of Science and Technology (Japan); T. Mikami, Okamoto Optics Co., Ltd. (Japan)

This paper reports the high-accuracy Sellmeier and thermo-optic dispersion formulas for -BaB2O4 (BBO) that provide an excellent reproduction of the optical parametric oscillator (OPO) tuning curves up to 3.25μm and the temperature dependent-phase-matching conditions for second-harmonic generation (SHG) and sum-frequency generation (SFG) in the 0.1934-0.6420μm range.

Because our proposed Sellmeier equations do not fit the SFG below 0.2048μm and the 0.5321μm-pumped OPO tuning points above 2.5μm, we have first adjusted the IR dispersion terms from the phase-matching angles (=21.8°, =23.5°) observed for type-1 and type-2 SFG between the idler output of the RbTiOPO4 (RTP/OPO) at 3.1092μm and SHG of its pump source at 1.0642μm. These modifications led to the perfect reproduction of the retracing points at 0.664 and 0.640μm that we have measured the type-1 and type-2 OPO by pumping with a frequency-doubled Nd:YAG laser.

We next have constructed the separate Sellmeier equation for ne below 0.2048μm by adjusting the uv dispersion term from the phase-matching conditions for the type-1 SFG between the signal output of the BiB3O6(BIBO/OPO) pumped by SHG of a Nd:YAG laser and SHG of the same pump source. This also gives the perfect agreement between theory and experiment in the 0.1925-0.2048μm range.

We also formulated the thermo-optic dispersion formula for this material by using the literature values of dno/dT and dne/dT, and iteratively adjusted them to give the best fit to the temperature phase-matching bandwidths (FWHM) for SHG and SFG that we have measured at 20-120°C by using the Nd:YAG laser harmonics and the BIBO/OPO. This formula when combined with our new Sellmeier equations gives Δ ext/ΔT=0.91mrad/°C for SFG between 0.7086 and 0.2660μm radiation, which is in excellent agreement with Δ ext/ΔT=0.93mrad/°C measured by Merriam et al at 225-300K.

7582-56, Poster Session

UV supercontinuum excitation source generated by SPM and XPM in photonic crystal fiber

R. R. Alfano, V. A. Kartazaev, I. S. Zeylikovich, The City College of New York (United States); D. A. Nolan, Corning Inc. (United States)

A broadband bright light sources covering UV to mid-IR is based on supercontinuum (SC) generation due to the nonlinear laser interactions inside an optical medium via self phase modulation (SPM), four-wave mixing, and stimulated Raman scattering. The SC is an ideal excitation source for many applications in biology, chemistry and medicine. It can be used for nonlinear optical imaging using CARS, multi photon absorption and STED for high resolution microscopy.

In this report, we demonstrate that the bandwidth of the supercontinuum spectrum generated by femtosecond Ti:Sapphire laser in photonic crystal fiber (PCF) can be increased into the UV by using small core diameter PCF with ZD wavelength shorter 600nm. SC is generated in the region 350 to 1000nm with modulation less than 10 dB and with maximum spectral intensity in 350-450nm. It is further shown that spectral intensity in the UV spectral region can be increased by employing dual-wavelength pumping using the second harmonic of Ti:Sapphire laser as a second pumping wavelength for generating cross phase modulation (XPM).

A detailed experimental study of the SC spectra generated in PCF on pump power and fiber length will be presented for single wavelength pumping at 800nm and 400 nm and for dual wavelength pumping at 800 and 400nm.

7582-57, Poster Session

Accurate evaluation of free carrier refraction in InP

L. P. Gonzalez, S. Guha, Air Force Research Lab. (United States)

Nonlinear absorption in semiconductors is a coupled process where multiphoton absorption of light generates free carriers, which further absorb the incident light. The generated free carriers also modify the refractive index of the semiconductor, thereby giving rise to nonlinear refraction (NLR). For a given incident irradiance, as the pulse duration of the beam increases, so do the free carrier induced effects. Often the accurate determination of NLR coefficients is hampered by inaccurate knowledge of the spatial amplitude and phase of the incident beam. This has been overcome in this work by use of a phase retrieval method. By capturing images of the incident beam as well as a second image located a known distance away, the Gerchberg Saxton algorithm was implemented to retrieve the spatial phase profile of the incident beam. Detailed knowledge of the phase distribution of the incident laser beam allowed nonlinear beam propagation through the sample to be accurately analyzed.

Nonlinear refraction was experimentally investigated in InP at 1.064 and 1.535 µm using ns duration lasers. A phase retrieval algorithm was used to determine the amplitude and phase profiles of the incident beams which were used to model nonlinear propagation through the sample. With the sample held fixed at focus and the incident energy increased, images of the transmitted beam a fixed distance away were recorded as a function of irradiance. Excellent agreement was observed between recorded beam images and those generated from the numerical model allowing, for the first time to our knowledge, the extraction of free carrier nonlinear refraction parameters of InP.

7582-59, Poster Session

1 W at 490 nm on a compact micro-optical bench by single-pass second harmonic generation

C. Fiebig, G. Blume, D. Feise, D. Jedrzejczyk, A. Sahm, M. Uebernickel, K. Paschke, G. Erbert, Ferdinand-Braun-Institut für Höchstfrequenztechnik (Germany)

High power visible lasers with good beam quality are required for many applications, such as spectroscopy, optical data storage or display technology. Visible gas and solid state laser systems are often large-scale and limited to their specific wavelength. Using a small edge-emitting diode laser and a nonlinear bulk crystal for second harmonic generation (SHG) in a single-pass configuration is a simple way to generate visible light above 1 W. This was already done by several groups using a macroscopic setup with a

Distributed-Bragg-Reflector (DBR) tapered diode laser and a periodically poled MgO:LiNbO3 crystal [1, 2].

At the conference we will show results on the miniaturization of such a single-pass SHG setup on a compact micro-optical bench (MIOB). The footprint of the MIOB is only 50 x 10 x 5 mm³. The setup offers a simple integration of different optical components as well as a thermal management to realize the temperature difference from the diode laser to the crystal of about 70 K. Using a 3 cm long SHG crystal we achieved an optical output power above 1 W at 490 nm. As a pump source we used a DBR tapered diode laser with 9.5 W optical output power. The maximum achieved optical conversion efficiency is above 10%. The output power stability is better that ±2% over one hour and the blue laser beam shows an excellent beam quality of M^2 =1.2 (M^2-beam propagation factor) in vertical and M^2 =2 in lateral direction, respectively. Furthermore, we will show the design of the MIOB as well as the properties of the applied DBR tapered laser and the SHG crystal will be given.

[1] O. B. Jensen, P. E. Andersen, B. Sumpf, K.H. Hasler, G. Erbert, and P. M. Petersen, "1.5W green light generation by single-pass second harmonic generation of a single-frequency tapered diode laser" Optics Express, Vol. 17, Issue 8, pp. 6532-6539 (2009).

[2] C. Fiebig, G. Blume, M. Uebernickel, D. Feise, C. Kaspari, K. Paschke, J. Fricke, H. Wenzel, and G. Erbert, "High-power DBR tapered laser at 980nm for single path second harmonic generation", IEEE J. Select. Topics Quantum Electron., vol. 15, no. 3, pp. 978-983 (2009).

7582-61, Poster Session

Dense optical gain media based on buffer-gas cooled atomic vapors

T. Hong, Shanghai Institute of Optics and Fine Mechanics (China); A. V. Gorshkov, D. Patterson, A. S. Zibrov, J. Doyle, M. D. Lukin, M. G. Prentiss, Harvard Univ. (United States)

We demonstrate that a buffer-gas cooled atomic vapor combined with an optical fiber can be used to create optical gain media for optical pulses in the high optical depth regime. Demonstration of this generic technique opens novel pathways to make pulsed solitary fiber lasers.

We use helium buffer gas to cool 87Rb atoms to below 7 K and slow atom diffusion to the walls. Electromagnetically induced transparency with a probe light intensity of ~ 90 micro Watts/cm^2 sent in through an optical fiber allows us to see not only a reduction of the optical depth but also amazingly an amplification of the input pulses due to four-wave mixing effect in the high optical depth regime. Our numerical simulation indicates this experiment results are consistent with the theoretical explanation.

7582-23, Session 6

Bound states of dissipative solitons in optical fiber systems

S. Latas, M. Ferreira, Univ. de Aveiro (Portugal)

We analyze the characteristics of pulse propagation in a transmission line where amplifiers having linear and nonlinear gains and narrow-band filters are periodically inserted. These systems are called dissipative and can be described by the complex Ginzburg-Landau equation (CGLE). In particular, we investigate the interaction between solitary-pulse solutions of the quintic CGLE and look for a clear understanding of fundamental properties of the bound states (BS's), especially as concerns their stability. We use the two-dimensional phase space (distance-phase difference) to analyze the dynamics of the two soliton system and show that this phase space adequately describes the system. We have found stable BS's of both plain pulses and composite pulses when the phase difference between them is . Two-composite pulses bound states have zero velocity, which is in contrast with the behaviour of the bound states formed by plane pulses. As a consequence of the existence of two-soliton bound states, three-soliton and other multisoliton bound states also exist. In particular, we show numerically the possibility of constructing stable bound states of multiple plain pulses with zero velocity by choosing appropriately the phase profile of the whole solution. The impact of intrapulse Raman scattering in the formation and stability of the soliton bound states is also discussed.

7582-24, Session 6

Extraction of a single soliton from a bunch of solitons generated by pulse breakup

M. A. Bello-Jiménez, E. A. Kuzin, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); O. Pottiez, Ctr. de Investigaciones en Óptica, A.C. (Mexico); B. Ibarra-Escamilla, A. Flores-Rosas, M. Durán-Sánchez, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

Pulses propagating in a fiber with anomalous dispersion are broken up

and transformed into a bunch of soliton. The extraction of an individual soliton from the bunch can be used for soliton generation and also for investigation of the process of the soliton formation. In this work we experimentally demonstrate that the NOLM allows the extraction of an individual soliton. Earlier we have shown numerically that the NOLM has high transmission for the solitons with a range of durations while solitons with shorter and longer durations are strongly rejected. The range of the durations with high transmission depends on the NOLM length and also can be moved by amplification of solitons before entering to the NOLM. In experiment we launched 25-ps pulses with about 10 W of power into a 500-m single mode fiber with dispersion equal to 20 ps/nm-km. As a result of pulse breakup, a bunch of solitons is formed at the fiber output. The resulting solitons are launched into a EDFA and then into a NOLM made from 40-m of the same fiber. The NOLM parameters are adjusted to transmit the highest soliton in the bunch (about 50 W of power and 1 ps of duration according to theoretical estimations). In experiment we detected at the NOLM output a single pulse with duration of 1.46 ps and autocorrelation function similar to that of soliton. When a 1-km fiber was attached to the NOLM at the fiber output we detected a soliton with duration of 0.9 ps.

7582-25, Session 6

Self-focusing in gain-guided optical fibers and pulse propagation characteristics

R. Zhou, B. Ibarra-Escamilla, J. W. Haus, P. E. Powers, Q. Zhan, Univ. of Dayton (United States)

Large-mode area Gain-guided (GG) fibers can be used to design high-power fiber lasers. We examine self-phase modulation effects, which are important for self-focusing effects and especially, Kerr lens mode-locking in solid-state lasers. We theoretically explore the self-phase modulation effect in a fiber cavity and determine if a self-focusing effect can be used to mode-lock the fiber laser. The mode-locking mechanism is the fiber analog of a Kerr lens mode-locking used in solid-state laser designs. In a mode-locked fiber laser design a passive fiber passes the pulse into the GG fiber where it expands to fit its larger mode profile. The other end of the gain-guided (GG) fiber section is spliced to a passive fiber span with a smaller mode profile. A simple proposed mode-locked cavity design includes the coupling of the light from the GG fiber to a single-mode fiber with a smaller mode profile to effectively limit the transmission and thus provide additional cavity loss. For small input powers the mode profile is close to the linear fiber mode profile. The amplification in the GG fiber with the addition of the self-phase modulation effect focuses the light at high input powers.

Our simulations include a full 2D transverse mode and a radial symmetry mode plus temporal beam propagation simulations in the GG fiber. The input field is varied from a small value to a large value to cover the range of intensity dependent transmission characteristics. The overlap of the modes between the GG and passive fibers determines the transmission function. At an optimum input intensity the overlap is a maximum and the cavity losses are minimized. The spatial dispersion changes along the pulse, which leads to an effective additional temporal dispersion for the pulse in the single-mode fiber.

7582-26, Session 6

Monolithic high SBS threshold pulsed fiber laser and frequency doubling for LIDAR and remote sensing spectroscopy

W. Shi, NP Photonics, Inc. (United States); E. B. Petersen, NP Photonics, Inc. (United States) and Univ. of Arizona (United States); D. T. Nguyen, Z. Yao, J. Zong, NP Photonics, Inc. (United States); M. A. Stephen, NASA Goddard Space Flight Ctr. (United States); A. Chavez-Pirson, NP Photonics, Inc. (United States); N. Peyghambarian, NP Photonics, Inc. (United States) and College of Optical Sciences, The Univ. of Arizona (United States)

We have achieved more than kilowatt peak power in 100 ns spectrally transform-limited pulses from a monolithic pulsed fiber laser system based on a MOPA configuration. The system features specialized high SBS threshold fiber amplifiers based on highly co-doped phosphate glass fibers, and represents an important new development for coherent LIDAR and remote sensing applications. The implemented Q-switched fiber laser seed at 1530 nm has pulse widths of 100-500 ns, Gaussian-like pulse shape, and transform-limited linewidth. In order to achieve high SBS threshold fiber amplifiers, we have designed and fabricated a large core single mode (SM), polarization-maintaining (PM) fiber with core size of 25 um and cladding size of 400 um. This core size is the largest one for the phosphate active fibers. And most importantly, this fiber has real SM performance due to the low core NA=0.0395, achieved by precisely controlling the glass refractive indices. The high Er/Yb co-doping concentration in phosphate glass fibers results in the highest gain per unit length in the C-band. By using this new fiber in the 2nd power amplifier stage, we have achieved the highest peak power of 1.2 kW for 105 ns pulses with transform-limited linewidth; the corresponding pulse energy is about 0.126 mJ, which is the highest value for monolithic fiber laser pulses. The achieved high-energy pulses at 1530 nm have been successfully frequency doubled by using a commercial periodically poled lithium niobate (PPLN) crystal, and high peak power of 271 W has been achieved for SHG pulses at 765 nm.

7582-27, Session 6

Experimental demonstration of fiber optical parametric chirped-pulse amplification

Y. Zhou, K. K. Cheung, P. Chui, K. K. Wong, The Univ. of Hong Kong (Hong Kong, China)

Optical parametric chirped-pulse amplification (OPCPA) has been investigated comprehensively and is recognized as a key technique to amplify ultrafast pulses. In this paper, we experimentally demonstrated, for the first time to the best of our knowledge, OPCPA in optical fibers, which is called fiber optical parametric chirped-pulse amplification (FOPCPA). Compared with conventional OPCPA systems, FOPCPA allows a longer interaction length, eliminates the need for alignment and offers further integration with fiber components. A picosecond signal at 1542 nm with a pulsewidth of 1.76 ps is broadened by a spool of dispersion compensation fiber (DCF) to 40 ps, and then amplified by a 100-ps pulsed pump with a center wavelength of 1560 nm. The gain medium is a spool of highly-nonlinear fiber (HNLF). After the fiber optical parametric amplification (FOPA), the signal is amplified and a corresponding idler at 1578 nm is generated. Since the signal and idler are phase-conjugated, the same spool of DCF used to stretch the signal is deployed to compress the idler. The idler is compressed to 3.8 ps by using this method. The difference of the pulsewidth between the original signal and compressed idler may because of their propagation distances are not exactly the same. We use another spool of single mode fiber (SMF) to further compress the idler to 1.87 ps. The peak power of the signal is amplified from 20 mW to 2 W, which corresponding to a gain of 20 dB. Therefore, this technique has a potential application in amplification of ultrashort pulses in non-conventional wavelengths bands.

7582-28, Session 6

Far-UV solid state lasers for semiconductor processing

J. J. Jacob, Actinix (United States); D. J. Armstrong, Sandia National Labs. (United States); A. V. Smith, AS-Photonics, LLC (United States)

Liquid immersion interference lithography (LIIL) is envisaged as a possible alternative to EUVL for mainstream semiconductor manufacturing. LIIL is currently used for early-stage exploration of semiconductor imaging and process issues at leading-edge geometries, albeit over small test fields. The key to printing full-field gratings with an interference tool

Return to Contents

is having a high performance laser illuminator. First, a high degree of spatial coherence enables a large depth of focus and is required because the entire wavefront must be phase coherent in order to print a high fidelity pattern across the entire field. Second, the temporal coherence requirement is fairly strict when producing large fields with high visibility at small feature sizes. These dual coherence requirements cannot be achieved with EUV sources, synchrotrons, or excimer lasers. In addition the power of the source must be high enough to expose a full-field pattern and have sufficient headroom to allow for optical beam shaping to provide highly uniform exposures. We will discuss the development of a fiber laser based 197-nm illuminator source that embodies these critical performance traits. The laser system architecture is based upon pulsed erbium and ytterbium fiber lasers that are harmonically converted and sum-frequency mixed to provide an output a 197 nm. Phase compensation techniques will be employed to reduce self phase modulation in the fiber stages. The average power goal is 250 milliwatts and the coherence length target is 15 cm, which is sufficient to print sub 30-nm gratings over a two centimeter square field.

7582-29, Session 7

Single-frequency pulsed fiber lasers at ~1.5 µm and fiber-based THz sources

W. Shi, E. B. Petersen, J. Meair, D. T. Nguyen, J. Zong, Z. Yao, A. Chavez-Pirson, N. Peyghambarian, NP Photonics, Inc. (United States)

We report our recent achievements in high power single-frequency pulsed fiber lasers in the C-band and fiber laser based THz generation. In our monolithic pulsed fiber laser system based on MOPA configuration, the peak power can reach ~128 kW when the repetition rate is 10 kHz and the pulse width 2.5 ns. This result is based on a new large core single mode highly Er/Yb co-doped phosphate fiber with core size of 25 um. This is the highest peak power achieved so far for fiber laser pulses with transform-limited linewidth. An arbitrary waveform generator (AWG) is used to pre-shape the optical pulse shapes by driving an electro-optic modulator (EOM) to directly chop a CW single-frequency fiber laser - producing pulses shaped to avoid dynamic saturation in the cascade of fiber amplifiers. The single-pass generated THz peak power can reach 0.12 W based on difference frequency generation (DFG) of 1550 nm and 1538 nm pulses in a GaSe crystal. Moreover, the nanosecond pulsed fiber lasers have been successfully intensified by an external cavity, and the external cavity enhanced difference-frequency THz generation has been observed for the first time using single-frequency pulsed fiber lasers. The stability condition for a bowtie style ring cavity has been investigated based on ABCD matrices. We have obtained power enhancement factors from 10 to 25 for different pulse widths. Also, we have demonstrated for the first time that this method is applicable to multiple frequencies simultaneously resonant in the cavity.

7582-30, Session 7

Enhancement of optics-to-THz conversion efficiency by metallic slot waveguides

Z. Ruan, Stanford Univ. (United States); G. Veronis, Louisiana State Univ. (United States); K. L. Vodopyanov, M. M. Fejer, S. Fan, Stanford Univ. (United States)

A metallic slot waveguide, with a dielectric strip embedded within, is investigated for the purpose of enhancing the optics-to-THz conversion efficiency using the difference-frequency generation (DFG) process. To describe the frequency conversion process in such lossy waveguides, a fully-vectorial coupled-mode theory is developed. Using the coupled-mode theory, we outline the basic theoretical requirements for efficient frequency conversion, which include the needs to achieve large coupling coefficients, phase matching, and low propagation loss for both the optical and THz waves. Following these requirements, a metallic waveguide is designed by considering the trade-off between modal confinement and propagation loss. Our numerical calculation shows that the conversion efficiency in these waveguide structures can be more than one order of magnitude larger than what has been achieved using dielectric waveguides. Based on the distinct impact of the slot width on the optical and THz modal dispersion, we propose a two-step method to realize the phase matching for general pump wavelengths.

7582-31, Session 7

High-efficiency terahertz generation in novel organic nonlinear optical crystals

P. Günter, ETH Zürich (Switzerland)

Nonlinear optical techniques are widely used for the generation of THz radiation. Materials used for this purpose are on the one hand inorganic semiconductors, e.g. ZnTe and GaP, and on the other hand organic crystals, e.g. 4-N,N-dimethylamino-4'-N'-methyl stilbazolium tosylate (DAST), and the recently developed new materials DSTMS (4-N, N-dimethyl¬amino-4 -N -methyl-stilbazolium 2,4,6-trimethylbenzenesulfonate) and OH1 (2-{3-(4-hydro¬xystyryl)-5,5-dimethylcyclohex-2-enylidene}malononitrile). The much larger nonlinear optical susceptibilities for optical rectification of up to 560 pm/V observed in these materials make them much more efficient than ZnTe and GaP.

The requirements for high efficiency generation and detection of THz waves are phase-matching, a large nonlinear optical susceptibility, and low absorption of both the optical and the THz waves. These requirements are fulfilled exceptionally well in OH1. Its largest tensor element of the nonlinear optical susceptibility can be exploited for phase-matched generation and detection of THz frequencies between 0.3 and 2.5 THz using laser wavelengths between 1200 and 1460 nm. This coefficient d333 is even larger than the largest one d111 of DAST and DSTMS materials that has been shown to be most efficient THz emitters so far. The absorption coefficient 3 of OH1 is lower than the relevant absorption coefficient 1 of DAST for frequencies below 2.2 THz, in particular near the resonance frequency of DAST of 1.1 THz where 1 > 300 cm-1 for DAST and 3 > 3 cm-1 for OH1.

We generated THz pulses in a 0.365 mm thick OH1 crystal through optical rectification of 150 fs laser pulses with a central wavelength of 1460 nm from an optical parametric generator and amplifier (OPG/OPA) pumped with an amplifier Ti:sapphire laser. The electric field of the THz pulses was measured by electrooptic sampling in a ZnTe crystal using a probe beam with the second-harmonic wavelength (730 nm). The emission spectrum is continuous and ranges from 0.3 to 3.0 THz with a maximum at 1.3 THz.

The high efficiencies of these materials allows the realization of a compact turn key THz spectrometer (TeraSys 4000). The performance of this instrument and some examples of spectrometric measurements will be described.

7582-32, Session 7

Terahertz and optical frequency mixing in semiconductor quantum-wells

Y. Lee, A. D. Jameson, J. L. Tomaino, Oregon State Univ. (United States); J. T. Steiner, M. Kira, S. W. Koch, Philipps-Univ. Marburg (Germany); J. P. Prineas, The Univ. of Iowa (United States)

The exciton binding energy in GaAs-based quantum-well (QW) structures is in the range of ~10 meV, which falls in the THz regime. THz-induced nonlinear optical effects of excitons in QWs are of great interest because they not only provide new insights into the quantum coherence and wavepacket dynamics in semiconductors, but also have great potential for applications to THz-rate wireless interconnects and ultra-high speed optical signal processing. In this work, we have conducted a time-resolved study to observe the resonant interactions of strong narrowband THz pulses with coherent excitons in QWs, where the THz radiation is tuned near the 1s-2p intraexciton transition and the THz pulse duration (~3 ps) is comparable with the exciton dephasing time. The system of

interest contains ten high-quality, undoped 12-nm-wide GaAs QWs separated by 16-nm-wide Al 0.3Ga 0.7As barriers. The strong and narrowband THz pulses were generated by two linearly-chirped and orthogonally-polarized optical pulses via type-II difference-frequency generation in a 1-mm ZnTe crystal. The peak amplitude of the THz fields reached ~10 kV/cm. The strong THz fields coupled the 1s and 2p exciton states, producing nonstationary dressed states. An ultrafast optical probe was employed to observe the time-evolution of the dressed states of the 1s exciton level. The experimental observations show clear signs of strong coupling between THz light and excitons and subsequent ultrafast dynamics of excitonic quantum coherence. As a consequence, we demonstrate frequency conversion between optical and THz pulses induced by nonlinear interactions of the THz pulses with excitons in semiconductor QWs.

7582-33, Session 7

Efficient high power tunable THz sources using optical techniques

W. C. Hurlbut, V. G. Kozlov, Microtech Instruments, Inc. (United States); K. L. Vodopyanov, Stanford Univ. (United States)

Resonant cavity enhancement of the optical waves is the route to substantially improve the efficiency of photonic THz-wave generation via frequency downconversion. In the previous work [J.E. Schaar et al., Opt. Lett. 32, 1284 (2007)] , efficient generation of THz output was demonstrated at 2.8 THz by difference frequency mixing between resonating signal and idler waves of the linear-cavity type-II-phase-matched PPLN optical parametric oscillator (OPO). Here we present a new, dramatically simplified approach to resonantly-enhanced THz-wave generation in periodic GaAs, featuring (i) ring, instead of linear, OPO cavity with much higher finesse, (ii) type-0, instead of type-II-phase-matched PPLN crystal as a gain medium, resulting in much lower OPO threshold, (iii) a compact picosecond 1064-nm fiber laser as a pump source, and (iv) the use of a thin intracavity etalon with a free spectral range equal to the desired THz output frequency. Periodically-inverted GaAs samples used in our experiment were either optically-contacted wafers of GaAs (OC-GaAs) held in place by Van Der Waals force or diffusion-bonded samples (DB-GaAs). The samples were anti-reflection coated at 2.1 m to lower the reflection loss. Narrowband output in the range 1.4 - 3 THz was produced with more than 130 microwatts of average power at 1.5 THz using 6.6 W of average fiber-laser pump power. The demonstrated approach can be extended to generate 1-10 mW of THz output in a compact setup by optimizing the OPO PPLN crystal length and s optimizing spectral characteristics of the fiber pump laser.

7582-34, Session 7

Broadly tunable terahertz source

P. E. Powers, K. Kramb, J. W. Haus, Univ. of Dayton (United States)

We present the results of a terahertz (THz) source based on difference frequency generation (DFG) that tunes seamlessly from 1.4 to 13.3 THz. The outputs from two seeded periodically poled lithium niobate (PPLN) optical parametric generators (OPGs) are mixed in a DAST crystal to generate the THz frequencies. The OPG's have ~1 nsec pulse duration and an output energy of ~200 uJ. The corresponding high peak intensities in the DAST crystal leads to appreciable conversion efficiency such that a room temperature pyro-electric detector is used to measure the THz signal.

Phase matching in DAST requires the DFG inputs to have the same polarization. We implement a scheme where the output of one of the OPGs is sent through the second OPG such that the two beams are collinear with the same polarization without using a beam splitter. In one of the OPGs a continuously varying periodicity PPLN crystal is used to tune the output wavelength by translating the crystal. The crystal position and seed laser are computer-controlled and synchronized such that any wavelength within the seed laser's tuning range is randomly accessible, and hence any THz difference frequency between the two seed lasers is also randomly accessible. Finally, we implement a scheme where the inputs to the DAST crystal are multi-passed to further increase the THz average power.

7582-35, Session 8

Periodically poled silicon

B. Jalali, N. K. Hon, K. K. Tsia, D. R. Solli, Univ. of California, Los Angeles (United States)

Bulk centrosymmetric silicon lacks second-order optical nonlinearity x(2)- a foundational component of nonlinear optics. Here, we propose a new class of photonic device which enables x(2)as well as quasi-phase matching based on periodic stress fields in silicon - periodically-poled silicon (PePSi). This concept adds the periodic poling capability to silicon photonics, and allows the excellent crystal quality and advanced manufacturing capabilities of silicon to be harnessed for devices based on x(2) effects. The concept can also be simply achieved by having periodic arrangement of stressed thin films along a silicon waveguide. As an example of the utility, we present simulations showing that mid-wave infrared radiation can be efficiently generated through difference frequency generation from near-infrared with a conversion efficiency of 50% based on x(2) values measurements for strained silicon reported in the literature [Jacobson et al. Nature 441, 199 (2006)]. The use of PePSi for frequency conversion can also be extended to terahertz generation. With integrated piezoelectric material, dynamically control of x(2) nonlinearity in PePSi waveguide may also be achieved.

The successful realization of PePSi based devices depends on the strength of the stress induced x(2) in silicon. Presently, there exists a significant discrepancy in the literature between the theoretical and experimentally measured values. We present a simple theoretical model that produces result consistent with prior theoretical works and use this model to identify possible reasons for this discrepancy.

7582-36, Session 8

Polarization effects and fiber-laser-pumping of a 2-µm-pumped OP-GaAs OPO

C. Kieleck, M. Eichhorn, Institut Franco-Allemand de Recherches de Saint-Louis (France); D. Faye, E. Lallier, Thales Research & Technology (France); S. D. Jackson, The Univ. of Sydney (Australia)

Gallium arsenide combines a large nonlinear coefficient, a good thermal conductivity, excellent mechanical properties, and a wide transparency range (0.9-17 µm). Improvement in hybrid vapour phase epitaxy growing techniques of quasi-phase-matched orientation-patterned GaAs (OP-GaAs) allows larger sample thickness and permits efficient operation as a mid-infrared optical parametric oscillator at Watt-level average output powers.

Especially its low absorption loss (0.01 cm-1), its laser damage threshold comparable to ZGP (2 J/cm2) are suitable properties for efficient non-critical phase matched OPOs.

As there is no natural birefringence in GaAs, phase matching is independent of polarization and propagation direction, offering the ability to pump OP-GaAs with a variety of polarization states. Thus, even unpolarized or poorly polarized sources like simple fiber lasers have been efficiently used as pump sources.

The paper will discuss recent results obtained with an OP-GaAs OPO directly pumped by a 2.09 µm Q-switched Tm,Ho:silica fiber laser and a study on polarization effects using a Q-switched 2.09 µm Ho:YAG laser as the pump.

With a 2.09 µm Q-switched Tm,Ho:silica fiber laser pump source, up to 0.56 W of average output power was achieved at 20 kHz repetition rate in the mid-infrared range.

7582-37, Session 8

Bulk quasi-phase-matched device: large aperture PPMgLN and PPMgLT

T. Taira, Institute for Molecular Science (Japan)

The advent of periodically poled LiNbO3 (PPLN) devices, combined with the development of new laser sources based on solid-state technology, have led to the new stage of optical parametric oscillation (OPO) with previously unattainable performance capabilities. However, the high power applications were limited due to LN's poor photorefractive damage threshold. By multi-pulsed electric-field poling techniques at the elevated temperature, a large aperture (5-mm-thick) periodically poled 5-mol% MgO doped LN (LA-PPMgLN) device was fabricated because MgLN has large nonlinear coefficient, appropriate coercive field, and higher resistance to photorefractive damage. With this, the highly efficient high energy OPO has been demonstrated: the maximum parametric total output energy (s=1.8-µm, i=2.6-µm) was 77-mJ at the pump energy of 110-mJ (p = 1.06-µm, p = 12-ns), which is the power limit of our pump laser, with 72-% slope efficiency. Lately, its maximum output energy was up to 179-mJ with the 53-% slope efficiency. The narrow band output energy was up to 50-mJ using a volume Bragg grating based OPO for ZnGeP2 based differential frequency generation (ZGP-DFG) to generate high brightness tunable mid-IR (=5~11-µm, Δ <1.5-cm-1) with mJ level output. On the other hand, the LA-PPMgLN allows us a highly efficiency broadband optical parametric chirped pulse amplification (OPCPA) to produce 15.7-fs (2-cycle) 740-µJ pulses at the 2.1-µm carrier wavelength for higher harmonics generation (X-ray: ~5-nm). Recent results in our laboratory will be presented as well.

7582-38, Session 8

Adhesive-free bond quasi-noncritical phase-matched and quasi-phase-matched optical parametric oscillations

X. Mu, H. E. Meissner, H. Lee, Onyx Optics Inc. (United States)

Noncritical-phase-match (NCPM) has zero spatial walk-off and large angular acceptance. It is an ideal phase-matching condition for nonlinear optical frequency conversion since long crystal or tightly focused laser beam can be used for increasing of conversion efficiency. However, NCPM can only be achieved at particular wavelengths. More commonly, critical phase-matching (CPM) has to be used. For optical parametric oscillations (OPO's), this leads to distorted output beam quality and extremely high-energy pump requirements. With adhesive-free bond (AFB) technology, quasi-noncritical phase-matching (QNCPM) and quasi-phase-matching (QPM) can be achieved at any wavelength in walk-off compensated (WOC) AFB nonlinear optical composites, which can significantly reduce the pump requirements as well as improve the output beam qualities for OPO's and make them available to commonly laser pump sources. In this work, two KTP composites that consist of 16 layers of 2-mm thick single KTP crystals in each have been designed and prepared for QNCPM and QPM 1.064-mm pumped 2-mm OPO's. Output pulse energies of 49 mJ and 35 mJ have been achieved for QNCPM and OPM OPO's at pump energy of 523 mJ with pulse duration of 15 ns and repetition rate of 1 KHz, respectively. The OPO pump thresholds were measured as low as 254 mJ (44.6 MW/cm2) for the both types of OPO's. Even though the OPO outputs in our experiments contain o- and e-polarized signal and idler beams, diffraction-limit beam qualities have been measured.

7582-39, Session 9

Mode-locking with phase-sensitive (parametric) amplification

C. R. Jones, J. N. Kutz, Univ. of Washington (United States)

Among the crucial ingredients necessary to mode-lock a laser cavity is intensity discrimination that preferentially attenuates low-intensity portions of a pulse with respect to higher intensity portions. A phase-sensitive (parametric) amplifier (PSA) is a recently proposed technology that has been theoretically shown to achieve mode-locking in a laser cavity. We show that the PSA acts as a phase-filter for selecting the specific intensity dependent phase-rotation of the mode-locked pulse that locks the phase to the amplifier pump phase. The resulting averaged cavity evolution equation governing the electromagnetic fieldsdynamics and mode-locking is a Swift-Hohenberg type model with fourth-order diffusion and cubic-quintic nonlinearities. The governing equation also contains a linear growth term that couples to the nonlocal cavity energy via saturable gain. This term is typically a standard bifurcation parameter in Swift-Hohenberg models, but in this case is controlled by the cavity saturable gain. The impact that the inclusion of this physically motivated nonlocal gain parameter in the model has on mode-locking stability as well asthe mode-locked pulse dynamics is explored in both normal and anomalous dispersion cavities.

With increasing cavity gain, we also consider the onset of multi-pulsing behavior and pulse-to-pulse interactions.

7582-40, Session 9

Mode-locked laser pulse sources for wavelength division multiplexing

E. Farnum, Kean Univ. (United States); B. G. Bale, Aston Univ. (United Kingdom); J. N. Kutz, Univ. of Washington (United States)

Optical fiber communications networks rely on the two key technologies of wavelength division multiplexing (WDM) and optical time division multiplexing (OTDM). By combining high repetition rate data streams with a large number of WDM channels, transmission rates are now on the order of nearly 1 TB/s. This increased transmission performance has generated a demand for a source of ultra-short mode-locked pulses at multiple frequencies. We present and analyze a theoretical description for the formation of these multi-frequency mode-locked pulses, based on the standard Haus master mode-locking model. In a multiple frequency channel system, two gain saturation effects are present, homogeneous and inhomogeneous gain broadening. Recent theoretical investigations have demonstrated that the stability of such pulse solutions depends on the interplay between homogeneous and inhomogeneous gain saturation. In this paper, these results are generalized to determine conditions on each of the system parameters necessary for both the stability and existence of mode-locked pulse solutions for an arbitrary number of frequency channels. In particular, we find that the parameters governing saturable intensity discrimination and gain inhomogeneity in the laser cavity also determine the position and stability of various solution types. Furthermore, we determine a balance between cubic gain and quintic loss, which is necessary for existence of solutions as well. Finally, we determine the critical degree of inhomogeneous gain broadening required to support pulses in multiple frequency channels. With the increased demand for sources of shorter optical pulse-streams, this multi-frequency mode-locking model provides further insight into a promising source for WDM pulse generation to be used in WDM/OTDM technologies.

7582-41, Session 9

Dynamics of ultrashort pulse solutions of the complex Ginzburg-Landau equation

S. Latas, M. Ferreira, M. Facão, Univ. de Aveiro (Portugal)

Various forms of the complex Ginzburg-Landau equation (CGLE) and solitary-pulse solutions to them have been attracting a great deal of attention. This is stimulated both by physical applications, which extend from nonlinear fiber optics to traveling-wave convection in binary fluids, and by the interest to fundamental dynamical properties of models based on the CGLE. Among the rich variety of solutions of the CGLE, there are pulse-like, breathing localized, multisoliton, and other special soliton solutions recently found, like pulsating, erupting and creeping solitons.

In this paper we investigate numerically the dynamics of ultrashort pulsating, erupting and creeping soliton solutions of a generalized CGLE, which includes three higher-order effects: third-order dispersion (TOD), intrapulse Raman scattering (IRS) and self-steepening (SS). We show that these higher-order effects can have a dramatic impact on the dynamics of the above mentioned CGLE solitons. For small values of the higher-order terms, the periodic behavior of some of these pulses is eliminated and they are transformed into fixed-shape solitons. For increasing values of the third-order dispersion, it is found that the pulsating and creeping solitons spread with different velocities, whereas for the erupting solitons the behaviour of explosions is altered until they become completely chaotic. Increasing the IRS and the SS effects will transform the pulsating pulse into a pulse with a front on one side and a sink on the top, whereas the erupting soliton splits on the top. Regarding the creeping soliton, the same effects make the soliton breathe periodically on one side, whereas the other side spreads rapidly. Some particularly interesting cases are discussed concerning the combined action of the three higher-order effects.

7582-42, Session 9

Novel high-sensitivity Z-scan technique based on a Hartmann-Shack wavefront sensor

R. E. de Araujo, Univ. Federal de Pernambuco (Brazil); D. Rativa-Millan, Univ. College Dublin (Ireland); A. S. L. Gomes, Univ. Federal de Pernambuco (Brazil); B. Vohnsen, Univ. College Dublin (Ireland)

The field of Nonlinear Optics has provided many techniques to characterize photonic materials. The Z-scan method is a well established technique that exploits wavefront distortions of the light beam to determine the nonlinear properties of optical materials [1].

Here we report on a new variation of the Z-scan method to characterize the third-order optical nonlinearity of photonic materials. By exploiting a Hartmann-Shack (H-S) wavefront sensor on a Z-scan set up we demonstrate an improvement in sensitivity of the method. The H-S wavefront sensor consists of an array of microlenses, focusing an incident wavefront onto a CCD array. By sampling an array of lenslets all of the wavefront local tilts can be measured and the whole wavefront characterized. The wavefront obtained can be expressed in terms of a set of Zernike polynomials, Zn(x; y), as W(x; y) = ∑ cnZn(x; y), where cn are the Zernike coefficients [2]. Therefore, different wavefront distortions can be described using the Zernike functions.

Here nonlinear indices of refraction values have been obtained by analyzing the variation of the fifth-order Zernike coefficients c5 that describe defocus as function of the sample position on the Z-scan setup. The method is demonstrated by measuring the nonlinear refractive index in CS2 and SiO2 as standard materials, using a 1 KHz repetition rate Ti-Sapphire laser delivering 100 fs pulses.

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[2]. D. Malacara, “Optical Shop testing”, 2nd Ed. John Wiley & Sons, NY (1992).

7582-43, Session 10

The physical basis and modeling of Cr4+-based saturable absorbers

Y. Y. Kalisky, Nuclear Research Ctr. Negev (Israel); O. Kalisky, Jerusalem College of Technology (Israel)

This review provides an overview on the physical properties of Cr4+ doped solids as saturable absorbers. We shall review the spectroscopic concepts, spectral properties, structural characteristics and the experimental determination of some physical parameters of Cr4+ -doped various solids. The role of several Cr4+-doped garnets as saturable absorbers in various Nd and Yb doped diode-pumped systems will be discussed. We shall focus on the understanding the physics of saturation process in saturable absorbers, in order to improve their efficient utilization. Several passively Q-switched systems and their current applications will be discussed.

7582-44, Session 10

Comparison of nonlinear absorption and carrier recombination times in GaAs grown by hydride vapor phase epitaxy and Bridgman processes

L. P. Gonzalez, A. K. Carpenter, J. M. Murray, Air Force Research Lab. (United States); K. T. Zawilski, P. G. Schunemann, BAE Systems (United States); S. Guha, Air Force Research Lab. (United States)

Nonlinear absorption at the pump wavelength imposes a limitation in high power frequency conversion. In this work we study nonlinear absorption (NLA) in GaAs crystals fabricated using different methods. Orientation patterned GaAs (OP-GaAs) is a promising second order nonlinear optical material being developed for frequency mixing applications. One method of growing OP-GaAs is Hydride Vapor Phase Epitaxy (HVPE) in which GaAs is formed by reacting hot gaseous GaCl with Arsine (AsH3). Since HVPE is fast compared to other epitaxial growth processes, with growth rates exceeding 100 µm per hour, it can be used to grow crystals greater than 1 mm in thickness. The traditional way of growing thick GaAs crystals is the Bridgman technique of slow cooling of a melt.

A 760 µm thick GaAs crystal was grown using HVPE. Transmission spectrum of this sample showed minimal absorption for light having photon energy just lower than the bandgap energy, (i.e., at wavelengths near 1 um) indicating the absence of the EL2 defects commonly found in Bridgman grown samples. Irradiance dependent absorption measured at 1.535 µm using 100 nanosecond duration laser pulses showed increased NLA in the HVPE grown GaAs compared to samples grown by the Bridgman method. The dominant NLA process in both samples was absorption due to free carriers generated by two-photon absorption. Compared to Bridgman samples, the HVPE grown GaAs sample showed greater NLA due to longer carrier lifetimes, as indicated by the temporal shape of the nonlinearly absorbed laser pulse. Carrier lifetime measurements using a pump probe technique to confirm this result will be presented.

7582-45, Session 10

Efficiency of a one-phonon Bragg anomalous light scattering in tellurium dioxide single crystal with variously polarized incident light of visible range

A. S. Shcherbakov, D. Sanchez, S. E. Balderas, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

We determine the effective photo-elastic constants peculiar to a one-phonon Bragg anomalous light scattering in a tellurium dioxide cell oriented along the [001]- and [110]-axes when the slowest shear elastic mode was used for producing the dynamic diffractive grating. Due to an extremely specific anisotropy of this crystal, the efficiency of light scattering depends significantly on the ellipticity of the incident light polarization and on the direction of polarization vector rotation. The efficiency can increase by about two times when the state of polarization varies from linear one to the needed eigen-state of elliptic polarization, which is determined by the angle of beam incidence, optical wavelength, and accuracy of orienting the crystalline cell relative to the crystallographic axes. With the optimal coinciding of an external light polarization with the corresponding eigen-state in tellurium dioxide, the relative efficiency of light scattering by acoustic wave can reach a level being one of the highest known at this moment in anisotropic solid states. The analysis and numerical simulations are formulated in terms of the eigen-vectors for light modes in anisotropic medium and take into account the effect of optical activity in tellurium dioxide, which is principally significant for realizing a wide-band non-collinear anomalous acousto-optical interaction in this crystal. Our analysis is devoted to estimating and comparing the effective photo-elastic constants inherent in various regimes and directed to performing the acousto-optical cells with improved performance data. Then, the theoretical data are considered in connection with the obtained experimental results on a one-phonon Bragg anomalous light scattering.

7582-46, Session 10

One- and two-photon pumped soft lithographed DFB laser systems based on semiconductor core-shell quantum dots

I. Fortunati, S. Gardin, F. Todescato, R. Signorini, R. Bozio, Univ. degli Studi di Padova (Italy); J. Jasieniak, Commonwealth Scientific and Industrial Research Organisation (Australia); A. Martucci, G. Della Giustina, G. Brusatin, M. Guglielmi, Univ. degli Studi di Padova (Italy)

In the last years inorganic semiconductor (particularly CdSe and CdS) quantum dots (QDs) have received great attention for their important optical properties. These systems are characterized by 3D-nanoscale dimensions (R < 10 nm), corresponding to a strong confinement effect well defined when their dimensions are comparable or below the exciton Bohr radius. As the QD size decreases, the energy gap between the conduction and the valence bands increases, leading to a blue-shift of the emission band. In particular, the great possibility to tune the emission wavelength, together with their high fluorescence quantum efficiency and photostability, can be exploited in photonic and optoelectronic technological applications.

Pumping QDs into high-energy excited states, the population inversion and the build-up of optical gain is allowed giving the Amplified Spontaneous Emission (ASE) process. The main condition to be satisfied in order to maximize the optical gain is related to the relaxation down to the ground state: it should be faster than the Auger process time, so the competition between radiative and nonradiative processes is favourable to the former. In QDs, nonradiative carrier losses are dominated by surface trapping and multiparticle Auger relaxation. It is therefore fundamental to carefully control the surface quality of the semiconductor nanocrystals.

The design of DFB devices, based on QDs as active optical material, leads to the realization of compact laser systems.

In this work the distributed feedback (DFB) systems studied are based on CdSe-ZnS core-shell quantum dots dispersed in sol-gel matrix. The DFB pattern has been realized by imprinting or electron beam lithography on sol-gel films properly optimized. The final devices are characterized by one- and two-photon excitation, in a femtosecond regime. From experimental data the value of the optical gain of the core-shell quantum dot samples has been estimated. Moreover, one- and two-photon lasing threshold and stability are reported.

7582-47, Session 10

Nonlinear optical properties of colloidal Au and Ag nanoparticles dispersed in ionic liquids

M. A. R. C. Alencar, C. E. A. Santos, Univ. Federal de Alagoas (Brazil); L. F. Oliveira, C. W. Scheeren, J. Dupont, Univ. Federal do Rio Grande do Sul (Brazil); J. M. Hickmann, Univ. Federal de Alagoas (Brazil)

In recent years, the optical properties of different colloidal systems have been investigated aiming their applications in the development of optical and photonic devices. In particular, organo-metallic hybrid systems are among promising materials. In these materials there is a possibility to enhance the nonlinear response of organic liquids (OLs) exploiting the plasmonic effects associated with the metallic nanoparticles (MNP). However, many OLs with good optical response present undesirable chemical-physical properties, such as high volatility and low chemical stability under optical excitation, which are serious drawbacks for the development of any practical devices. Recently, we have investigated the nonlinear optical properties of ionic liquids [1]. These materials present an ionic-covalent molecular structure and different molecular architectures, low melting point, negligible vapor pressure, excellent thermal and chemical stability. Such desirable properties suggest that they can be very interesting systems to the development of hybrid media aiming applications in optics and photonics. In this work, we report on the investigation of the third-order nonlinear response of colloids consisting of Au and Ag nanoparticles dispersed in BMI.BF4 and BMI.PF6 ionic liquids respectively. Using the Z-scan technique with a femtosecond laser, large values of n2 were observed for both colloidal systems even for low filling factors (FF). Our results indicate that these new hybrid systems are promising materials to be exploited in the development of ultra-fast nonlinear optical applications.

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7582-48, Session 10

Synthesis and optical limiting characteristics of TiO2@SiO2 core-shell nanoparticles

K. Rahulan, G. Vinitha, P. Aruna, S. Ganesan, Anna Univ. (India)

Anatase-type TiO2 Nanoparticles were synthesized by hydrothermal method at 180°C from TiOSO4 aqueous solution with1m/lit concentration, which was then annealed at 700°C. The products were coated with silica by means of a seeded polymerization technique with a coating time of 1440 minutes to obtain well defined TiO2@SiO2 core-shell structure. The uncoated and coated nanoparticles were characterized by using UV-Vis Diffuse Reflectance Spectroscopy (UV-DRS), High Resolution Transmission Electron Microscopy (HR-TEM), X-Ray diffraction (XRD), Differential Scanning Calorimetry (DSC), TGA/DTA and Fourier Transform Infrared Spectroscopy (FT-IR). The shape, size and silica shell formation of the resultant particles were investigated by HRTEM and FTIR. The existence of Ti-O-Si chemical bonding at the interface between the silica coating layer and titania particle surface was confirmed from the FTIR results. The non linear optical limiting properties of TiO2 and TiO2@SiO2 nanoparticles dispersed in ethylene glycol were studied at 532nm using 5ns Nd:YAG laser pulses. Strong two photon absorption along with excited state absorption is responsible for good optical limiting characteristics in these nanoparticles and it is seen that the optical nonlinearity is enhanced in core-shell structures when compared with single counterparts. Experiments also show that oxide-protected nanoparticles are good optical limiters in the nanosecond regime.

Conference 7583: High-Power Diode Laser Technology and Applications VIII

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7583-01, Session 1

Reliability of high-performance 9xx-nm single emitter laser diodes

L. Bao, J. Wang, M. A. Devito, D. Xu, D. Wise, P. O. Leisher, M. Grimshaw, W. Dong, S. Zhang, K. Price, D. Li, C. Bai, S. Patterson, R. J. Martinsen, nLIGHT Corp. (United States)

This paper demonstrates reliable high power and high brightness 9xx nm single emitter laser diodes with a super large optical cavity (SLOC) structure, which have been specially designed for various multi-emitter fiber-coupled modules.

In order to reduce cost and satisfy more stringent reliability requirements in modules, single emitter lasers need to demonstrate less than 1 kFIT rate. Our 3.0mm laser-cavity laser devices have been being life-tested with currents up to 14A at 50°C/80°C heat-sink/junction temperatures and have accumulated more than 12000 hours of life-test duration. This has yielded sub-kFIT rate, with 90% confidence, at 8W and 33°C/52°C heat-sink/junction temperatures.

In order to further improve operational power and optimize beam quality, devices with 3.8mm cavity length have also been developed. The 3.8mm cavity length devices demonstrated more than 20W CW rollover power without catastrophic optical mirror damage (COMD). The device's near-field/far-field patterns have also been improved significantly. In addition to step-stress life-test, a multi-cell life-test was designed to ascertain acceleration factors relative to operation condition. Junction temperatures ranging from 60°C to110°C and current from 14A to 18A were used in this multi-cell life-test. Statistical analysis has been conducted, with models and collected results presented in detail. Ongoing multi-cell life-test data supports less than 1 kFIT, with 90% confidence, at 10W, 33°C/50°C heat-sink/junction temperatures. Fiber-coupled modules have demonstrated with >180W output power, from 100µm diameter fiber cores. The failure modes of 9xx nm devices are also studied extensively using various techniques.

7583-02, Session 1

Highly reliable 637-639 nm red high-power LDs for displays

T. Nishida, T. Yagi, N. Shimada, K. Ono, A. Shima, Mitsubishi Electric Corp. (Japan)

Red color high power LDs have gathered attentions for laser display applications, and shorter wavelength is required because of luminosity factor. Plural institutes have tried to realize short wavelength red high power LDs around 640nm. To the best of our knowledge, highly reliable operation at high temperature has not been demonstrated. In this paper, we demonstrate a highly reliable 637 nm broad area single emitter and a 639 nm array. In Red LDs, temperature characteristics become worse as lasing wavelength shortens. This is due to carrier overflow because of small energy difference of conduction band. We adopted not only a highly doped AlInP cladding for carrier overflow reduction, but also revised design for low quasi Fermi level and small internal loss. A single emitter and an array with 20 emitters have the same structure except the cavity length (the former of 1.0mm and the latter 1.5mm). Each emitter size is 40 um. The single emitter is assembled on the package with thermal resistance of 30 K/W and the array on 2 K/W. The single emitter lases at 637 nm at 25C, 300mW. 300mW CW aging test of the LDs was performed at 70C (junction temperature). The LDs show very stable operation over 1400 hrs. Extrapolated failure time of the LDs (20% power down) is 10 K hrs under the condition. The array emits 639 nm light at 8W, 25C. Aging at 8W CW with junction temperature of 50 C also shows extremely stable operation, suggesting lifetime of 130 K hrs.

7583-03, Session 1

Reliability of high-power QCW arrays

R. Feeler, J. Junghans, J. Remley, E. F. Stephens, Northrop Grumman Cutting Edge Optronics (United States)

Northrop Grumman Cutting Edge Optronics has developed a family of arrays for high-power QCW operation. These arrays are built using CTE-matched heat sinks and hard solder in order to maximize the reliability of the devices.

A summary of recent life tests is presented in order to quantify the reliability of QCW arrays as a function of a number of input variables. Lifetime data is presented as a function of drive current (ranging from 70 to 300 Amperes), repetition rate (10 Hz to 1 kHz) and pulse width (50 µs to 3 ms) for a number of output wavelengths. Many of the tests were targeted at particular solid-state laser pumping applications. Examples include Nd:YAG (80X and 88X nm, 150 µs pulse widths) and Yb:YAG (940 nm, 1-3 ms pulse widths).

A statistical analysis of the raw lifetime data is presented in order to quantify the data in such a way that is useful for laser system designers. The appropriate statistic (MTTF or MTBF, depending on array type) is presented as a function of a number of drive conditions.

The life tests demonstrate the high level of reliability of these arrays in a number of operating regimes. Expected lifetimes in excess of 10 billion shots are observed in many regimes, illustrating the suitability of these arrays for a variety of industrial applications.

7583-04, Session 1

Reliability and performance of 808-nm single emitter multi-mode laser diodes

J. Wang, L. Bao, M. A. Devito, D. Xu, D. Wise, M. Grimshaw, W. Dong, S. Zhang, C. Bai, P. O. Leisher, D. Li, H. Zhou, S. Patterson, R. J. Martinsen, nLIGHT Corp. (United States)

Various 808nm structures have been developed for applications such as solid state pumping, laser marking and material processing. Commercial 808nm single emitter lasers, with 200µm wide emitters and a large optical cavity (LOC) structure, have demonstrated good reliability and high operating power in various packages. Diodes soldered to AlN submounts have shown 2000 FIT for 6.5W and 33ºC heatsink operation for fiber coupled modules. C-mounts and CN mounts have been rated up to 10W for various commercial applications. In order to improve operational power and reliability further a high efficiency super large optical cavity (SLOC) laser structure has been developed. The new SLOC devices have shown higher efficiency and higher CW peak power than previous designs. Accelerated life testing at 12A, 50°C heatsink temperatures has been ongoing. With a test duration of more than 4000 hours collected to date, 1300 FIT has been calculated for devices operating at 6.5W and 33°C heasink temperature. Presently, no devices have shown catastrophic optical mirror damage (COMD). When the devices were re-tested after 2500 hours of lifetest under the accelerated conditions, devices retain rollover powers near 25W under CW conditions. No COMD is evident even with repeated roll-over iterations. In addition, this paper will also discuss lifetest failure modes for different structures and paths for reliability improvement.

7583-05, Session 1

Reliable operation of 8xx mini-bar-based hermetic modules

X. Jin, E. Wolak, Oclaro, Inc. (United States)

Fiber combination of multiple 9xx pump modules for fiber lasers has enabled power scaling with the thermal and reliability advantages of distributed architectures. In this work we show that mini-bar-based 8xx products show the reliability characteristics of independent emitter dropout and "non-degrading" drift plots similar to those of their 9xx counterparts. This fact is in part an outcome of the bonding process together with the heat-sink design. Multi-cell life testing confirms reliable operation of compact, fiber-coupled modules (200-um-diameter, 0.17 NA) at 25 W and 808 nm, with 35W at 880 nm.

7583-06, Session 1

Root cause investigation of catastrophic degradation in high-power multi-mode InGaAs-AlGaAs strained quantum well lasers

Y. Sin, N. Ives, N. Presser, S. C. Moss, The Aerospace Corp. (United States)

Optimization of broad-area InGaAs-AlGaAs strained-quantum-well lasers has led to successful demonstration of high power and high efficient operation for industrial applications. State-of-the-art broad-area single emitters show an optical output power of over 20W and a power conversion efficiency of over 70% under CW operation. However, understanding of long-term reliability and degradation process of these devices is still poor. This paper investigates root causes of catastrophic degradation in broad-area lasers by performing accelerated lifetests of these devices and failure mode analyses of degraded devices using various techniques.

We investigated MOCVD-grown broad-area strained InGaAs-AlGaAs single QW lasers at ~975 nm. Our study included both passivated and unpassivated broad-area lasers that yielded catastrophic failures at the facet and also in the bulk. Our accelerated lifetests generated failures at different stages of degradation by forcing them to reach a preset drop in optical output power. Deep-level-transient-spectroscopy (DLTS) was employed to study deep traps in degraded devices. Trap densities and capture cross-sections were estimated from a series of degraded devices to understand the role that point defects and extended defects play in degradation processes via recombination enhanced defect reaction. Electron-beam-induced-current (EBIC) was employed to find correlation between dark line defects in degraded lasers and test stress conditions. Time-resolved electroluminescence (EL) was employed to study formation and progression of dark spots and dark lines in real time to understand mechanisms leading to catastrophic facet and bulk degradation. Lastly, we will present our physics-of-failure-based model of catastrophic degradation processes in the broad-area lasers.

7583-07, Session 2

High-brightness fiber-coupled pump laser development

K. Price, S. R. Karlsen, P. O. Leisher, S. Patterson, R. J. Martinsen, nLIGHT Corp. (United States)

We report on the continued development of high brightness laser diode modules at nLIGHT Photonics. The module, based on nLIGHT's single emitter fiber coupled product platform, demonstrates continuing improvements in all key metrics to include output power, brightness, wavelength stabilization, and long wavelength performance. The unit is designed to couple diode laser light into a 105um fiber at an excitation NA of under 0.14. We demonstrate over 100W of optical power at 9xx nm with a diode brightness exceeding 20 MW/cm2-str and an operating efficiency of approximately 50%. Over 70W of optical power at 8xx nm is also demonstrated in a similar configuration, with a peak brilliance value of over 14 MW/cm2-str. Record brilliance at 14xx nm and longer will also be demonstrated. Finally, wavelength stabilized diodes at various pump wavelengths of 795, 885, 976, 1532, and 1910 nm will be shown. These results of high power, record brilliance, high efficiency, and wavelength stabilization demonstrate the pump technology required for next generation solid state, fiber lasers, and industrial laser systems.

7583-08, Session 2

Roadmap to low cost, high brightness diode laser power out of the fiber

D. Schröder, E. Werner, A. Franke, L. Wagner, G. F. Bonati, JENOPTIK Laserdiode GmbH (Germany); F. Dörfel, H. Ziemer, A. Liem, T. Gabler, JT Optical Engine GmbH + Co. KG (Germany)

Lasers for marking, direct application laser systems as well as high power solid state lasers require highly reliable, high efficient and low cost laser diodes. Especially fiber lasers and direct diode systems have additionally the need for high brightness.

For a very long time either single emitter solutions with low brightness and costs or beam shaped bar solutions with high brightness and high costs served those need.

Since roughly 2 years multiple single emitter solution are more and more penetrating the market showing a high potentiel for serving all needs of a broad customer base.

Based on the 50W product introduced mid of 2009 we like to show the design which is based on qualified and highly stable single emitters.

Utilizing bar shaping like technologies, a productions optimized optical setup and state of the art automation equipment me like to draft the way to get closer to the sorcerers stone of getting a high brightness at very low costs.

7583-09, Session 2

High-brightness 9XX-nm pumps with wavelength stabilization

A. Ovtchinnikov, V. P. Gapontsev, N. Moshegov, P. A. Trubenko, A. Komissarov, I. E. Berishev, N. Strougov, V. V. Chuyanov, O. Raisky, O. Maksimov, L. Wright, G. A. Ellis, IPG Photonics Corp. (United States)

We report on two high-brightness CW devices: high-power module launching over 100W and 25W wavelength-stabilized pump. Devices are based on single emitter platform and utilize 105 um core diameter fiber; radiation is confined within NA<0.12 in both designs. These hermetically sealed modules require passive cooling and were designed to operate with ≤ 30°C diodes' junction overheat. CW peak power efficiency is as high as 60% and 55% for 100W and 25W devices, correspondingly. The 25-30dB isolation option (feedback protection at 10XX-nm) is available in either package. Modules have industry smallest footprint and are perfectly suited to serve pumping fiber lasers and direct materials processing markets.

7583-10, Session 2

Dramatic advances in direct diode lasers

D. L. Havrilla, TRUMPF Inc. (United States); R. Brockmann, S. G. Strohmaier, TRUMPF Laser GmbH & Co. KG (Germany)

Until now, diode laser concepts were used in applications in the multi-kilowatt range, in which actively cooled diode bars were used and combined via stacking. Per diode stack, laser outputs of just over a kilowatt can be achieved. If outputs of several kilowatts are to be

achieved, a number of stacks must be coupled with each other. A multi-kilowatt laser with industrially useful beam quality can only be realized through appropriate procedures such as wavelength coupling. The beam quality of the coupled stacks corresponds to the quality of the individual stacks. If the beam quality of such systems is pushed to the limit of the feasible, this reduces the efficiency of the total system considerably.

Today, such conventional fiber delivered diode lasers with a beam quality of about 100 mm*mrad achieve an outstanding efficiency of about 40%, but can only be used for laser soldering or other surface processing. If the beam quality is improved to about 40 mm*mrad, the efficiency falls to about 32%. In order to tap all the efficiency advantages of direct application of diode lasers and further improve the beam quality, TRUMPF has implemented a new concept in its direct diode lasers of the TruDiode series. The basis of this concept is the use of a fiber-coupled and passively cooled diode module with previously unachieved technical output characteristics. This paper will highlight those characteristics, as well as provide technical details of the TruDiode series, extremely low running cost and associated application fields.

7583-11, Session 3

High duty cycle hard soldered kilowatt laser diode arrays

G. Klumel, Y. Karni, Y. Oppenheim, Y. Berk, M. Shamay, R. Tessler, SCD Semiconductor Devices (Israel)

High brightness laser diode arrays operating at duty cycle of 10-20% are increasingly needed for optical pumping of solid state lasers and for direct applications. In this range of duty cycling, the passive (conductive) cooling is of a limited use, while micro coolers with de-ionized cooling water seriously degrade the reliability of such laser diode arrays .

When designing and developing such laser diode arrays three main problems should be carefully addressed: effective local and overall heat removal, minimization the package induced and operational stresses as well as precise and accurate fast axis collimation.

In this article a novel laser diode array including a built in tap water cooling system, all hard solder bonding, passivated high power 940 nm laser bars and fast axis tight collimation, is presented.

It is shown that that original design of water cooling channels, proper selection of package materials, careful design of fatigue sensitive parts and active collimation technique allow to reach long life time and reliability, without compromising the laser diode array efficiency, optical power density, brightness and compactness.

Among the main performance parameters are: 150W/bar optical peak power at 10% duty cycle, >50% wall plug efficiency and <1˚ fast axis divergence. The lifetime of >0.5 Ghots at less than 10% degradation was experimentally proven.

The laser diode arrays were also successfully tested at harsh environmental conditions, like thermal cycling of the coolant temperature between -20 °C and 40 °C at rate of 15 °C/min and mechanical shocks at 500g acceleration .

The results of both performance and reliability testing confirm the effectiveness and robustness of the discussed solution for high duty cycle devices.

7583-12, Session 3

Micro-optic solutions for beam formation of individually addressable high-power single-mode diode laser arrays

M. Forrer, D. Kura, E. Langenbach, FISBA OPTIK AG (Switzerland)

The solution presented consists of innovative and high precision micro optics lenses and assembly procedures for Fast Axis Lens and Slow Axis Lens Array. Single mode beam formation is critical for the industrial application and has to be costeffective in production and assembly.

The integration of the solution to application of computer to plate printing has proven most successful and is the basis for a continued interest in this field.

7583-13, Session 3

KW-class industrial diode lasers comprised of single emitters

K. Price, nLIGHT Corp. (United States); F. Pfeffer, OptoTools Gmbh (United States); P. O. Leisher, S. R. Karlsen, S. Patterson, R. J. Martinsen, nLIGHT Corp. (United States)

Direct semiconductor diode laser-based systems have emerged as the preferred tool to address a wide range of material processing, solid-state and fiber laser pumping, and various military applications. We present an architectural framework and prototype results for kW-class laser tools based on single emitters that addresses a range of output powers (500W to multiple kW) and beam parameter products (20 to 100 mm-mrad) in a system with an operating efficiency near 50%. nLIGHT uses a variety of building blocks for these systems: a 100W, 105um, 0.14 NA pump module at 9xx nm; a 600W, 30 mm-mrad single wavelength, single polarization building block source; and a 140 W 20 mm-mrad low-cost module. The building block is selected to realize the brightness and cost targets necessary for the application. We also show how efficiency and reliability can be engineered to minimize operating and service costs while maximizing system up-time. Additionally we show the flexibility of this system by demonstrating systems at 8xx, 9xx, and 15xx nm. Finally, we investigate the diode reliability, FIT rate requirements, and package impact on system reliability.

7583-14, Session 3

High-power diode laser modules from 630 nm to 2200 nm

B. Köhler, H. Kissel, M. Flament, P. Zolichowski, M. Haag, T. Brand, J. Biesenbach, DILAS Diodenlaser GmbH (Germany)

We report on high-power diode laser modules covering a wide spectral range from 630 nm to 2200 nm.

Driven by improvements in the technology of diode laser bars with non-standard wavelengths, such systems are finding a growing number of applications. Fields of application that benefit from these developments are direct medical applications, printing industry, defense technology, polymer welding and pumping of solid-sate lasers.

Diode laser bars with standard wavelengths from 800 - 1000 nm are based on InGaAlAs, InGaAlP, GaAsP or InGaAs semiconductor material with an optical power of more than 100 W per bar. For shorter wavelengths from 630 - 690 nm InGaAlP semiconductor material is used with an optical power of about 5 W per bar. Extending the wavelength range beyond 1100 nm is realized by using InGaAs on InP substrates or with InAs quantum dots embedded in GaAs for wavelengths up to 1320 nm and (AlGaIn)(AsSb) for wavelengths up to 2200 nm. In these wavelength ranges the output power per bar is about 6 - 20 W.

We will present a detailed characterization of these diode laser bars, including measurements of power, spectral data and life time data. In addition, we will show different fiber coupled modules, ranging from 630 nm with 6 W output power (400 µm fibre, NA 0.22) up to 1940 nm with more than 50 W output power (600 µm fibre NA 0.22).

7583-15, Session 3

Fiber coupling of high-power diode laser stack for direct polycarbonate processing

E. Vidal, Tekniker (Spain) and MONOCROM S.L. (Spain); D. Otaduy, I. Quintana, Tekniker (Spain); E. Mendez, G. Viera, M. Galán, MONOCROM S.L. (Spain)

We present a novel optical system for fiber coupling of a commercial high power diode laser stack and the application of this laser system to transmission welding of engineering thermoplastics. The diode laser stack is made up of two 20% fill factor bars, emitting at 808 nm and with a total maximum output power of 120W CW. The stack was collimated using FSAC micro-optics lenses in the fast and slow axis, with a full angle divergence of <4mrad and <25mrad respectively. The optical design and simulations were carried out using ZEMAX®. Based on the design we built an optical set up, which is divided in two subsystems. The first one collimates the laser beam in order to achieve the best focus and couple it into the 400µm core fiber with NA0.22 and 70% efficiency. The second subsystem is designed for beam conformation after the fiber output, using collimation and beam shaping to have a Gaussian beam profile on the work piece. The laser system was applied to study the welding of polycarbonate plastics, based on the effects of selected welding parameters on the seam geometry and surface integrity. The quality of the spot welding has been analyzed obtaining welded seams with a mean diameter about 500-600µm, preserving the good technological properties of the thermoplastic considered in this work. The results show that we have successfully developed a novel laser system which is highly efficient for thermoplastics processing.

7583-16, Session 4

Expansion matched heat sinks made by micro-metal injection molding

M. Leers, E. Liermann, Fraunhofer-Institut für Lasertechnik (Germany); P. Imgrund, L. Kramer, J. Volkert, Fraunhofer-Institut für Fertigungstechnik Materialforschung (Germany)

There is an ongoing and increasing interest in using expansion matched micro-channel heat sinks for high-power diode laser bars. In this new approach the heat sinks are produced by µ-metal injection molding (µ-MIM). Unlike conventional heat sinks which are made of copper, these particular heat sinks are made of copper-tungsten because of it combination of low coefficient of thermal expansion (CTE) and reasonable thermal conductivity. Manufacturing heat sinks with the µ-MIM process allows for an economic mass production of complex micro near net shape parts. Especially when manufacturing over 1000 parts with the µ-MIM process, manufacturing costs per part reduce considerably. The main goal is to use the opportunities µ-MIM offers. That means producing complex parts, which have a matched CTE in this case to gallium arsenide (GaAs). Therefore a material which combines good thermal conductivity behavior with a low coefficient of thermal expansion is needed. And an additional advantage of the µ-MIM process is that the needed green bodies of the heat sink can be joint together in a co-sintering process.

In this paper the current status of production of heat sinks with micro¬structured surfaces by µ-MIM for thermal management applications are presented. The range of operation and the limitations are outlined with special concern regarding the materials and the minimal structure size. The implication and advantages of using ultrafine powders are emphasized. Therefore sintering behavior, microstructure of sintered parts and characteristic properties as density, CTE, thermal conductivity and electro-optical characterization are shown.

7583-17, Session 4

Simple method for modeling thermoelectric cooler (TEC) performance of single-emitter semiconductor-laser packages with concentrated heat sources

J. Du, M. Au, L. Zavala, P. Yalamanchili, J. A. Skidmore, E. P. Zucker, JDSU (United States)

High-power single-emitter semiconductor lasers may dissipate up to several Watts heat load during operation. The heat may be generated from a narrow stripe, as low as a few microns in width by several millimeters in length. Thermoelectric Coolers (TEC) are widely deployed to control the laser junction temperature in single-emitter semiconductor-laser packages. TEC manufacturers supply performance curves under the assumption of uniform heat load applied to the cold plate. In reality, the heat will spread laterally across the cold plate creating a temperature gradient across the couples. Consequently, the actual performance of the TEC may be significantly degraded as compared to that predicted from the manufacturer's guidelines. A quantitative analysis that includes these deviations is necessary to properly size the TEC and optimize the package design. This paper provides a simple method for modeling the TEC performance parameters on concentrated heat loads using commercially-available FEA software. Experimental data of TEC cooled single-emitter laser packages will also be presented that corroborate the results of our model.

7583-18, Session 4

Alternatives to copper microchannel coolers for high-powered laser diode arrays

R. Feeler, J. Junghans, E. F. Stephens, Northrop Grumman Cutting Edge Optronics (United States)

Laser diode arrays based on copper microchannel coolers have become standard in the industry due to the coolers' ability to extract large amounts of waste heat. However, copper coolers have several fundamental problems that limit their usefulness in fielded systems. These problems range from erosion/corrosion issues to the need for deionized cooling fluids. Northrop Grumman Cutting Edge Optronics has developed three packaging solutions that eliminate the need for copper microchannel coolers.

For high-power applications (> 80 Watts/bar), NGCEO has developed microchannel coolers based on a ceramic material set. These coolers offer excellent thermal performance without the need for deionized cooling fluids. The results of several life tests in excess of 3000 hours are presented to demonstrate the validity of this approach for industrial, military, and scientific applications. These devices exhibit minimal power degradation and no erosion or corrosion of the internal cooling structure.

Also presented are results from two other designs that address mid- to low-power applications (< 80 Watts/bar) that require tight pitches that were previously possible only with copper microchannel coolers. The first design is a stacked array with 1.7 mm pitch based on a highly-efficient backplane cooler that is electrically isolated from the diode bars, thereby allowing it to utilize standard filtered water (not deionized) as the cooling fluid. The thermal performance of this package is compared to that of a copper MCC stack, and preliminary life test data is also presented.

Additionally, a novel conductively-cooled vertical stack with a 1.7 mm pitch is also presented. Output powers in excess of 400 Watts for a 6-bar stack are presented for a fast-axis lensed stack that has approximately the same size footprint as a standard Cs package. Thermal resistance data is presented and found to be comparable to other industry-standard packages. This demonstrates the validity of this approach as a low-cost MCC replacement that does not require deionized water.

7583-19, Session 4

Progress in the development of active heat sink for high-power laser diodes

J. Vetrovec, Aqwest (United States)

High-power diode bars are typically mounted on stackable microchannel heat exchangers cooled by water. High water flow rates (typically 0.4 liters/minute/bar) are required to obtain appropriate cooling of the bars. In many applications, the associated water supply system adds undesirable complexity, size, and weight. Alternatively, diode bars are mounted on passive heat sinks that conduct diode waste heat to structures, air, or water. However, traditional passive heat sinks and heat spreaders have a significant thermal impedance, large thermal inertia, and are not conducive to accurate temperature control under varying operating or ambient conditions.

We have previously introduced an innovative active (quasi-passive) heat sink for high-power laser diodes offering unparalleled capacity in high-heat flux handling and temperature control [1]. The heat sink receives diode waste heat at high flux and transfers it at reduced flux to environment, coolant fluid (e.g., air), heat pipe, or structure. Thermal conductance of the heat sink can be electronically adjusted, which allows for precise control of diode temperature and the diode light wavelength. In particular, when pumping solid-state or alkaline vapor lasers, diode wavelength can be precisely tuned to the absorption features of the laser gain medium.

This paper presents the active heat sink theory, scaling laws, model predictions, and data from initial testing. This work was in-part funded by the US Department of Energy and by the US Air Force.

1. J. Vetrovec, “Quasi-passive heat sink for high-power laser diodes,” SPIE vol. 7198-12.

7583-20, Session 5

Recent development of high-power-efficiency 808-nm diode laser bar at Lasertel

L. Fan, C. Cao, I. Ai, B. Caliva, L. Zeng, P. Thiagarajan, M. McElhinney, Lasertel, Inc. (United States)

This paper gives an overview of recent development of high-efficiency 50-W CW 808-nm diode laser bar at Lasertel. Focused development of device design and MBE growth processes has yielded significant improvement in power conversion efficiency (PCE) of 50-W CW 808-nm laser bar. We have achieved CW wallplug efficiencies of 67% to 64% at heat-sink temperature of 5 oC and 25 oC, respectively. Life-testing indicates that the reliable powers of devices based on the new developments exceed those of established, highly reliable, production designs.

7583-21, Session 5

Extending the wavelength range in Oclaros high-brightness broad area modules

S. Pawlik, A. Guarino, B. N. Sverdlov, J. Müller, C. Button, S. Arlt, D. Jaeggi, N. Lichtenstein, Oclaro, Inc. (Switzerland)

Within the last years the performance for high power pump modules in the 9xx wavelength range improved significantly. More than 10 W light output power from a single emitter module with a 105 um fiber is now a standard.

Recently the demand for high power laser diodes modules in a shorter wavelength range grew continuously.

The progress in the eye safe fiber lasers requires reliable pumps at 793 nm, modules at 808 nm are used for small size DPSSL applications and fiber-coupled laser sources at 830 nm are widely used in the printing industry. So far the power levels achieved in this wavelength range are still lower than for 9xx nm.

We report on the approaches to increase the reliable output power in our latest generation of high power pump modules in the wavelength range between 780 and 890 nm. The 793 nm single emitter deliver more than 10 W of output power from a 100 µm wide stripe in CW mode with wall plug efficiency as high as 58 %. For 808 nm devices excellent long-term stability has been proven for power levels ~6 W per 100 µm of active area width in a multi cell life test. At 830 nm, first life test results indicate the reliable operation of ~7 W per 100 µm stripe width. The output power can be scaled dependent on the fiber core required in the application. Further increase of output power can be achieved by using the same devices in module designs with more complex coupling schemes.

7583-22, Session 5

975-nm high-power broad area diode lasers optimized for narrow spectral linewidth applications

P. A. Crump, C. Schultz, A. Pietrzak, M. Spreemann, S. Knigge, O. Brox, A. Maasdorf, F. Bugge, G. Erbert, Ferdinand-Braun-Institut für Höchstfrequenztechnik (Germany)

975nm broad area diode lasers with stripe widths in the 90-100 µm range are commercially important as pumps for Yb-doped fiber lasers, as well as for direct applications. The ideal source would have high power conversion efficiency at high power, narrow far field and narrow spectral width. Two parallel technical approaches were investigated. Firstly, sources were optimised for external stabilization with Volume Bragg Gratings, where narrow far fields are sought for low cost optical assembly. Progress to date has enabled sources with measured full width half maximum (FWHM) vertical and lateral far field angles of 15° and 6.5° respectively (30° x 9.9° with 95% power content) at 7 W continuous wave operation power, with peak power conversion efficiency of 58%. Secondly, high performance broad area DFB lasers were investigated, constructed using buried gratings based on the FBH’s overgrowth technology. Here, we have developed 100µm stripe 975nm DFB lasers that operate with spectral width <0.35nm to 100°C. Narrow vertical far fields (14° FWHM, 39° with 95% power content) and reasonable peak conversion efficiencies (39.5%) were achieved. We detail the technological developments required to deliver these results and discuss the options for delivering further improvements in performance. This work was funded as part of the German Government (BMBF) development Project, SpektraLas (Project Reference Number 13N9725).

7583-23, Session 5

Mid-infrared high-power diode lasers and modules

M. T. Kelemen, J. Gilly, m2k-laser GmbH (Germany); M. Rattunde, J. Wagner, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany); S. Ahlert, J. Biesenbach, DILAS Diodenlaser GmbH (Germany)

High-power diode lasers in the mid-infrared wavelength range between 1.8µm and 2.3µm have emerged new possibilities for applications like processing and accelerated drying of materials, medical surgery or for pumping of solid-state and semiconductor disc lasers.

We will present results on MBE grown (AlGaIn)(AsSb) quantum-well diode laser single emitters with 90µm and 150µm emitter width. In addition laser bars with 20% or 30% fill factor have been processed. Whereas single emitters show output power up to 2W, 20W have been demonstrated from laser bars at 20°C heat sink temperature. More than 30% maximum wall-plug efficiency in cw operation for single emitters and laser bars has been reached. Even at 2200nm more than 15W have been demonstrated with a 30% fill factor bar.

Due to an increasing interest in pulsed operation modes for these mid-infrared lasers, we have investigated single emitters at 1870nm for different pulse times and duty cycles. More than 8W have been measured at 30A with 500ns pulse time and 1% duty cycle without COMD.

Most applications mentioned before need fiber coupled output power, therefore fiber coupled modules based on single emitters or laser bars have been developed. Single-emitter based modules show 600mW out of a 200µm core fiber with NA=0.22 at different wavelengths between 1870nm and 1940nm. At 2200nm an output power of 450mW ex fiber impressively demonstrates the potential of GaSb based diode lasers well beyond wavelengths of 2µm. Combining several laser bars, 20W out of a 600µm core fiber have been established at 1870nm.

7583-24, Session 5

High-temperature and high-peak-power 808-nm QCW bars and stacks

G. Bacchin, A. Fily, B. Qiu, D. Fraser, S. Robertson, V. Loyo-Maldonado, S. D. McDougall, B. E. Schmidt, Intense Ltd. (United Kingdom)

Applications of QCW bars and stacks, such as diode-pumping solid state lasers, require ever higher optical power density and higher operating temperature. In this paper, we present our latest development for high peak power 808 nm QCW bars and stacks operating reliably even at high temperatures.

808 nm QCW bars were fabricated by quantum well intermixing with a fill factor of 80% incorporating 76 emitters per bar. Cavity length and epitaxial design were optimised at 1.6 mm long active region. The bars were mounted with AuSn onto CuW spacers and then soldered with AgSn on BeO to form an H-mount device mounted on a Cu test fixture. At room temperature, reliable operation has been demonstrated yielding 400W at 400A per single 1-cm bar. The device has been tested at various pulse widths (up to 1.5 ms) and duty cycles. Both optical power and wavelength dependencies on the various operating conditions have been studied. More than 300W optical power at 400A has been demonstrated at temperatures on the Cu base as high as 95°C.

The same bars were mounted onto 10-bar G-stacks using AuSn hard solder technology. At room temperature, reliable operation has been demonstrated at 3kW at around 300A drive current. The device has been tested at various pulse widths and duty cycles. Both optical power and wavelength dependencies on the various conditions have been studied. High temperature operation has been demonstrated for temperature on the G-stack base as high as 95°C.

7583-25, Session 5

Eye safe high-power laser diode in the 1410-1550 nm range

J. Boucart, Oclaro, Inc. (Switzerland); B. de Largy, M. Q. Kearley, Oclaro, Inc. (United Kingdom); N. Lichtenstein, Oclaro, Inc. (Switzerland)

Oclaro has the experience of fabricating very reliable devices for telecommunication based on InP and high power high reliability lasers for industrial applications based on GaAs. Both technologies are now combined to realize high power devices such as single emitters, bars and modules (single- or multi-emitters) at 1435nm, 1470nm, 1532nm. We will present in this talk the most recent results on these devices.

Our 1470nm single emitter deliver more than 2.5W of output power in CW mode with wall plug efficiency as high as 38%. A length series was measured to extract internal parameters such as internal losses and internal efficiency of 3.6cm-1 and 74% respectively. Fiber coupled single emitter modules with a 105µm fiber core and 0.22NA have been built delivering more than 2W at 8A. Using the platform developed at Oclaro, multi-emitter modules will be built to obtain more than 10W coupled in the fiber. Initial reliability results show no degradation for more than 1000h at 6.5A despite the fact that no burn in was carried out prior to the lifetest.

Bars have been fabricated on the material emitting at 1470nm and assembled on CS Mount and on Microchannel coolers (MCC). The bars are formed by 19x90µm emitters with a fill factor of 18%. On passive we achieve powers higher than 20W and on MCC more than 30W in CW mode. Pulsed measurement (1µs pulse, 1%DC) allowed to measure more than 80W of output power. More devices are now fabricated to address 1532nm wavelength. Results on those bars will be presented at the conference.

7583-26, Session 6

High-power DFB laser diodes

W. Zeller, J. Koeth, nanoplus GmbH (Germany); M. Kamp, Julius-Maximilians-Univ. Würzburg (Germany)

Distributed feedback (DFB) laser diodes nowadays provide stable single mode emission for a high variety of applications in a wide wavelength range. A major drawback is the limited power due to catastrophical optical mirror damage (COD) caused by the small facet area. In the 980 nm wavelength range COD limits the output power of DFB lasers to typical values of 150 mW. For applications such as gas detection this is sufficiently high. Other applications however require a much higher output power. The standard way to improve the COD threshold of semiconductor laser diodes is passivation and coating of the mirror facets.

We developed a process that combines optimizations of the layer structure with a new lateral design of the ridge waveguide. By implementing a large optical cavity with the active layer positioned not in the middle of the waveguide layers but very close to the upper edge, the lasers' farfield angles can be drastically reduced. By tapering the width of the ridge waveguides situated above such a structure from about 2 µm to less than 0.5 µm at the laser facets, the travelling light mode can be pushed down into the large optical cavity, where it spreads over a much larger area. Consequently, the surface power density is reduced drastically, resulting in much higher COD thresholds. This concept is fully compatible with standard coating and passivation processes. We present DFB lasers based on this concept emitting at wavelengths around 980 nm yielding COD thresholds of more than 1.5 W.

7583-27, Session 6

Comparison of concepts for high-brightness diode lasers at 976 nm

J. Gilly, P. Friedmann, m2k-laser GmbH (Germany); H. Kissel, J. Biesenbach, DILAS Diodenlaser GmbH (Germany); M. T. Kelemen, m2k-laser GmbH (Germany)

Especially for fiber pump applications there is a strong demand for high-brightness diode lasers in the 10W power regime. Broad-area and tapered laser concepts seem to be the most promising candidates for high brightness, which is proportional to output power divided by beam quality. Within this talk we give a comparison of both concepts identifying the possibilities and limitations of both concepts.

Whereas fast axis far fields show mostly a current independent behaviour, for broad-area lasers near- and far-fields in the slow axis suffer from a strong current and temperature dependence, limiting the brightness. For tapered diode lasers the brightness is limited by the temperature characteristics of M2 and astigmatism. Therefore for both concepts it is essential to have lasers with excellent thermal management, which can be realized by 4-5mm long resonators in combination with wall-plug efficiencies well beyond 60%.

To fulfill these issues, we have realized MBE grown InGaAs/AlGaAs broad-area and tapered lasers with resonator lengths between 4mm and 5mm and 45° fast axis far field emitting at 976nm. For a 5mm long broad-area laser with 90µm stripe width a beam parameter product of less than 5.9 mm x mrad (M2<10) has been achieved at 10W with a slope efficiency of 1.1W/A and a maximum wall-plug efficiency of 65%. For a tapered laser with a taper angle of 4° and 5mm resonator length, 10W have been demonstrated with a slope efficiency of 1.05W/A and a maximum wall-plug efficiency of 56%. Beam quality is three times better than for a broad-area laser.

7583-28, Session 6

Scaling brilliance of high-power laser diodes

H. Koenig, G. Groenninger, C. Lauer, W. Reill, M. Arzberger, OSRAM Opto Semiconductors GmbH (Germany); H. Kissel, J. Biesenbach, DILAS Diodenlaser GmbH (Germany); A. Koesters, J. Malus, V. K. Krause, Laserline GmbH (Germany); U. Strauss, OSRAM Opto Semiconductors GmbH (Germany)

New direct diode laser systems and fibre lasers require brilliant fibre coupled laser diodes for efficient operation. We investigated several semiconductor laser designs with tailored beam parameter products, which were adapted for efficient fibre coupling. The investigations are part of the German project HEMILAS, which was funded by the German Federal Ministry of Education and Reseach.

In this paper we demonstrate results on 9xx and 1020nm bars suitable for coupling into 200µm fibres. With OSRAM's mirror technology and optimized epitaxial structure COD-free laser bars were fabricated with maximum efficiency above 66%. For short bars consisting of five 100µm wide emitters 75W CW maximum output power was reached. In QCW-mode up to 140W are demonstrated.

The 10% fill factor bars with 4mm cavity are mounted with hard solder. Lifetime tests in long pulse mode with 35W output power exceed 3000 hours of testing without degradation or spontaneous failures. Slow axis divergence stays below 7° up to power levels of 40W and is suitable for simple fibre coupling into 200µm NA 0.22 fibres with SAC and FAC lenses.

For fibre coupling based on beam rearrangement with step mirrors, bars with higher fill factor of 50% were fabricated and tested. The 4mm cavity short bars reach efficiencies above 60%. Lifetime tests at accelerated powers were started.

7583-29, Session 6

JENOPTIK diode lasers and bars optimized for high-power applications in the NIR range

R. Hülsewede, M. Zorn, H. Schulze, J. Sebastian, JENOPTIK Diode Lab GmbH (Germany); P. Hennig, D. Schröder, JENOPTIK Laserdiode GmbH (Germany)

The demand for competitive diode lasers and laser bars featuring high output powers at reasonable production costs drives the device development at JENOPTIK Diode Lab. A high efficiency reduces the costs for mounting and cooling and a high brightness increases the coupling efficiency. For an ideal optical coupling new diode laser arrays, half-bars and highest power bars have been developed. With their high brightness and small slow axis beam divergence the devices are well suited for various applications in industry and medicine.

Optimizing design, epitaxy, and processing leads to devices with a very good performance. Further adapting the filling factor to the coupling concept results in low-cost, high-efficient, and customer-oriented diode laser sources.

Latest high-performance device data in the wavelength range from 792 nm to 998 nm and with output powers of up to 300W will be presented.

7583-30, Session 7

High-brightness 635-nm tapered diode lasers with optimized index guiding

D. Feise, G. Blume, H. Dittrich, C. Kaspari, K. Paschke, G. Erbert, Ferdinand-Braun-Institut für Höchstfrequenztechnik (Germany)

High-brightness diode lasers emitting at 635 nm could serve as laser sources for a variety of display applications such as pocket projectors, Laser TVs, Lasershows, and projectors for virtual reality simulators.

Tapered diode lasers are the instrument of choice for such applications because they combine high optical output power with a good beam quality. They consist of two sections monolithically integrated into a single chip: an index-guided ridge waveguide (RW) section and a gain-guided tapered (TA) section. The RW section provides a beam with good beam quality, whereas the TA section amplifies the radiation.

We will present tapered diode lasers emitting near 635 nm. The lateral structure of these diode lasers is optimised through variation of several design parameters. The beam quality can be improved by adjusting the width of the RW as well as the length of the RW section. To improve the optical output power, the area of the TA section has to be enlarged. To optimise both, the beam quality as well as the output power, we fabricated devices in which the width of the RW and the length of the RW and TA sections are varied. All diode lasers were mounted p-side down with a common contact for both sections on a CVD-diamond heat spreader and soldered on C-mounts. Optimised tapered diode lasers provide 500 mW cw optical output power with a good beam quality of M2(1/e2) = 1.8. Maximum optical output power is 780 mW at 639 nm.

7583-31, Session 7

Characteristics of red-emitting broad area stripe laser diodes with zinc diffused window structures

T. Ohno, M. Takiguchi, K. Wakabayashi, H. Uchida, K. Naganuma, S. Ito, S. Hirata, Sony Corp. (Japan)

Catastrophic optical damage (COD) of a red-emitting broad area stripe laser diode (BALD) has been successfully suppressed by applying zinc diffused window mirror structures for the first time. The BALD consisting of a 60 um width stripe and a 1000 um length cavity is mounted junction-down to a heat-sink. The reflectance of the front facet is 15 % with an Al_2O_3 film and that of the rear facet covered by SiO_2 / TiO_2 films is 95 %. A lasing wavelength was about 640 nm, which is suitable for a red optical source in laser display systems. A maximum optical output power from the BALD was 1.5W at 25 degree C, which was limited by a thermal rollover. It is roughly twice the power of a conventional BALD limited by COD without the window structures. To estimate the COD level of the BALDs, the BALDs were operated by a 5 us pulsed current. We found that some of them were damaged at an output power of 5.5 W, which is four times as high as that in the conventional BALD. We should note that a top-hat shaped near field pattern was achieved in the BALD with the window structures. Long-term reliability of an array consisting of 25 emitters aged at an output power of 10W was investigated and remarkable improvement was observed.

7583-32, Session 8

Compact 500-W 200-um fiber-coupled module based on single emitters

S. R. Karlsen, K. Price, A. Brown, R. Mehl, S. Patterson, R. J. Martinsen, nLIGHT Corp. (United States)

We report on the development of a high power, high brightness, high efficiency, and easily configurable fiber coupled diode laser module as an addition to nLIGHT's PearlTM product line. This product is based on

multiple single emitters that are free-space coupled into a single fiber. This configuration leverages the advantages of single emitter diodes including high brightness sources, highest diode reliability, unsurpassed optical to optical efficiency, and the possibility for passive cooling. The compact module can be easily configured to support fiber sizes from 100um to greater than 400um diameter, at a range of different wavelengths and power levels. For 200um 0.22NA fiber it is capable of greater than 500W of cladding free laser output power at 976nm with an electrical to optical efficiency greater than 45%. With a 20mm-mrad beam quality, the module addresses needs in the fiber laser pumping and materials processing markets. In this paper we cover the diode laser requirements, the optical design principles, and the reliability requirements for system realization.

7583-33, Session 8

Demonstration of high pointing accuracy dual-axis collimation of 49 emitter diode bar using a laser-written custom phase-plate

N. Trela, Heriot-Watt Univ. (United Kingdom)

Previously we reported brightness restoration by a laser-written phase-plate technique used to correct the fast-axis collimation errors of diode laser bars. Recently, we extended the technique to combine fast-axis correction with slow-axis collimation (SAC) in a single element, here called a dual-axis phase-plate. A customized focal length lens array enables optimization of slow-axis fill-factor and is very beneficial with single-mode and tapered emitter bars, thus particularly attractive for brightness scaling experiments.

We applied the dual-axis phase-plate to a full-length Bookham diode bar, with 49 single mode emitters and 30W cw output at 975 nm. Fast-axis smile and lens error correction is combined with laser-cut 0.9mm focal length slow-axis lens to give highly parallel beams with 10/90 full-width far-field divergence of 2 mrad and 15.7 mrad in fast and slow-axis, respectively. A low value of the fast-axis RMS pointing error (3% of the far-field full-angle divergence) has been achieved. For the slow-axis direction, RMS pointing varies within 6% of far-field divergence.

The single-mode emitter bar allowed us to perform discerning observations of the individual spatial properties of all 49 beams. Whilst fast-axis pointing remains consistent for all the emitters, pointing in slow-axis direction exhibits linear variation along the bar. Measurements reveal a temperature dependent pitch mismatch between the laser chip and the slow-axis collimation silica lens, typically 0.04% of the 200 micron pitch. Accurate slow-axis collimation turns out to be optically demanding due to the thermal expansion and bonding-induced deformation of the laser chip. However, our flexible technique has the capability to correct the fixed component of slow-axis errors and provide super-collimation in both directions.

7583-34, Session 8

Coherent beam combining for high-power broad-area laser diode array

B. Liu, Y. Liu, Y. Braiman, Oak Ridge National Lab. (United States)

We will discuss our experimental results on coherent beam combining from large arrays of high power broad-area semiconductor lasers. Our laser array consists of 47 high-power AR coated broad-area semiconductor lasers each one capable of emitting 1.8 W when uncoated (the maximum power in array is 80W). By using external V-shape cavity design (B. Liu, Y. Liu, and Y. Braiman, Optics Express 16, 20946 (2008)), in our initial experiments with this array we demonstrated above 12 W of coherently combined power and the line-width of 0.07 nm (in fact, this is the limit of our optical spectrum analyzer). We expect to achieve higher coherent powers from the array in the very nearest future. We will also discuss theoretical aspects and experimental challenges to achieve an excellent beam quality while maintaining high power emission from the broad-area laser diode array.

7583-35, Session 8

Progress in high-brightness diode laser development at Coherent

S. D. Roh, D. M. Grasso, N. Shou, Q. Dong, D. A. Schleuning, R. Pathak, Coherent, Inc. (United States)

The state-of-the-art beam quality from high-brightness, fiber-coupled diode laser modules has been significantly improved in the last few years, with commercially available modules now rivaling the brightness of lamp-pumped Nd:YAG lasers. We report progress in the development of these systems for a variety of applications, such as material processing and pumping of solid state and fiber lasers. Experimental data and simulation results for wavelength stabilized outputs from 100 µm and 200 µm diameter fibers at 88x nm and 97x nm for power levels greater than 100 W will be presented. The enabling technology in these products is supported by key developments in device design, micro-optics, diode laser packaging, and system architecture.

7583-36, Session 8

Coherent polarization locking of a diode emitter array

S. P. Ng, Nanyang Technological Univ. (Singapore); P. B. Phua, DSO National Labs. (Singapore) and Nanyang Technological Univ. (Singapore)

Coherent beam combining has been actively explored as a technique to increase the brightness of laser sources. Passive phase-locking of a diode array in a common resonator, in particular, is an attractive approach owing to its inherent simplicity and good beam quality. In this work, we present the coherent combining of an array of diode emitters in a conventional diode bar configuration using the coherent polarization locking technique. An external laser cavity is designed so that the diode emissions from several 976 nm diode emitters are spatially overlapped via a series of birefringent walk-off crystals and passively phase-locked by a polarizing beam splitter. The key optical element in this beam combining scheme is the novel YVO4 birefringent spatial beam combiner that not only provides spatial overlap, but also identical optical path lengths for the diode beams. This facilitates design of the cavity for achieving a close match between the mode size of the Gaussian beam and the asymmetric emitting area at the front facet of the diode emitters. The phase-locking technique, coupled with the required standard bulk optical crystals and standard diode bar configuration, yields a robust laser architecture which retains the advantages of diode lasers in terms of cost, size and wavelength tunability. With the coherent combining of four diode emitters, we achieved a nearly diffraction limited beam at 1030 mW, which represents a 50 times increase in brightness over the standard incoherent diode bar. The coherent locking approach is highly scalable. Further experiments to coherently combine eight to sixteen diode emitters are in progress.

7583-37, Session 8

High-brightness emission from stripe-array broad area diode lasers operated in off-axis external cavities

A. Jechow, D. Skoczowsky, Univ. Potsdam (Germany); M. Lichtner, M. Radziunas, Weierstrass-Institute für Angewandte Analysis und Stochastik (Germany); R. Menzel, Univ. Potsdam (Germany)

Phase-coupled stripe-array diode lasers show a strong double lobed far field because adjacent stripes tend to operate in the out-of-phase mode. One way to achieve a stable phase relationship and global coupling of the emitters of such a stripe-array is off-axis feedback.

Here, results that have been obtained with gain guided stripe arrays are presented. The stripe width was 4 μm and the pitch between the stripes was 10 μm. The substructuring was realized by etching trenches through the cap layer. Emitters between 200 μm and 600 μm width have been investigated.

Diffraction-limited, single longitudinal mode operation with a brightness as high as 87MW/cm^2-str has been achieved with a 40 stripe 400 μm wide single emitter operated in a Littrow type off-axis external cavity.

The technique of off-axis feedback was also adapted to realize spectral beam combining of 25 emitters of a laser bar. The resulting beam quality of the laser bar emission was 7 times better than that of a single emitter. Furthermore, the potential for coherent coupling of stripe-array laser bars is discussed.

The experimental data are compared with results from numerical simulations.

7583-38, Session 8

250W diode laser for low pressure Rb vapor pumping

A. Podvyaznyy, G. B. Venus, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); V. I. Smirnov, OptiGrate Corp. (United States); D. A. Hostutler, Air Force Research Lab. (United States); L. B. Glebov, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

The diode pumped alkali vapor lasers operating at subatmospheric pressure require developing of a new generation of high-power laser diode sources with around 10 GHz wide emission spectrum. The latest achievements in the technology of volume Bragg gratings (VBGs) recorded in photo-thermo-refractive glass opened new opportunities for the design and fabrication of compact external cavity laser diodes, diode bars and stacks with reflecting volume Bragg gratings as output couplers.

In this work we present a development of a diode laser system providing up to 250 W output power and emission spectral width of 20 pm (FWHM) at wavelength of 780 nm. The stability and position of central wavelength of such a laser is determined by central wavelength of a VBG which is controlled by temperature variations. The wavelength shift due to temperature is about 7 - 14 pm/°C for 780 - 1500 nm spectral region. It was low enough to guarantee stability of pumping wavelength within 1 pm for temperature controlling with the precision of at least 0.1°C. At the same time it was high enough to provide thermal tuning of the wavelength for maximum overlapping with absorption spectrum of a Rb-cell.

The designed system consists of 7 channels coupled to a single output fiber. All the channels are tuned to the same wavelength corresponding to D2 spectral line of Rb87 or Rb85. Analogous systems would work for other Rb spectral lines as well as for lasers based on other alkali metal vapors (Cs and K).

7583-40, Poster Session

Degradation analysis of individual emitters in 808-nm QCW laser diode array for space applications

O. M. Rehioui, Lab. d'Intégration du Matériau au Système (France) and Quantel Laser Diode (France); L. Bechou, Y. Ousten, Lab. d'Intégration du Matériau au Système (France); A. Kohl, T. Fillardet, G. Volluet, Quantel Laser Diodes (France)

Over recent years, high power laser diodes have shown a strong increase of available power per bar. While the power increased the reliability of the devices was constantly improved at the same time. Today the reliability is often still limited by the distribution of packaging induced stress. For further progress of the reliability as required especially for space application a deep understanding of the failure mechanism of these components is needed. This requires more detailed reliability and performance data of the bars at emitter level. In this paper, 808nm, TE-Polarized, 1cm-bars with 25 emitters each 200μm wide and 1.2mm cavity length were studied, the importance of individual emitter characteristics and effect of aging test are analyzed. A specific test bench dedicated to individual emitter measurement has been developed; this set-up measures optical power, optical spectra and degree of polarization of each emitter. These parameters are well known to be depending on the electronic band structure of the quantum well and they are highly affected by induced stress. Aging tests up to 4.4Gshots have shown different failure signatures for a number of emitters. We found that individual emitter degradation can be correlated with its initial set of DOP and max parameters. Especially, for emitters showing dislocations defects after aging ("V-defect"), a weak DOP value and an infrared wavelength shift has been observed during initial characterisation. These V-defects at the front facet lead to catastrophic optical degradation over time. Another type of failures have been observed and correlated to initial characteristics. These results are interpreted in terms of stress and strain and are supported by thermo-mechanical simulations. Taking into account this study we demonstrate that the homogeneity of emitters electro-optical characteristics is a relevant parameter to ensure the reliability of the device for space applications.

7583-41, Poster Session

High-power single-lateral-mode InAs/GaAs quantum dot laser diode with double bend waveguide structures

K. C. Kim, Korea Institute of Science and Technology (Korea, Republic of) and Korea Univ. (Korea, Republic of); I. K. Han, J. I. Lee, Korea Institute of Science and Technology (Korea, Republic of); D. H. Kim, T. G. Kim, Korea Univ. (Korea, Republic of)

High-power quantum dot (QD) laser diodes (LDs) in single-lateral-mode operations have attracted much attention because of their wide scale applications in areas of pumping sources for erbium-doped fiber amplifier and solid-state lasers, and material surgery and treatment. In general, the lateral dimension of single-lateral-mode LDs is designed to be narrow in order to cutoff the propagation of higher order modes. Several problems such as reduced catastrophic optical mirror damage (COMD) levels, larger diffraction angles, and limited output power due to the small gain volume arise from the narrow geometry. A new LD design is required for high-power, single-lateral-mode applications.

We report high-power, single-lateral-mode InAs/GaAs QD LDs with double bend (DB) waveguide structure. In this device scheme, only a fundamental mode is allowed to propagate while higher order mode is suppressed at two bent regions. DB LDs enable us to use wide ridge width for fundamental mode operations, which eventually reduces the optical intensity at the facet and increases the optical power before COMD. InAs/GaAs QD DB LDs with 10- -wide stripe and 1.7-mm long cavity exhibit a kink-free output power of 310 mW with an external efficiency of 0.34 W/A without facet coating, in the single-lateral-mode during continuous wave operations.

7583-42, Poster Session

Methane concentration measurements with a mid-infrared quantum-cascade laser

L. Li, Y. Wang, M. Cong, Y. An, B. Li, Jilin Univ. (China)

The authors reported a quantum cascade laser operating at a wave number of 1300.110 cm-1 was used for infrared absorption spectroscopy of methane (CH4). The measured laser line-width was 1.1 MHz. A methane concentration of ~10 parts in 10-6 in the room temperature was measured in a 126mm optical path length when the signal was acquired over 100 scans. The response time is about 2s.These years infrared

absorption spectroscopy is used to monitor ambient gas species which could influence the normal life. It is known to be an effective tool than other ways, such as carrier catalytic and gas-sensitive semiconductor. Methane is also an important greenhouse gas in the atmosphere. In this paper, we demonstrated the application of a differential absorption measurement with QC laser to CH4 detection. Simply adjust the operating current which was supplied by a low-noise driver controlled by a function generator. The generator resulted in a pulsed voltage waveform from 12v-15v at the same time current varied from 600mA to 1.4 A. The wavelength of our laser can achieve the absorption line at 1300.110 cm-1 and the concentration of CH4 can be precisely measured by comparing the output signals from the sample cell and the reference cell. These experimental results provide a good basis for the development of practical gas sensors.

7583-43, Poster Session

High-power distributed-feedback tapered master-oscillator power amplifiers emitting at 1064 nm

D. Jedrzejczyk, O. Brox, F. Bugge, J. Fricke, A. Ginolas, K. Paschke, H. Wenzel, G. Erbert, Ferdinand-Braun-Institut für Höchstfrequenztechnik (Germany)

High-power diode lasers emitting radiation in a single spectral and spatial mode in continuous-wave (CW) or pulsed operation are required for many applications such as second-harmonic generation, pumping of fiber amplifiers and lasers or free-space optical communication.

In this work, we investigate experimentally optimized monolithic distributed-feedback (DFB) tapered master-oscillator power amplifiers (MOPA). The devices consist of three autonomously driven sections: a 1 mm long DFB ridge-waveguide (RW) laser, a 1 mm long RW pre-amplifier and 2 mm or 4 mm long tapered amplifiers. The ridge width and the full taper angle are 5 µm and 6°, respectively. Both laser facets are anti-reflection coated. The second order Bragg gratings in the DFB laser were realized by holographic photolithography, wet-chemical etching and a two-step epitaxy.

The DFB tapered MOPAs emit nearly diffraction limited spectral single mode CW radiation at 1064 nm. The 6 mm long devices provide an optical power of about 7 W at DFB laser, pre-amplifier and tapered amplifier currents of 150 mA, 100 mA and 10 A, respectively. The 4 mm long devices generate more than 3 W at a tapered amplifier current of 5 A. A spectral width at FWHM of 1.5 pm at 6.5 W output power was measured with the ELIAS III spectrometer from LTB Berlin. The spectral drift versus output power is below 50 pm/W.

At the conference we will report on the optical power, optical spectrum and beam quality in dependence on the currents injected into the three device sections. Furthermore, the influence of the coupling coefficient of the Bragg grating will be investigated.

7583-44, Poster Session

CW to QCW power scaling of high-power laser bars

J. Müller, R. Todt, M. Krejci, Y. Manz-Gilbert, N. Lichtenstein, Oclaro, Inc. (Switzerland)

There is a growing interest in intermediate qcw operation modes ranging from 0.1 to 10 milliseconds and duty cycles of 2-25%, requiring peak output power of 200W or more. The design rules for best thermal stability and highest power conversion efficiency do not necessarily coincide with the optical power density at the facet required for sufficiently high facet destruction levels. The Oclaro E2 facet passivation technology enables design solutions matching both, as the waveguide design and confinement factors chosen play a secondary role for the facet stability.

808nm bars with 80% filling factor and assembled on CS-mount were characterized in qcw modes with pulse lengths ranging from 0.2-2ms and duty cycles of 1-11%. In addition, the cooler temperature was varied between 15-75°C. 300W output power was obtained for 300A drive current, 75°C cooler temperature, 200µs pulse width and 1% duty cycle. Estimations based on threshold currents and slope efficiencies obtained at different temperatures resulted in T0 and T1 values of 200K and 450K, respectively. Less than 0.5% power degradation resulted from a life test at 220W peak power, 400µs pulse length and 750 Mshots with 808m bars operated at 25°C.

For 9xx and 10xx bars we report the extension of the wavelength region to 1080nm. Bars at 1060nm with power conversion efficiency of 65% offer a new wavelength range for direct diode applications. The electro-optical qcw capabilities of Oclaro 9xx and 10xx bars will be demonstrated, and a life test performed at 500A, 500µs, 5% duty cycle will be presented.

7583-45, Poster Session

1043-nm semiconductor disk laser

Y. Song, P. Zhang, J. Tian, X. Zhang, Beijing Univ. of Technology (China)

Semiconductor Disk Laser hold the advantages of both of the traditional surface-emitting lasers and the diode-pumped solid-state lasers. In this paper, we designed a wafer and described a comprehensive theoretical analysis and the experimental results of the 1043nm VECSELs with anti-resonant semiconductor micro-cavity. Photoluminescence (PL) spectrum of VECSELs reflected the essential emission properties of the QWs. Taking into account of the intraband relaxation and the valence band coupling between the two of the heavy hole band, light hole band and the orbit-spin separation band in band structure of the strained quantum wells (QWs), the edge emitting PL spectrum of VECSELs was theoretically calculated by using Lornetz linear function. The results were in good agreement with the experimental data. The longitudinal confinement factor of anti-resonant semiconductor microcavity was numerically simulated, and the outcome was used to explain the shaping mechanism of surface emitting PL spectrum of the VECSELs. A model of laser output which considered of thermal effect was used to simulate our VECSELs' output characteristics. The results were compared with the experimental phenomena. We also discussed some other characteristics of the 1043nm VECSELs, such as red shift of edge emitting PL, surface emitting PL and laser spectrum. The oscillation wavelength selection and the thermal rollover of the lasers were discussed as well. 710mW continuous-wave output power at 1043nm is produced using a 3% output coupler and 6100mW incident pump power. The slope-efficiency is 14.2% and the optical- to-optical conversion efficiency is 11.6%.

7583-46, Poster Session

High-power high-brightness QCW bars

H. Huang, J. Wang, M. A. DeVito, A. L. Hodges, S. Zhang, L. Bao, D. Wise, M. Grimshaw, D. Xu, C. Bai, nLIGHT Corp. (United States)

A new class of high power high brightness 808nm QCW laser diode bars has been developed. These devices use nLight's nXLT facet passivation technology to provide highly reliable, high intensity output. With improvements in the epitaxial structure, reliable 150W operation for a 3.0mm wide mini-bar has been demonstrated, and the peak efficiency is over 60%. COD level on these 3.0mm wide mini bars exceeds 200W output power, the testing of which is currently limited by the available power supply.

Data on 10.0mm wide QCW bar will be presented, which is expected to deliver reliable output power greater than 300W with peak efficiency over 60%.

The high power, high brightness QCW bars are tested under various QCW conditions, up to millisecond pulse width. These bars are soldered to different packages, including conduction cooled packages with hard solder, and a water cooled micro-channel package. The performance of the various configurations will be compared.

The high efficiency high brightness QCW bars are suitable for portable and efficient eye-safe range finding applications, and high power high efficiency QCW stack applications.

Reliability study is currently being carried out to meet a 3x109 shot lifetime target. A study of large pulse width reliability will also be presented. Failure analysis of the various configurations will be discussed.

7583-47, Poster Session

Long-wavelength fiber-coupled diode laser modules

P. O. Leisher, K. Price, S. R. Karlsen, M. Reynolds, A. Brown, L. J. Bintz, R. J. Martinsen, S. Patterson, nLIGHT Corp. (United States)

Applications such as resonant end pumping of Er- and Ho-doped solid state and fiber lasers, direct diode medical lasers and infrared countermeasures are driving the development of high brightness diode modules operating in the 1400 nm to 2100 nm band. To meet these needs, nLight has extended its high-brightness Pearl platform, a conductively-cooled fiber-coupled package format based on arrays of single-emitters, to this wavelength regime. In this work, we report on recent advancements in the approach. At 1530 nm, power in excess of 30 W is demonstrated as measured from the distal end of a 105 µm, 0.15 NA fiber. A similar package, designed for efficient coupling to a 200 µm, 0.22 NA fiber delivers >50W at the same wavelength. At 1907 nm, power in excess of 16 W is demonstrated from a similar 200 µm, 0.22 NA fiber-coupled module. In some cases, the naturally broad, temperature-sensitive, spectrum offered by long-wavelength diode laser sources is undesirable. To mitigate this effect, nLight has developed a wavelength locking approach, based on external volumetric holographic gratings, which offers a greater-than order-of magnitude improvement in the spectral bandwidth and spectral stability over temperature, without compromise to the power or efficiency of the module. Application of this approach to the aforementioned modules is also presented.

7583-48, Poster Session

Advancements in broad-area InP-based diode lasers operating from 1400 nm to >2100 nm

P. O. Leisher, W. Dong, X. G. Guan, M. Grimshaw, J. Patterson, S. Patterson, nLIGHT Corp. (United States)

A wide variety of applications, including resonant pumping of Erbium- and Holmium-based lasers, direct diode medical systems, and infrared counter-measures (IRCM) are being enabled by nLight's rapid commercial deployment of high brightness diode laser modules operating in the 1400-nm to 2100-nm wavelength band. In this work, we describe recent progress in the development of long-wavelength single-emitter chip technology which serves as the primary building block for nLight's conductively-cooled fiber-coupled laser platform. These InGaAsP-based chips are specifically designed to deliver high power with high efficiency in a hard-soldered single-emitter format. At 1530 nm, hard-soldered 100 µm stripe emitters now demonstrate a record >6.5 W with >40% power conversion efficiency (peak). In the same single-emitter chip format, we demonstrate >3.5 W around 1700 nm and >2 W around 1940 nm. These results were achieved through careful modifications of the laser epitaxy design which have enabled efficient scaling of the optical mode volume. Results on scaling the operating wavelength of the design to beyond 2100 nm are also reported. Preliminary lifetesting results (>40,000 device hours collected to date), obtained under accelerated operating conditions, confirm the robustness of the design and are also discussed.

7583-50, Poster Session

Development of asymmetrical epitaxial structures for 65% efficiency laser diodes in the 9xx-nm range

M. Levy, Y. Karni, N. Rapaport, Y. Don, Y. Berk, D. A. Yanson, SCD Semiconductor Devices (Israel)

High-power single emitters have recently become a viable alternative to laser diode bars for fiber pumping applications. Single emitters offer a tenfold increase in brightness over bars, and can be optically combined to scale the power towards several 100W with high brightness. Wall-plug efficiencies >60% are needed to warrant the use of fiber-coupled single emitters in fiber laser systems, which requires careful minimization of the optical loss, electrical resistance and voltage defect of the emitters. Epitaxial wafer design necessarily involves multiple trade-offs, since doping concentrations have opposing effects on the electrical resistance and optical losses. In this paper, we investigate asymmetrical epitaxial waveguide designs for high-efficiency laser operation at 9xx nm. We present a simulation study of the influence of design parameters such as the number of quantum wells, doping profiles and overlap integral of each epilayer. We also show that by introducing a second waveguide into the lower cladding, we can control the overlap of the optical mode with the doping profiles - as well as the vertical far-field - without compromising the electrical resistance. The optimized structures were grown and devices fabricated, with optical losses reduced to 0.4 /cm and resistivity to 6.5 Ohm sq.cm. An optical power of 12W with 65% efficiency was achieved from 100-micron stripe emitters. Reliability data at high temperature operation are presented.

7583-51, Poster Session

Progress and applications of on-chip wavelength stabilized high brightness laser diodes

L. Vaissie, R. M. Lammert, W. Hu, X. Yang, C. Wang, T. Liu, J. E. Ungar, QPC Lasers, Inc. (United States)

On-chip wavelength stabilization using internal gratings (Brightlock) offers significant manufacturing and practical benefits over external wavelength stabilization schemes. Recent advances at key wavelengths for pumping applications are discussed, enabling power scaling to multi-kW, athermal operation and stabilized CW or QCW operation. We demonstrate conversion efficiency of 50% at 808 nm, brightness of 50 mW/um, and wavelength locking over 60C. We also present new results for athermal 532nm green laser operation and multi-kW power scaling for high power lasers.

7583-53, Poster Session

Laser-assisted shearing: new application for high-power diode lasers

M. Emonts, C. Brecher, Fraunhofer-Institut für Produktionstechnologie (Germany)

The development of a hybrid laser-assisted shearing process enables conventional punching machines to produce punched sheared edges with continuous clear-cut surfaces in stainless steel plates (1.4301), spring steel plates (1.4310) and titanium alloy plates (3.7165). The new combination of localized laser-induced softening of the plate material in the shearing zone and the shearing process significantly reduces both process forces and process-related noise emissions. Essential precondition for the avoidance of local overheating of the material is a homogeneous laser intensity distribution which is accomplished by high-power diode lasers. A modular system-upgrade for existing punching machines allows laser-assisted shearing to be implemented without the

Return to Contents

need for expensive new machine designs. The principle of the laser-assisted shearing process is based on briefly and selectively heating the material in the shearing zone via local absorption of laser radiation on the underside of the sheet metal plate before the punching tool comes into contact on the upper side of the metal plate. Laser-induced heating softens the material in the shearing zone within the material within a few tenths of a second. The laser-induced softening mechanisms also lead to a significant decrease of cutting forces as well as a reduction of tool wear, warping and noise emissions. Current process results for laser-assisted shearing spring steels (1.1248 and 1.4310) show clear-cut surface ratios of 100% of material thickness; cutting forces are reduced by 80%. The paper comprises the operational procedure descriptions and a discussion of the influence of the different process parameters.

7583-54, Poster Session

High brightness 975 nm surface-emitting distributed feedback laser and arrays

M. Kanskar, J. Cai, D. Kedlaya, D. Olson, Y. Xiao, T. Klos, M. G. Martin, C. Galstad, S. H. Macomber, Alfalight, Inc. (United States)

High power, semiconductor diode laser is an indispensable technology for many types of solid-state lasers, fiber lasers and hybrid lasers. Over the past few decades, diode laser technology development has achieved remarkable improvement in power, reliability and efficiency. Spectral brightness, wavelength-stabilization and spatial brightness are becoming increasingly important for precision-pumping of novel solid-state gain media and fiber lasers especially for efficient and power-hungry industrial and military applications. Specifically, we will discuss the benefits of using 975 nm narrow-band curved grating Surface-emitting Distributed Feedback (SE-DFB) lasers for pumping fiber lasers and thin disk lasers. SE-DFB lasers with < 0.25 nm emission bandwidth, 0.07nm/°C thermal wavelength drift with >50% power conversion efficiency has been achieved with a single emitter producing >70W of CW power. Two-dimensional arrays of these lasers have been made for power scaling to achieve 1kW of power with <1nm spectral bandwidth. We will discuss the results and key advantages of using spectrally and spatially bright diodes for pumping fiber and thin disk lasers.

7583-55, Poster Session

Beam shaping and fibre coupling of laser diode bars by means of a single micro optical element

J. Meinschien, L. Aschke, A. Bayer, U. Fornahl, T. Mitra, LIMO Lissotschenko Mikrooptik GmbH (Germany)

A new concept for beam shaping and fibre coupling of laser diode bars is presented.

Typically, high power diode lasers are made of laser diode bars and several optical elements. These optical elements are mainly micro lenses for fast axis collimation, lenses for slow axis collimation, complex optical systems for symmetrisation of beam parameters and macro lenses for focussing the laser light into an optical fibre. Such arrangements with 4 to 6 optical elements are often critical in terms of numbers of components, number of alignment and mounting steps during assembly and therefore finally critical in terms of manufacturing costs.

The new concept requires only a single multifunctional micro optical element for all beam shaping aspects from collimation to fibre coupling. Design aspects are discussed in this presentation. High efficiency coupling is feasible into a 600 µm fibre core of NA 0.22.

Advantages of this approach are rather obvious as just one optical element is needed to be produced, aligned and mounted as well as just two optical surfaces need be antireflection coated and contribute to reflection losses.

High power diode laser systems with the presented approach are highly suitable for cost sensitive applications with limited requirements on brightness.

7583-56, Poster Session

High brightness fibre coupling of laser diodes for configurations with single and multiple minibars

J. Meinschien, D. Bartoschewski, U. Fornahl, M. Jarczynski, T. Mitra, C. Schroers, A. Timmermann, LIMO Lissotschenko Mikrooptik GmbH (Germany)

Optical designs and system concepts are presented for beam shaping and high brightness fibre coupling of single and multiple laser diode bars.

Recent developments of high power diode laser technology increasingly lead to approaches with laser diode bars of smaller number of emitters (minibars) and higher brightness compared to conventional 10 mm bars. Sophisticated concepts for beam shaping of such laser diode bars are discussed. They are capable to end up in state of the power and brightness of fibre coupled systems. These systems are advantageously to multi single emitter approaches especially in terms of robust operation, compact design and manufacturing aspects.

Specifically, laser systems of 1, 3 and 5 mini bars with a single wavelength are presented in detail including measurement data from laboratory set ups. Power levels of 30 W to 150 W are demonstrated for optical fibres of 100 µm to 150 µm fibre core and numerical aperture of 0.12 to 0.15. These diode lasers are well suited for pumping applications and material processing. The power level of the laser modules for material processing can directly be scaled up to a couple of hundred Watts by wavelength coupling.

Conference 7584: Laser Applications in Microelectronic and Optoelectronic Manufacturing XV

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Laser Applications in Microelectronic and Optoelectronic Manufacturing XV

7584-01, Session 1

Black silicon

E. D. Mazur, Harvard Univ. (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 resulting textured surface is highly absorbing and looks black to the eye. The properties of this 'black silicon' make it useful for a wide range of commercial devices. In particular, we have been able to fabricate highly-sensitive PIN photodetectors using this material. The sensitivity extends to wavelengths of 1600 nm making them particularly useful for applications in communications and remote sensing.

7584-02, Session 1

Femtosecond laser synthesis of metastable metallic nanoalloys in liquids

M. Meunier, S. Besner, P. M. Boyer, Ecole Polytechnique de Montréal (Canada)

Metastable nanoalloys are currently impossible to synthesize using standard chemical synthesis due to the strongly dissimilar reduction kinetic of the individual metal salts. They would be however of great interest in various biomedical, magnetic and chemical catalysis applications. In this paper, we show that laser synthesis can be used to fabricate unique metastable metallic nanoalloys based on various elements, including Au, Ag, Cu, Co and Fe. The method implies the self-transformation of the femtosecond pulse into a supercontinuum to initiate a controlled laser-induced growth (LIG) or fragmentation (LIF) of micro/nanoparticles in solution [1]. This approach significantly broadens the achievable size range of near monodispersed nanoparticles in comparison to the direct laser ablation of a solid in a liquid. Appropriate tuning of the chemical environment (solvent, solutes, type of colloids, etc.) and of the laser parameters allows an efficient control of the size and composition of the nanoparticles for Ag-Au-Cu system. Optical breakdown and mechanical stress produced by femtosecond laser followed by the rapid temperature quenching by contact with the liquid leads to the formation of non thermodynamic structures. The proposed approach allows the formation of a new class of nanomaterials, such as CoAu and FeCoAu due to the rapid quenching of the excited nanoparticles in liquids. In many cases, the metastable nanoalloys exhibited unique properties in comparison to individual elemental counterparts. For example, laser-synthesized AgAu nanoalloys showed improved plasmonic response in comparison to pure gold and much better resistance to photo-induced oxidation in comparison to pure silver. Introduction of small amount of gold into Co or FeCo nanoparticles increased the magnetization due to the spin coupling of the Au 4s electrons with Co and Fe, to the reduction of magnetic surface disorder and to the suppression of the oxidation.

[1] S. Besner, and M. Meunier, "Laser synthesis of nanomaterials" in Laser Precision Microfabrication, K. Sugioka, M. Meunier, A. Pique, Eds., Springer (To be published 2009)

7584-03, Session 1

F2 excimer laser generated transient absorption centers in single crystal CaF2

S. George, S. C. Langford, J. T. Dickinson, Washington State Univ. (United States)

Single crystal CaF2 is a wide bandgap dielectric (11.8 eV) used as an optical material for several UV-VUV laser applications, including at 157 nm. At high intensities at 157 nm we and others have shown that two photon absorption results in the formation of point defects in CaF2 that include F-centers, M-centers (F-center dimers) and metallic Ca nanoparticles. Here we use time resolved UV-VUV absorption spectroscopy to examine the time dependence of the formation and significant disappearance of these and other point defects generated by single pulses and by a series of pulses at fluences well below plasma formation. One extremely important transient defect absorbs strongly at the incident laser wavelength and is therefore critical to understand for a variety of applications. The latter absorption has been attributed to a substitutional hydride ion (H- in a F- site); annealing crystals in H2 increases this transient absorption, strongly corroborating this assignment. Once this absorption center has been produced by laser exposure and allowed to "recover" (disappear), we find complete regeneration of the absorption requires only a few laser pulses. We propose that electron transfer out of the defect and then (rapidly) back to the defect is the underlying cause of the transient absorption. Thus, we have an optical switch similar to that reported previously by us in alkali halides (Appl. Surf. Sci. (2007), 253 pp.7874-7878). Oher laser generated absorptions in CaF2 due to F-centers (at 375 nm) and a Ca+ defect (at 220 nm) show similar switching behavior, again explained by rapid electron transfer.

7584-04, Session 1

Limits to the nanoscale control during pulsed laser deposition

G. Baraldi, Consejo Superior de Investigaciones Científicas (Spain); V. Resta, Consejo Superior de Investigaciones Científicas (Spain) and ENEA (Italy); A. Perea Folgueras, J. A. Gonzalo, C. N. Afonso, Consejo Superior de Investigaciones Científicas (Spain)

Pulsed laser deposition is a versatile technique that allows producing high quality materials and alternate ablation of multiple targets gives further access to material configurations such as alloys, multilayers, nanocomposites or doped materials. We have successfully applied this versatility to produce layered nanostructures containing nanoparticles of metals such as Cu, Bi, Ag ,Au, or combinations of two metals, all embedded in an amorphous Al2O3 host.

However, sputtering effects associated to high kinetic energy species arriving to the substrate have an essential role in the growth process and can even limit it. The aim of this work is to understand and quantify the effect of species bombardment on the production of metal nano-objects embedded in an oxide host and eventually, separate the self-sputtering effects during metal deposition from those produced during the embedding process. A Langmuir probe has been located along the central axis of the expanding plasma in order to determine the kinetic energy distribution of ions produced during the ablation of several metals, including Al, as well as Al2O3. The results show that whereas self-bombardment during metal deposition is very important for implantation of the metal into the host, the bombardment with the host species appears responsible for the final nanoscale control, i.e. the dimensions of the metal nano-objects or the sharpening of dimension distribution. Conditions under which the shape or the composition of the nano-objects can be modified will finally be discussed.

(*) Permanent address V. Resta: ENEA, Advanced Physical Technologies and New Materials Dept., S.S. 7 - Km 706, I-72100 Brindisi, Italy

7584-05, Session 2

Direct laser writing of photoresponsive colloids for microscale patterning of 3D porous structures

P. V. Braun, Univ. of Illinois at Urbana-Champaign (United States)

Multiple routes exist for microscale patterning of materials in three dimensions, including multilayer photolithography, nanotransfer printing, LiGA, microstereolithography, and multiphoton polymerization. Each of these routes, however, typically yields a solid structure, yet novel porous architectures such as those assembled from colloidal building blocks, are required for applications ranging from microfluidic filters and mixing elements to catalyst supports. To overcome this limitation, we harness the power of multiphoton direct laser writing to locally define the interactions between photoswitchable colloidal microspheres suspended in an organic solvent. Through this novel approach, we create porous-walled 3D structures including microscale rectangular cavities that exhibit size-selective permeability and 3D microfluidic pathways.

7584-06, Session 2

Burst-train filamentation assisted laser machining of high aspect ratio holes in glass

S. Rezaei, Univ. of Toronto (Canada); D. Esser, RWTH Aachen (Germany); J. Li, P. R. Herman, Univ. of Toronto (Canada)

Burst-train filamentation assisted laser machining of high aspect ratio holes is presented in transparent glasses by using a purpose-built burst resonator to generate high repetition rate (38.5MHz/26ns MHz) trains of femtosecond (fs) laser pulses. Single Ti:Sapphire laser pulses (wavelength = 800 nm, pulse duration = 50 - 5000 fs, Ep = 2 mJ, f = 500 Hz) were trapped in a passive resonator and released into controllable burst profiles by computer generated delays to a fast Pockels cell switch. Various temporal profiles of 3 to 12 pulse burst trains were generated and examined for tailoring self-focusing filamentation effects in bulk glass to assist surface ablation. Unlike low-repetition rate laser machining, a build-up of heat accumulation and other transient effects with burst trains have combined form heat sheaths that mitigate shock-induced microcracks while self-focusing filaments appeared to guide vias into high aspect ratio holes of ~ 20 um diameter and up to 1 mm length. We describe the optimization of burst profiles for deep penetration drilling at least 10-fold deeper than possible with low repetition rate. The burst trains dramatically accelerate the etching rate and depth of holes while maintaining uniform and smooth cross-sectional profile over the full depth. Detailed time resolved images of ablation holes and laser filaments are presented as they evolve over many trains of pulses inside the bulk glass.

7584-07, Session 2

Flexible 3D deep microstructure fabrication in silica glasses by laser-induced backside wet etching

T. Sato, R. Kurosaki, A. Narazaki, Y. Kawaguchi, H. Niino, National Institute of Advanced Industrial Science and Technology (Japan)

Laser micromachining of transparent materials are widely studied as an important technique for fabricating MEOMS components, microfluidic chips, and so on. Deep and complex microstructures are often required in such microdevices. Deep and complex microstructures in glass materials were successfully fabricated by multi-step laser-machining, femtosecond laser-assisted etching, while deep microstructures can be fabricated by laser-induced backside wet etching (LIBWE), a one-step laser micromachining technique for silica glass. However, deep etching by LIBWE proceed only to the direction of incidence of the laser light. Toward flexible 3D deep microstructure fabrication, the well-controlled fabrication of microtrenches including inclined parts under normal irradiation with shifting the irradiated area was demonstrated. Inclined trenches could be successfully fabricated by shifting the irradiation area gradually to the direction perpendicular to the trench. The trenches with tilting angles with upto 29° were obtained by changing the shifting speed of the irradiation area. The tilting angles of the inclined parts were determined by the ratio between the vertical and lateral etch rates. The ratio of maximum lateral etch rate to vertical etch rate was about 55 %, resulting in the formation of the inclined parts with maximum tilting angle of 29°. In this method, tilting angle can be changed within one deep trench. Flexible structure formation at the deep inside the silica glass can be achieved.

7584-08, Session 3

Pulsed laser deposition: 15 years later

R. F. Haglund, Jr., Vanderbilt Univ. (United States)

Pulsed laser deposition (PLD) of thin films is closer to half a century old, but the first LAMOM conference, begun a few years after PLD of oxide superconductors was introduced, has provided a forum for introducing many novel PLD applications and techniques. This review will seek to be illustrative, rather than comprehensive or historical. One obvious feature is the increasingly variegated palette of materials that can be deposited by PLD: metals, semiconductors and insulators, as well as polymers, organics and biological materials. Significantly, the laser ablation plume is increasingly viewed as a kind of micro-reactor in which condensation into nanostructures and even useful chemistry can take place prior to deposition. Another obvious feature of PLD fifteen years on is the wide range of laser wavelengths, pulse durations and pulse repetition rates now in use. Dominated in the beginning by relatively low repetition rate excimer and (harmonics of) Nd:YAG lasers, the spectrum of lasers these days ranges from infrared to ultraviolet, with pulse durations from femtoseconds to microseconds and repetition rates up to GHz. The strong emphasis on understanding the laser-materials interaction in PLD has led both to increasing acceptance of PLD and to the vigorous development of related techniques that in some cases can approach the precision of molecular beam deposition. These developments exemplify a productive synergy between experiment and theory, and between science and technology, that has made LAMOM - and the many other conferences relating to the topic - a lively and growing forum for research and development in pulsed laser deposition.

7584-09, Session 3

Laser manufacturing of durable goods: a 15-year perspective

J. Mazumder, Univ. of Michigan (United States)

No abstract available

7584-10, Session 4

Pulsed laser deposition in device research and manufacturing

D. B. Chrisey, Rensselaer Polytechnic Institute (United States)

It was about 23 years ago that pulsed laser deposition (PLD) was re-discovered for use in the deposition of the high temperature superconductor $YBa_2Cu_3O_7$ and since that time research and development using PLD has exploded and with them the fundamental understanding of the process and its application to a multitude of material systems which has led to many successful implementations in high quality thin film form. Indeed, pulsed laser deposition has been a transformative technique providing a unique and cost-effective solution

to the difficult problem of depositing complex and multi-component oxide ceramics, nitrides, and metallic multilayers. These material systems display a wide range of disparate functionalities, e.g., superconductors, semiconductors, transparent conducting oxides, ferroelectrics, ferrites, and biocompatible oxide thin films. The novelty in PLD comes from (i) the laser - material interaction that governs the vapor profile produced; (2) the harsh ambient environments that can be used; and (3) the subsequent mechanism of film nucleation and growth. What is especially interesting from a historical perspective is that PLD has found a unique niche in terms of thin film deposition techniques in that it has been especially enabling to researchers in fabricating prototype device structures with which to examine fundamental material properties and basic device performance. In most basic research settings, the simple equipment required to carry out prototype PLD depositions is easily obtained and this is as compared to more expensive stand-alone MBE or PECVD systems. Application of PLD to industrial manufacturing has not been so quick or successful despite the success of lasers in other areas of industrial manufacturing. This is due to the shortcomings of the technique, e.g., particulates, areal deposition profile, and in situ deposition control. To find a home in industry, a new technique must either perform a deposition task cheaper or deposit something unique, i.e., that cannot be done otherwise. Herein, PLD has been an enabling research tool allowing material systems to be quickly explored in high quality thin film form, but when a new application is ready for transition to industrial insertion typically a more established technique will be utilized. New opportunities exist, though, for future application of PLD in industry. This talk will summarize the success this transformative technique has had since its re-discovery in device research and manufacturing.

7584-11, Session 4

Excimer ultraviolet sources for thin film deposition: a 15 year perspective

I. W. Boyd, Univ. College London (United Kingdom)

No abstract available

7584-12, Session 4

Low-fluence laser interaction with materials: research and applications shaped by tools advancement

H. Helvajian, The Aerospace Corp. (United States)

No abstract available

7584-13, Session 5

Holographic femtosecond laser processing

Y. Hayasaki, Utsunomiya Univ. (Japan)

Femtosecond laser processing inside transparent materials has advantages of high spatial resolution due to multi-photon absorption and reduced thermal destruction of the target due to the extremely short pulse duration. Therefore, the femtosecond laser processing has been used to develop three-dimensional (3-D) optical devices. To fabricate the 3-D optical devices composed of a huge number of processing points, parallel femtosecond laser processing with high throughput is indispensable.

Holography gives the features of high throughput, high light use efficiency, and material-dependent light distribution ser to the femtosecond laser processing. Especially, computer-generated holograms (CGHs) are very useful and powerful tool, because the CGH can generate a desired arbitrary beam, such as a spatially-shaped beam, a split beam, a focused beam, and a wave-front corrected beam, with low loss of light. The CGH is variably displayed on a liquid-crystal spatial light modulator (LCSLM). A key requirement in the design of the CGH is a precise control of the diffraction peak intensity. Some methods for the control have been applied.

In this paper, we demonstrate recent progresses in our study of holographic femtosecond laser processing, including two- and three-dimensional parallel processing, line processing, and adaptive optimizations of hologram for higher uniform processing.

7584-36, Session 5

Micromachining of metal and silicon using high average power ultrafast fiber lasers

E. P. Mottay, Y. Zaouter, Amplitude Systemes (France); C. Loumena, M. Faucon, J. Lopez, ALPhANOV (France)

Ultrafast laser micromachining has been widely proven to be a high quality, high flexibility process, with numerous potential industrial applications.

The ultrashort pulse duration (< 10 ps) and the very high intensity on the target (up to 1014 W/cm²) lead to a complete ionization of the irradiated volume by non-linear effects. Since pulse duration is below the heat diffusion time, the irradiated volume is ejected before any heat diffusion or thermal damage, and consequently side-effects are significantly reduced compared to longer pulses. Hence, reduced side-effects enable to preserve the functionalities of the material and to perform fine and accurate microfabrications such as drilling , cutting, engraving, and internal marking. Low pulse energy is generally required for micromachining (<100µJ).

Until recently, a main drawback was the low processing speed due to the limited average power available from ultrafast lasers. Recent advances in commercial ultrafast lasers have significantly increased the average power available to the user. However, parallel advances in process development are required to take full advantage of these new capabilities.

We report on micromachining and engraving of metal and silicon using a variety of high average power ultrafast lasers. We used both crystal-based systems and fiber lasers, operating in the picosecond and femtosecond regimes. We will present comparative results on the influence of pulse duration, of laser wavelength and ambiant pressue on the ablation rate and processing speed. Processing speeds greater than 5 m/s are reached with smooth sidewalls and no burr.

7584-37, Session 5

Ultrafast laser-based tools enable advanced silicon solar cell efficiency enhancement processes

F. Colville, Coherent, Inc. (United States)

The recent availability of industrial-grade turn-key short-pulse (picosecond and sub-picosecond pulse-width) solid-state lasers offers new opportunities within next-generation crystalline-silicon solar cell production: specifically, for multi-c-Si types based upon standard front/back contact cells operating with average efficiencies in volume in excess of 17%. As new applications for short-pulse lasers are transitioned from solar research institutes to pilot cell production lines, an established equipment supply chain is now required to ensure laser-source and application qualification (marking the switch from non-laser based tooling to laser-based processes for solar cell production).

This paper examines first the process windows associated with applications such as laser-assisted selective-emitter formation and mask-writing for diffusion/plating during cell manufacture; how these demand both the use of both short-pulses and short-wavelengths from advanced solid-state lasers; and why legacy industrial-grade lasers (in particular nanosecond and long-wavelength options) failed to meet production acceptance criteria. The requirements then on laser-based process tools are outlined, with a direct comparison to the solar industry roadmaps

being discussed currently; including the additional constraints from cell producers which impact on laser-tool design, performance, throughput, and return-on-investment.

Finally, the applications in question here for short-pulse lasers will be used as a representative case-study for the generic industrial adoption of state-of-the-art solid-state lasers; in particular, where they enable research-proven work to be taken into a production environment (hitherto laser-source limited) with a well-defined market pull.

7584-38, Session 5

Picosecond laser patterning of NiCr thin film strain gauges

O. Suttmann, J. Duesing, U. Klug, R. Kling, Laser Zentrum Hannover e.V. (Germany)

I would like to paticipate in the studen competition.

Strain measurement of technical components is realised by strain gauges based on polymer foils. Conventional strain gauges suffer from creeping and swelling through alternating ambient humidity as well as a low positioning accuracy.

A new approach for strain measurement is the integration of sputtered thin film strain gauges. These are often based on a sensing NiCr film. The sensing film is electrically isolated from the component to be measured by an insulating Al2O3 film. Both films are deposited by means of high rate PVD processes. In the next step the sensor is patterned by picosecond laser pulses. The use of laser radiation for the patterning allows the realization of sensors on 3D surfaces. This paper presents results of experiments on patterning of NiCr thin films with thicknesses ranging from 23nm to 246nm on Al2O3 substrates with picosecond laser pulses. Laser ablation with picosecond laser pulses enables thin film patterning with low thermal load and reduced risk of electrical shortcuts. Investigated parameters are fluence, number of pulses, film thickness and substrate roughness. The influence of the parameters on the ablation rates, thresholds and morphology as well as on the incubation factor is analyzed. The incubation factor describes changes of the ablation threshold after irradiation of multiple pulses below the ablation threshold. All investigated film thicknesses show a decrease of the ablation threshold with increasing number of irradiations. The ablation thresholds increase with a growing film thickness. This correlation is stronger for substrates with a higher roughness.

7584-39, Session 5

High repetition rate femtosecond laser processing of metals

J. Schille, U. Loeschner, R. Ebert, Univ. of Applied Sciences Mittweida (Germany); P. Scully, N. Goddard, Univ. of Manchester (United Kingdom); H. Exner, Univ. of Applied Sciences Mittweida (Germany)

(I would like to be considered in this year's student competition.)

In this study a high repetition rate femtosecond fibre laser source (IMPULSE; Clark MXR) has been applied in 3D laser micro structuring of metals. We are going to discuss the investigated significant laser material interaction mechanisms in high repetition rate laser processing such as heat accumulation and particle shielding. Laser machining with repetition rates in the range of 500 kHz has shown interaction effects of the incident laser beam with the ablated particles and clusters induced by the foregone laser pulse. At higher repetition rates heat accumulation causes a higher energy input which locally leads to a temperature rise and results in better absorption conditions and lowered ablation thresholds of the irradiated material. In this machining regime energy losses forced by particle shielding have been overbalanced and a considerable increase of the ablation depth has been detected. Additionally due to a high laser energy input the formation of laser induced periodical micro structures have been observed. We found that the origin, shape and density of these conical structures can be influenced by processing parameters. However, the formation mechanism is still under discussion.

Finally we are going to present machining examples to discuss possibilities and limits of high repetition rate laser processing in 3d micro structuring. By using innovative scanning systems a high machining throughput can be reached which attract interest of the novel laser technology in Rapid Micro Tooling. Furthermore efficient fabricated laser induced micro structures can be applied in novel application due to enhanced material surface behavior.

7584-14, Session 6

Gold nanorods enhanced femtosecond laser nanoablation of silicon

M. Meunier, P. Desjeans-Gauthier, E. Boulais, Ecole Polytechnique de Montréal (Canada)

When an electromagnetic wave hits a metallic nanostructure of a size less than its wavelength, the wave's energy is absorbed and locally reemitted as near field in close proximity to the nanostructure, but with a multiplied intensity. This local field enhancement is mainly attributed to the surface plasmon resonance of the nanostructures and can be used to perform nanoprocessing of the substrate surface on which the nanostructures are deposited. Actually, if the field enhancement is high enough, it is possible to send a femtosecond pulse below the ablation threshold of the substrate that will be powerful enough, once amplified, to locally perform nano-ablation under the nanostructures. In this research, we investigate the use of gold nanorods as an efficient nanostructure for plasmonic enhanced fs laser nanoprocessing. The field enhancement AF value can be experimentally determined by comparing the lowest laser fluence for which sample surface ablation is observed to the normal sample surface ablation threshold. In this study, we used a Ti-Sapphire femtosecond pulse laser at 800 nm wavelength irradiating a Si substrate. Values for AF was determined to be ~ 2.3 for a 25 nm diameter x 75 nm long gold nanorod. Comparison with gold nanospheres with diameters ranging from 20 to 200 nm has been made. While for gold nanoparticles, single nanoholes are usually produced, double nanoholes separated by few tens of nm could be fabricated, all oriented in the polarization directions of the irradiation beam when gold nanorods are used. In order to understand the basic mechanism of plasmonic enhanced laser nanoablation of silicon, we performed three dimensional simulations to obtain the electromagnetic field distribution surrounding the gold nanorod after an interaction with a 800nm 120 fs laser pulse. Calculation of the electromagnetic field distribution by a finite-element based method clearly shows a double lobe field enhancement, in agreement with experiments.

7584-15, Session 6

Efficient femtosecond laser nanohole processing on substrate surface using high dielectric constant particles with small size parameter

Y. Tanaka, G. Obara, A. Zenidaka, M. Obara, Keio Univ. (Japan)

We present the experimental and theoretical results on the nanohole processing using high dielectric particles with small size parameter. Nanohole processing mediated with the dielectric particle exhibits the smaller features than the diffraction limit. The use of dielectric particles has attracted much attention for industrial applications, because fabrication of the monolayer 2D particle arrangement seems much easier than the metallic ones. Based on Mie scattering theory, the enhanced near-field is determined by the size parameter x=pi*D/lambda, defined as pi* particle diameter D divided by optical wavelength lambda. The clear nanohole is obtainable with x~pi but not with the smaller size parameter x<pi/2 due to the weak enhanced near-field for frequently used particles like polystyrene particle. Therefore, the shorter wavelength is required for downsizing the processed nanoholes, which needs the

sophisticated wavelength up-conversion in ultrashort time domain and vacuum UV (lambda<200 nm). Using dielectric particles having high dielectric constant, the strong enhanced near-field is generated even with small size parameters due to the strong scattering cross-section of the particle. The resonant refractive index of the particle depends on the size parameter, meaning that the used material should be selected as a function of size parameter. In the ablation processing with 2D arrayed particles, the optical field interaction such as inter-particle multiple scattering should be considered and then the optimal spectral condition is different from the single particle case. The obtained results indicate that the use of high dielectric particles becomes a promising technique for downsizing the produced nanoholes.

7584-16, Session 6

Effect of target structure on interfering femtosecond laser processing

Y. Nakata, T. Hiromoto, N. Miyanaga, Osaka Univ. (Japan)

Interfering ultra-short pulse laser processing was applied to induce nanostructures on metallic thin films. The nanostructures are nano-waterdrop, nanocrown, and nanobump. They are generated by thermally process with nano-period, and basic structure can be controlled by target structure, such as film thickness, base substrate, etc.. Peaked structure has curvature radius smaller than 10 nm, and the value was beyond the resolution of ordinal ultra-short pulse laser processing.

7584-40, Session 6

Brighter light sources from the black metal

A. Y. Vorobyev, C. Guo, Univ. of Rochester (United States)

No abstract available

7584-17, Session 7

Femtosecond laser processing of hybrid micro- and nano-structures in silicate glasses

P. Mardilovich, J. J. Witcher, L. B. Fletcher, S. H. Risbud, D. M. Krol, Univ. of California, Davis (United States)

I would like to be considered in this year's student competition.

Ultrafast laser processing had been used to induce structural modifications in the bulk of transparent dielectric materials, such as glass. This has enabled a creation of several optoelectronic device-oriented structures, such as waveguides, splitters and couplers, Bragg gratings, amplifiers etc. So far most of these structures have been homogeneous on a nanometer scale. Manufacturing heterogeneous structures of micro-scale domains with nano-scale inclusions will greatly expand the toolbox available for optoelectronic device design.

In certain doped glasses it is possible to nucleate and grow metal or semiconductor nanocrystals under certain thermal conditions. Using a focused femtosecond laser it has been shown possible to manipulate the nucleation process, allowing sufficient control to define where nanocrystal precipitation will take place.

In this work, we explored a range of processing parameters, a combination of tightly focused femtosecond laser irradiation and heat treatment, in the context of nucleation control in several silicate glass compositions. We studied the resultant structures using absorption measurement, optical and electron microscopy, and characterized structural modifications of the glass matrix using fluorescence and Raman spectroscopy.

We will discuss the results and how the processing parameters, such as laser pulse power, repetition and scan rates, and heat treatment temperature, affect the structure properties. We will specifically address these effects with respect to corresponding phase separation dynamics.

7584-18, Session 7

Structure modification of glass-ceramics thin films and layers by ultrashort laser action

V. P. Veiko, St. Petersburg State Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

Glass-ceramics (GCs) usually have glass structure doped with microcrystalls that are responsible for main properties: mechanical, chemical, optical etc. Different laser technologies for modification of structure of GCs has been developed. The most important thing is that optical transparency of GC drastically increases in visible and near IR range due to the appearance of new glassy structure. Variation of laser treatment conditions (power, exposure, wavelength from IR to UV) as well as selection of composition of GCs allows to control mentioned characteristics. Most interesting now is local structure modification of GC under short pulses laser action - from nanosecond to pico- and femtosecond. All 3 types of these lasers on different wavelengths have been used for experiments (2 - 10.6 mcm, 200 ns; ArF - 193 nm, 10 ns; Nd-YAG - 266 nm, 355 nm, 532 nm, 30 ps, Ti-sapphire -0.8 mcm,100 fs). We used two compositions of GCs with crystalline phases of TiO2-SiO2 (Sitall ST-50) and Li2O-SiO2 ("Fotoform"). As a result of above mentioned research mini- and micro-optical components based on two GCs have been fabricated and demonstrated: lenses and lens arrays, modulators, waveguides and other waveguiding components, gratings, integrated diaphragms etc.

Veiko V.P., Novikov B.Yu.. Shakhno E.A., Yakovlev E.B. Physical Mechanisms of Fast Structure Modification and the Appearance of Waves of Optical Bleaching in Glass Ceramics. Laser Physics, Vol. 18, No. 4, pp. 1-11, 2008.

7584-19, Session 7

Two-photon lithography and nanoprocessing with picojoule extreme ultrashort 12 femtosecond laser pulses

K. König, M. Schug, H. Zhang, S. Saremi, D. Feili, H. Seidel, Univ. des Saarlandes (Germany)

A novel ultrashort femtosecond laser scanning microscope with 12 femtoseconds pulse width at the focal plane has been employed in material nanoprocessing. The laser system is based on a 10 fs 85 MHz laser resonator in combination with a precompensation unit with chirped mirrors. The near infrared laser beam was focused with an objective of high numerical aperture.

A variety of photoresists could be activated via a two-photon excitation process with microwatt mean powers based on the broad emission spectrum (maximum 780 nm) of the 12 femtosecond near infrared pulses. 3D two-photon lithography was realized via beam scanning and stage scanning.

Nanoprocessing (drilling, cutting, ablation) was performed with sub-20 mW mean powers due to multiphoton ionization and plasma formation. We report on the nanostructuring of polymers, glass, and silica.

7584-20, Session 7

Individually controlled multi-focus laser processing for two-photon polymerization

K. Obata, J. Koch, B. N. Chichkov, Laser Zentrum Hannover e.V. (Germany)

Two-photon polymerization (2PP) of photosensitive polymer materials using femtosecond (fs) lasers is one of the unique techniques for true three-dimensional micro- and nano-scale structuring. Femtosecond laser induces two-photon absorption at local volume leading to precise microfabrication with structural dimensions much smaller than the

diffraction limit of the incident laser beam. Recently, the increasing 2PP process resolution requiring much longer processing time became a problem for practical use. To overcome this problem, some groups have demonstrated unique 2PP setup with beam separation techniques such as parallel process with a fly's eye type lens, or diffractive optical elements (DOE). However these techniques can realize an efficient mass production, they are not suitable for the fabrication of single complex structures and unsymmetrical array structures in rapid prototyping. In this study, a novel beam separation technique with spatial light modulator (SLM) is demonstrated for acceleration of two-photon polymerization process.

In this experiment, fs laser pulses are illuminated onto the reflective type liquid crystal SLM displaying a computer generated holographic (CGH) pattern to modulate the phase of the incident laser beam. The reflected laser beam forms multi-focus spot pattern at the Fourier plane and is projected into the liquid phase inorganic/organic hybrid polymer (Ormocer) sample with a 100x immersion microscope objective (NA=1.4). These multi-focus beams can induce 2PP at each focus position. In addition, each focus spot can be independently controlled in position and laser intensity with SLM.

7584-21, Session 7

Up-conversion of crystal oscillator frequency in silicon package by near infrared, ultra-short laser

Y. Ito, R. Tanabe, F. Sato, Y. Shinohe, Nagaoka Univ. of Technology (Japan); K. Tada, Citizen Finetech Miyota Co., Ltd. (Japan)

Crystal oscillators are key component in electronic equipments. They are contained in ceramic or metal packages and sealed off after adjusting their frequencies to designated values by adding or removing small mass from the crystal. Lasers are widely adopted as tools for it. The process has, however, risks of contamination before sealing and of frequency changes stimulated by sealing processes. If the frequency adjustment could be done after packaging, these risks are avoidable. The adjustment after sealing has made possible by adopting glass lid, which is transparent at laser wavelength used. Recently, packages made of silicon have been developed. The silicon package has several advantages compared to ceramic or metal packages. To adjust the frequency after sealing, however, laser irradiation must be done through the silicon lid.

Using a laser with photon energy smaller than the band-gap of silicon, machining of substances located at back of a silicon substrate should be achievable. To demonstrate this, machining of a silicon substrate as well as machining of gold film on it was carried out using femtosecond lasers, wavelength of which lay between 1.5 to 2.5 micrometer.

It is demonstrated that the rare surface of the silicon and the gold film placed at the back of the substrate can be machined with no detectable change on the front surface of the substrate. Frequency adjustment of the silicon-packaged crystal oscillator is tried. Up-conversion of the frequency is achieved by removing small amount of thin gold film on the crystal by irradiation of 1.5 micrometer laser through the silicon lid.

7584-22, Session 8

Femtosecond laser fabrication of birefringent directional couplers in fused silica

L. A. Fernandes, Univ. of Toronto (Canada) and INESC Porto (Portugal); J. R. Grenier, P. R. Herman, J. S. Aitchison, Univ. of Toronto (Canada); P. V. S. Marques, INESC Porto (Portugal)

The fabrication of integrated polarization splitting directional couplers is demonstrated in a bulk fused silica substrate with femtosecond laser direct writing. The laser writing system consists of a Yb:fiber chirped pulse amplified system, with a center wavelength of 1044 nm operating at 300 fs, 150 nJ and 500 kHz repetition rate. The laser was frequency doubled to 522 nm to drive stronger refractive index contrast in fused silica glass.

The waveguide birefringence was controlled by the writing beam polarization, being perpendicular or parallel to the waveguide axis. By fabricating a single step Bragg grating waveguide, a peak birefringence of 2 x 10-4 was measured from the spectral splitting of the Bragg reflection peak with respect to the polarization state of the inserted broadband light. This birefringence was then used to develop polarization splitting directional couplers with various spectral responses designed for the C and L Telecom bands. Birefringent directional couplers designs are presented for broadband and WDM polarization beam splitting application that present very stable components for new applications such as differential polarization phase-shift keying in optical communication and quantum encryption receivers.

7584-41, Session 8

A frontier in optical data storage: five-dimensional optical data storage

M. Gu, Swinburne Univ. of Technology (Australia)

In this presentation, I will give a review on our recent progress on the utilisation of nanoparticles including quantum dots/rods and metallic nanorods in multi-dimensional optical data storage [Peter Zijlstra, James W. M. Chon, Min Gu, Nature, 459 (2009), 410-413; Xiangping Li, James W. M. Chon, Richard A. Evans, Min Gu, Opt. Express, 17 (2009), 2954-2961]. We have introduced a new concept of multi-dimensional optical storage based on multi-photon excitation of nanoparticles. In this new technology, the information can be stored not only in different positions of a thick medium but also in polarisation and spectral domains. The tuneability of optical properties of the nanoparticles provides the various erasable and non-erasable polarisation and spectral encoding mechanisms in the same spatial position to break the data density limit imposed by the 3D optical storage technology. This nanophotonic approach will lead to a horizon of the new-generation 5D optical data storage technology that is of a potential toward a data storage capacity of Petabytes.

7584-42, Session 8

The influence of glass structure on femtosecond laser waveguide writing in erbium-doped phosphate glass

L. B. Fletcher, J. J. Witcher, D. M. Krol, Univ. of California, Davis (United States); R. K. Brow, Missouri Univ. of Science and Technology (United States)

Permanent structural changes induced by fs lasers can be used inside active glasses to fabricate waveguide lasers, with applications in three-dimensional photonic circuits. Phosphate glasses are excellent glass host systems for achieving high rare-earth oxide concentrations with low luminescence quenching effects, and are ideal for fabricating compact high gain waveguide lasers that operate in the C-band.

Previous research with zinc phosphate glasses has demonstrated that the bulk glass structure is important to determining the resulting morphological changes after femtosecond laser waveguide writing. Glasses with shorter average phosphate chain lengths exhibited local structural densification inside the irradiated area that can be used to fabricate single mode waveguides. In the present study, we have investigated how the addition of erbium to zinc polyphosphate glass affects the response of the glass structure to modifications by femtosecond laser pulses.

Waveguides have been fabricated using a regenerative amplifier Ti:sapphire (Merlin-Spitfire Spectra Physics) 1 kHz, 180 fs laser system with pulse energies ranging from 0.2 µJ - 4 µJ. The femtosecond laser beam was directed through a 20x (0.4 NA) microscope where the glass sample was translated parallel to the femtosecond laser beam at a constant scan speed of 50 μm/s. In this study we have written waveguides in a variety of erbium doped zinc polyphosphate glass compositions. Near field guiding profiles and white light images as well as insertion losses were measured after waveguides were written. Laser-induced structural changes in the glass were characterized using confocal fluorescence and Raman microscopy.

7584-43, Session 8

Birefringent elements based on femtosecond laser-induced nanogratings

L. Ramirez, M. Heinrich, S. Richter, F. Dreisow, R. Keil, Friedrich-Schiller-Univ. Jena (Germany); A. V. Korovin, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany); U. Peschel, S. Nolte, A. Tünnermann, Friedrich-Schiller-Univ. Jena (Germany)

We will report on the fabrication of birefringent optical components based on femtosecond laser induced nanogratings.

In recent years, the femtosecond laser processing technique has been established as a versatile method for the fabrication of three-dimensional structures within the bulk of transparent materials. In a certain range of processing parameters so-called nanogratings, i.e. self organized periodic structures with sub-wavelength dimensions, are formed within the focal region of the writing objective. As a result, the induced structures feature a characteristic birefringent behaviour. This type of modification is of great interest for a wide field of practical applications, since it promises the opportunity for the rapid fabrication of three-dimensional birefringent elements of arbitrary shape and position-dependent retardation.

We will present the results of our experiments on the formation process of such nanogratings in fused silica. We studied the influence of various fabrication parameters, thereby identifying possible ways to systematically control the grating properties such as orientation, pitch and effective refractive index. Based on our work, we were able to fabricate nanograting based birefringent optical elements with various retardations and orientations, demonstrating the practical applicability of this approach.

7584-44, Session 8

Femtosecond laser written embedded diffractive optical elements and their applications

J. Choi, M. Ramme, T. P. Anderson, M. C. Richardson, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

Femtosecond laser direct writing (FLDW) has been widely employed to create volumetric structures in transparent materials that are applicable as various photonic devices such as active and passive waveguides, couplers, gratings, and diffractive optical elements (DOEs). The advantages of fabrication of volumetric DOEs using FLDW include not only the ability to produce embedded 3D structures but also a simple fabrication scheme, ease of customization, a clean process, etc. We present DOE fabrication techniques using FLDW as well as the characterization of laser-written DOEs by various methods such as refractive index change measurement and diffraction efficiency measurement. Gratings and Fresnel zone plates were fabricated in oxide glasses using various femtosecond laser systems in high and low repetition rate regimes. The diffraction efficiency as functions of fabrication parameters was measured to investigate the dependence on the different fabrication parameters such as repetition rate and laser dose. Furthermore, we demonstrate several integration schemes of DOE with other photonic structures for compact photonic device fabrication.

7584-36, Poster Session

An experimental identification of the relationship between laser scattering image and micro-surface roughness for solar cell wafer

Y. Hong, G. Kim, Y. Jin, Chungju National Univ. (Korea, Republic of)

In this paper, micro surface roughness has been experimentally identified using laser scattering images. At first, previous surface evaluation methods, laser scattering parameters and optical deflected rays are investigated and then laser scattering inspection mechanism is developed. The design of experiment is applied to determine optimal laser scattering parameters. Control factors which give effects on the laser scattering intensity and optical ray, are chosen as laser incident angle, camera viewing angle, machined ray, and F-number. In case of an experiment specimen, micro grinding surface (Ra: 0.05 ~1.6) is used and is inspected using a dark-field laser scattering technique. Likewise optimal parameters are determined using analysis of variance, in order to obtain distinctive laser scattering images in which periodical common features are represented. It is shown that the mean of vertical scattering distributions is characterized as wavelet in the laser scattering images. The wavelet is directly related with the grinding surface information. Also, the dominant and specific feature in laser scattering images is linearly increased according to grinding surface roughness. This point can be used as an important factor for the measurement and evaluation of various micro surface roughness. In the future, the explicit relationship between the laser scattering image and micro surface roughness will be identified. Also, the proposed laser scattering method will be applied to the evaluation inspection of crystalline silicon wafer surfaces for solar cell.

7584-37, Poster Session

Modeling of laser drilled microhole profiles in carbon fiber composites in low fluence regime

F. F. Wu, MetroLaser, Inc. (United States)

In this paper, a model describing laser microhole drilling processes in carbon fiber composites (CFC) has been developed, which can predict the drilled profiles of the microholes for several kinds of specific incident beam profiles. The report tries to answer how the peak fluence, the beam diameter, and the material parameters affect the hole shapes. Although the model is specific to CFC, it can be applied to any other laser micromachining process for materials such as polyimide, polymethylmethacrylate (PMMA), polyethylene terephthalate (PET) etc.

The model not only provide the drilled hole profiles but also explain why hole drilling will stop under certain circumstances, i.e., under certain circumstance, more shots applied to the process will not generate any further drilling effect-stabilized or saturated drilling happens. High efficient laser processing can be predicted from the model, i.e. what are the best parameters for certain processed materials. This model is suitable for most well defined beams and materials such as polymers, fiber CFC, glass fiber composites and some ceramics. This paper mainly concentrate on the modeling while the comparison of the modeling and experimental data will publish in the following paper.

7584-38, Poster Session

Comparison of the modeling and experimental data of the laser drilled microhole profiles in carbon fiber composites in low fluence regime

F. F. Wu, MetroLaser, Inc. (United States)

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7584-39, Poster Session

Second harmonic optimization of a hologram

S. Hasegawa, Y. Hayasaki, Utsunomiya Univ. (Japan)

Precise control of diffraction peaks of a hologram is indispensable in holographic femtosecond laser processing. To obtain the uniform diffraction peaks, an adaptive optimization with the diffraction peaks measured by an image sensor was proposed. It was based on one-photon absorption. The structure, however, processed by femtosecond laser pulse is based on multiple-photon absorptions. Therefore, a mismatch between the optimized diffraction peaks and the processed structures was observed. In this paper, an adaptive optimization method using second harmonics induced by parallel beam irradiations to a nonlinear optical crystal is proposed to solve this mismatch. In the experiment, the hologram generating twenty-four diffractive peaks was optimized. In the optimization process, the uniformity of the second harmonic intensity was improved from 0.70 to 0.92. The uniformity was defined as the ratio of the minimum to the maximum of the second harmonic intensity. Furthermore, we demonstrated holographic femtosecond laser processing with a hologram designed with the second harmonic optimization.

7584-40, Poster Session

Near-IR femtosecond and VUV nanosecond laser processing of TeO2 crystals in air

S. Beke, K. Sugioka, RIKEN (Japan); J. Bonse, Federal Institute for Materials Research and Testing (Germany); K. Midorikawa, RIKEN (Japan)

Tellurium dioxide crystals (c-TeO2) play an important role in acousto-optical devices due to their beneficial photo-elastic properties, high optical homogeneity, low light absorption and scattering, and high optical damage resistance. To our knowledge, a laser microprocessing of this material has never been investigated elsewhere.

Near-IR femtosecond (= 150 fs,   =775 nm, rep. rate 1 kHz) and VUV nanosecond (= 20 ns,   =157 nm, rep. rate 2 Hz) laser pulse ablation of single-crystalline TeO2 (c-TeO2, grown by the balance controlled Czochalski growth method) surfaces were performed in air using the direct focusing technique with a 20x microscope objective.

The joint observation using optical microscopy, atomic force microscopy and scanning electron microscopy revealed the surface morphology of the ablated craters. This allowed to precisely characterize the lateral and vertical dimensions of laser ablated craters for different laser pulse energies and pulse numbers at each spot. Based on the obtained information, we quantitatively determined the ablation threshold fluence for different pulse numbers applied to the same spot by using two independent extrapolation techniques. We found that in case of NIR femtosecond laser pulse irradiation, the ablation threshold significantly depends on the number of laser pulses applied to the same spot indicating that incubation effects play an important role in this material. In case of VUV ns laser pulses the ablation rate is significantly higher due to the high photon energy and the predominantly linear absorption in the material.

These results are discussed on the basis of recent models of the interaction of laser pulses with dielectrics.

7584-41, Poster Session

Design of micron-scale universal optical logic gates

A. Rahmani Nejad, Islamic Azad Univ. (Iran, Islamic Republic of) and Iran Airports Co. (Iran, Islamic Republic of)

In this paper, it is tried to provide an innovative method to overcome several limitations of state of the art of logical gates and microprocessors, by implementation of micron-scaled optical gates. This technology can overcome such limitations, i.e. processing speed, heat dissipation, electromagnetic radiation and electrical noise immunity. This technology can be fully or partially feasible by substitution of common semiconductor technology with optical logic gates. By implementation of micron-scale optical fiber, optical couplers, fiber optical amplifiers, or fiber lasers, optical attenuators, optical fiber brag grating, femto-second optical lasers, and implementation of fundamental properties of optical coherent light, e.g. superposition, interference, phase delay, etc, it is possible to fabricate micron-scale universal logical gates, i.e. optical NAND gates, optical NOR gates, optical Exclusive-OR, optical exclusive-NOR gates and subsequently fabrication of sequential circuits (optical flip-flops), that all are fundamental blocks of microprocessors. Optical coherent light is produced by femtosecond lasers and is supplied to a network of micron-scaled fiber optics, fiber optical lasers, attenuators, fiber optical couplers, and finally are supplied to opto-couplers that change optical signals to electrical signals to be read by output console or to be written on memory cells. It is also possible to implement a combination of optical and semiconductor gates to decrease above mentioned limitations. The method of fabrication of optical gates is discussed in details and all necessary logical and technical aspects are provided too. The fundamental implemented aspect is superposition of coherent lights in fiber optic couplers. By implementation of femtosecond laser pulses, it is possible to reach to much higher frequencies of about hundreds to thousands of terahertz. Alternative optical method is provided here, e.g. implementation of fiber loops as clock circuit or even as an optical oscillator. By implementation of this technology, there will be one hundred years advance in respect to state of the art technology.

for more information, Refered to:

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Optics and Photonics for Information Processing III

Theory, design and micron-scale implementation of fully-optical logic gates and optical clock circuits

Paper 7442-46

7584-42, Poster Session

MOPA fiber laser with controlled pulse length and peak power for optimizing micromachining applications

S. T. Hendow, Multiwave Photonics (United States); J. M. Sousa, Multiwave Photonics, S.A. (Portugal)

An optimized MOPA fiber laser configuration is described for generating pulse widths, 10ns to 250ns, at pulse repetition frequencies that range from single-shot to 750kHz. These parameters, as well as pulse peak power, can be independently controlled. Test results are shown for processed materials using pulse energies up to 0.5mJ and peak powers up to 10kW. Such control of pulse parameters is significant for optimizing the processing of many hard materials and films, while minimizing HAZ, by independently adjusting pulse lengths and peak power.

7584-43, Poster Session

Ronchi test with equivalent wavelength

A. Garcia Arellano, F. Granados-Agustin, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

The Ronchi test has been one of the most successful tests applied to determine the quality of optical surfaces. Its physical interpretation as a lateral sheared interferometer and the technique known as equivalent wavelength, commonly used in interferometry, which is based on using two distinct wavelengths to create a synthesized wavelength, are considered in this proposal. The procedure described here to evaluate an optical surface uses the Ronchi test with the equivalent wavelength; some results, achieved by registering and computing the Ronchigram for each wavelength, are shown to demonstrate the enhancement of the test in the fabrication process of optical surfaces.

7584-44, Poster Session

Applicability of drilling with laser to deal with shally formations in Iranian oilfields: a case study

S. Ghadami, M. Nabaei, A. Roohi, A. Moazeni, Islamic Azad Univ. (Iran, Islamic Republic of)

Since the onset of 20th century rotary drilling replaced with the old version of drilling style in the oil and gas industry. Although from that time drilling industry improved till now mechanical system is yet in use. Also humans have made lots of tries to enhance the efficiency of drilling operation to reduce final cost and time of the drilling. In this way they tried drilling with laser as a new approach in this industry to overcome drilling problems. During 2 recent decades use of laser become high demanded and has shown a remarkable increase in the efficiency of operations in use e.g. perforation and drilling.

In this paper we try to propose a short description of laser, its different types and its usage in petroleum industry which will be followed by its pors and cons. Related drilling problems in shally formations in one of Iranian oilfields are covered and effectiveness of drilling with laser is compared with other approaches in use to deal with shally formations while applicability of this approach is economically assessed. Results show a decrease in time related to drilling shally formations and it shows optimistic to get use of drilling with laser in such formations.

7584-45, Poster Session

Centimeter-long microfluidic channel with an aspect ratio above 1,000 directly fabricated in fused silica by femtosecond laser micromachining

F. He, Y. Cheng, Z. Xu, Shanghai Institute of Optics and Fine Mechanics (China); K. Sugioka, K. Midorikawa, RIKEN (Japan)

Femtosecond laser micromachining has emerged as a promising technique for creating three dimensional (3D) microstructures. As an essential building block for microfluidics, homogeneous microfluidic channel with high aspect-ratio is indispensable for lab-on-a-chip (LOC) applications.

Fused silica is considered to be an excellent substrate material for LOC applications due to its low thermal expansion coefficient, low autofluorescence, excellent optical qualities and exceptional transmittance over a wide spectral range. Microfluidic channels can be directly fabricated inside fused silica by femtosecond laser direct writing followed by a subsequent wet chemical etching. However, the fabricated channels usually display a tapered feature and highly elliptical cross-section with limited length (usually <5 mm) and poor inner surface smoothness, which would hamper their applications.

Herein, we demonstrate direct fabrication of homogeneous microfluidic channels embedded in fused silica by femtosecond laser direct writing, followed by wet chemical etching and glass drawing. With these procedures, the homogeneity of the fabricated channels has become excellent. Namely, the taper of the microchannels is greatly reduced while their cross-sectional shape becomes circular after the drawing. In addition, an inner surface smoothness of ~0.2 nm can be realized by this method. Finally, the glass drawing method can lead to centimeters long microfluidic channels with an aspect ratio as high as ~1,000. We expect that these microfluidic channels will have important applications in optofluidics in the future.

7584-23, Session 9

Optical protein patterning and microfabrication for cellular biology research

S. Costantino, Univ. de Montréal (Canada)

The study of cellular responses to changes in the spatial distribution of molecules in development, immunology and cancer, requires reliable methods to reproduce in vitro the precise distributions of proteins found in vivo. We recently developed a new technology to fabricate such patterns which relies on photobleaching fluorophores to adsorb proteins on a cell culture substrate: laser-assisted protein adsorption by photobleaching (LAPAP).

As opposed to alternative techniques, LAPAP combines high spatial resolution (close to diffraction limit), large macroscale size, low-cost chemical reagents and mechanical hardware and an impressive dynamic range (protein concentration can be varied over three orders of magnitude). Recent advances in LAPAP enabled us to create arbitrary patterns made of several different proteins simultaneously, to reduce the fabrication time more than one order of magnitude and to use secondary antibodies to significantly enlarge the spectrum of proteins that can be employed. As a result, unique multi-component protein gradients can be produced using reagents that are typically available in life science research laboratories on a standard inverted microscope equipped with a camera port. We provide an extensive characterization of the technique and demonstrate, as proof of principle, axon guidance by gradients of substrate-bound laminin peptide generated in vitro using LAPAP.

We believe that one of the most important characteristics of LAPAP is that its simple implementation can lead to a major boost in the number of groups that can access new technologies for protein patterning.

7584-24, Session 9

Optical far- and near-field femtosecond laser micro/nanostructuring and applications

V. Zorba, Lawrence Berkeley National Lab. (United States)

We study the interaction of femtosecond laser pulses with Si surfaces in the optical far- and near-field. Laser-material interaction in the far-field leads to the formation of self-organized possessing hierarchical micro- and nanostructures on Si. These surfaces, exhibiting controlled dual-scale roughness, qualitatively and quantitatively mimic both the structure and the water repellent characteristics of the natural Lotus leaf and constitute one of the most water-repellent artificial surfaces ever reported.[1]

In a second part of this work Laser Induced Breakdown Spectroscopy (LIBS) at two distinct wavelengths (400 and 800 nm) was used for chemical analysis with a goal to identify the minimum crater size from which spectral emission could be measured from Si. Emission from sub-micrometer craters was possible which are among the smallest ever reported for femtosecond LIBS.

Finally the effect of laser wavelength (400 nm and 800 nm) on the near-field processing of Si through sub-wavelength NSOM apertures was studied. Distinct differences in the obtained nanostructures are found in each case both in terms of their physical sizes as well as their structure which can be tuned between craters and protrusions. Surface structures with lateral dimensions as low as 30 nm could be created under optimal conditions. [2]

[1] V. Zorba, E. Stratakis, M. Barberoglou, E. Spanakis, P. Tzanetakis and C. Fotakis, “Biomimetic artificial surfaces that quantitatively reproduce the water repellency of the lotus leaf”, Adv. Materials 20, 4049 (2008).

[2] V. Zorba, X. Mao and R.E. Russo, “Laser wavelength effects in ultrafast nearfield nanostructuring of Si”, Appl. Phys. Lett. 95, 041110 (2009).

7584-25, Session 9

Nano-aquarium fabrication with cut-off filters for mechanism study of Phormidium assemblage

Y. Hanada, K. Sugioka, I. Ishikawa, H. Kawano, A. Miyawaki, K. Midorikawa, RIKEN (Japan)

In this paper, we fabricate nano-aquariums by femtosecond (fs) laser for mechanism study of Phormidium assemblage to seedling root. Phormidium travels away to the seedling root in soil, resulting in acceleration of vegetable growth. However, conventional observation of the Phormidium assemblage using a Petri dish filled with an agar gel has taken long time. Therefore, we attempted to apply nan-oaquariums composed of the microchannel circuit inside the photosensitive glass (Foturan) for the efficient observation. The fabrication procedure consists of (1) fs laser exposure, (2) thermal treatment and (3) wet etching in acid. After the fabrication, Phormidium and the root were placed in opposite microreservoirs, each to each, connected with the microchannel and filled with water. The nano-aquarium drastically reduced the observation time, in other words, the time for assemblage and thereby revealed that the assemblage proceeds only under a bright condition. To investigate this phenomenon, partial cut-off filters of visible light were formed around the embedded microchannel by the fs laser processing. The cut-off filters were realized by the fs laser exposure followed by thermal treatment, since the processed regions became lithium metasilicate crystallite which has brown color. By integrating the filters in the glass, only 20 % visible light can transmit into the microchannel. As a result, Phormidium stopped the assemblage behavior at the entrance of microchannel covered with the filter, which suggests that light illumination to Phormidium is necessary for the assemblage to the seeding root. Further mechanism study of Phormidium assemblage is discussed using the nano-aquarium.

7584-26, Session 10

Processing of metals and dielectric materials with ps-laserpulses: Results, strategies, limitations and needs

B. Neuenschwander, G. F. Bucher, C. Nussbaum, B. Joss, M. Muralt, U. W. Hunziker, P. Schuetz, Berner Fachhochschule (Switzerland)

Ultra short (ps, fs) laser pulses are used, when high requirements concerning accuracy, surface roughness, heat affected zone etc. are demanded for surface structuring. Since industrial suited ps-lasersystems are available, they are of great interest for many practical applications. Actual results in the field of 3-d structuring (metals and transparent materials), induced processes and structuring of flexible solar cells will be presented in the first part of the talk.

Beside the pulse duration, which is given by the laser system, the user has a wide variety of optimization parameters such as fluence, repetition rate and wavelength. Based on a simple model it will be shown, that there exist optimum laser parameters to achieve maximum ablation rates (in volume per time) at a given average power. To take benefit of these optimum parameters and to prevent harmful effects like plasma shielding and surface melting, adapted structuring strategies, depending on the requirements, have to be used. Today’s ultra short pulsed systems have average powers from a few W up to a few 10W at high repetition rates. The actual available beam guiding systems are limited and can often not fulfill the requirements needed for high throughput structuring with optimized parameters. Based on the achieved results, the needs for future beam guiding systems will be discussed.

7584-27, Session 10

Laser texturing of doped borosilicate glasses

A. M. Streltsov, J. E. Dickinson, Jr., R. R. Grzybowski, D. Harvey, S. L. Logunov, A. Ozturk, M. Potuzak, J. S. Sutherland, Corning Inc. (United States)

We describe a novel process of laser-assisted fabrication of surface structures with heights reaching 10 - 13% of the glass thickness on doped borosilicate glasses. This effect manifests itself as a swelling of the glass when irradiated with a focused laser beam. The extent of such swelling depends on the glass base composition and on the dopant. Doping with Fe, Ti, Co, Ce, and other transition metals allows the glass absorption to be adjusted so that the feature size can be maximized. For Fe- and Co-doped borosilicates, one can use near-infrared diode-pigtailed or fiber continuous-wave lasers with 10-50 W output powers. Structures on glass include discrete bumps exceeding 200 micrometers in height and continuous lines several tens of microns tall. In the case of bumps, we observe reversible glass swelling and the bump height can increase or decrease depending on whether the consecutive laser pulse has higher or lower energy compared with the previous one. In addition, glasses doped with Fe and Co exhibit strong visible bleaching in the exposed areas. The hypothetical mechanism includes laser heating of glass, glass melting, and directional flow. We review several potential applications of such glass swelling.

7584-28, Session 10

Lasers in the manufacturing of LEDs

M. Mendes, M. Hannon, J. P. Sercel, J. Fu, X. Song, C. Porneala, J. Stearns, JPSA (United States)

Lasers are becoming increasingly important in today’s LED revolution and are essential for increasing the efficiency and reducing manufacturing cost of LEDs. Excimer lasers provide unique homogeneous illumination of large areas, and are ideally suited for laser lift off (LLO) of the LED film from the sapphire substrate used for epitaxial growth. In this paper we will discuss the excimer laser lift off technique for manufacturing vertical type LEDs, and how it can be applied to GaN and AlN based LEDs. On the other hand, diode pumped solid state lasers excel in scribing and cutting of a number of materials relevant to the LED industry: sapphire, silicon, silicon carbide, III-nitrides (gallium nitride and aluminum nitride), as well as III-V semiconductors (gallium arsenide, indium phosphide, gallium phosphide). In this paper we will discuss some of the recent laser scribing techniques and how adequate selection of laser parameters and beam delivery optics allows for a high quality high throughput process.

7584-29, Session 10

Recent advancements in technology of compact laser plasma EUV sources

H. Fiedorowicz, A. S. Bartnik, Military Univ. of Technology (Poland); T. Feigl, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); R. Jarocki, J. Kostecki, Military Univ. of Technology (Poland); L. Pina, Czech Technical Univ. in Prague (Czech Republic); M. Szczurek, P. W. Wachulak, Military Univ. of Technology (Poland)

It was demonstrated that laser plasma EUV sources based on a gas puff target can be useful for application in metrology and processing polymers. In this paper the recent advancements in technology of compact laser plasma EUV sources are presented. EUV radiation in the wavelength range from about 5 nm to about 50 nm is efficiently produced in result of irradiation an xenon or krypton gas puff target with laser pulses (0.8 J/4 ns/10 Hz) from a Nd:YAG laser. The use of the gas puff target instead of a solid target makes possible to generate EUV light without debris production associated with the laser ablation. The sources are equipped with optics to focus EUV radiation. Three various EUV optical system have been designed and developed. The grazing incidence axisymmetrical ellipsoidal mirror, the “lobster eye” grazing incidence multifoil mirror, and the ellipsoidal mirror with Mo/Si multilayer coating. The grazing incidence mirrors allow to focus EUV light in a relatively broad wavelength range with maximum near 10 nm with EUV fluency of about 30 mJ/cm2 in the focus at a diameter of about 0.5 mm. In the case of the Mo/Si mirror EUV fluency in the focus was about 20 mJ/cm2, however, in a narrow wavelength band near 13.5 nm. Quasi-monochromatic EUV source at 13.8 nm dedicated for nanoimaging using a Fresnel zone plate has been demonstrated combining an argon gas puff target with the Mo/Si mirror. Application of these new sources in high aspect ratio micromachining of polymers, modification of polymer surface, and imaging are presented and discussed.

7584-30, Session 11

Femtosecond laser direct writing of volume Fresnel zone plates

P. Srisungsitthisunti, O. K. Ersoy, X. Xu, Purdue Univ. (United States)

We propose a method of using femtosecond laser for direct writing of volume Fresnel zone plates with high diffraction efficiency. A volume zone plate consists of a number of Fresnel zone plate layers designed to focus light coherently to a single spot. We fabricated both low numerical aperture (NA) and high NA zone plates, resulting in a significant increase in overall diffraction efficiency. Low NA phase zone plates yield considerably higher diffraction efficiency, mainly due to the longer length of the filaments generated with modified index of refraction and robustness against phase errors caused during fabrication. High NA zone plates are more sensitive to light absorption and phase shift errors, but they achieve a reasonable performance with rapid laser direct writing. The performance of the volume zone plate is also simulated using the Hankel transform beam propagation method (Hankel BPM). The method utilizes circularly symmetric geometry and small step propagation to calculate the diffracted wave fields by VFZP layers. With the Hankel BPM, fast and accurate diffraction results can be obtained. The results show an excellent agreement with the scalar diffraction theory and the experimental results. The numerical method allows more comprehensive studies of the VFZP parameters to achieve higher diffraction efficiency.

7584-31, Session 11

High-quality percussion drilling of silicon with a CW fiber laser

J. X. Z. Yu, P. J. L. Webster, J. M. Fraser, Queen’s Univ. (Canada)

It has been shown that 200 nanosecond duration pulses from a MOPA fiber laser (wavelength: 1064 nm) cleanly micromachines silicon with little cracking or heat-affected zone. Results are far superior to previous work with shorter duration pulses (5 ns). The surprisingly high quality cuts achieved with this thermal machining process has been attributed to subsurface phase explosions occurring on time scales of 10 - 100 µs after laser exposure or a high-speed vaporization front that moves through the sample. Its true nature, however, is still uncertain. In this paper, we show that similar results can be achieved using a 1070 nm CW fiber laser pulsed with a 10 µs duration (average power 30 W) in combination with coaxial nitrogen assist gas. The holes are cut at 45 kHz repetition rate with a resulting diameter on the order of 50 µm. Hole size is increased for longer pulses (17 µs) and the heat-affected zone broadens to greater than 100 µm with no assist gas. By combining low-coherence microscopy with machining, we can look below the machining front and obtain in situ images during and after the cutting process showing rich cut dynamics and relaxation in real time. This diagnostic, in combination with modeling, is being used to further elucidate the underlying mechanisms of the machining process.

7584-32, Session 11

MOPA based Yb fibre laser: a new low cost tool for micromachining

K. Li, W. O’Neill, Univ. of Cambridge (United Kingdom)

Fibre laser in MOPA configuration is a very flexible tool for micromachining applications since the pulse parameters such as repetition rates, pulse energy and pulse duration (indirectly) can be adjusted independently while maintaining a constant beam quality.

The developed fibre laser provides a wide range of pulse parameters at a maximum average power of 20W. Its full pulse duration and repetition rate are continuously changeable from 10ns to 200ns and from 25kHz to 500kHz. Ablation experiments were carried out on silicon, silicon carbide, stainless steel and glassy carbon with the goal of optimising removal rates or surface finish using nanosecond pulses of different parameters. Maximum removal rates are achieved on all four materials using relatively similar pulse parameters. For silicon, pulse duration of 200ns at 25kHz and 0.8mJ pulse energy resulted in optimum removal. In percussion drilling experiments a significant influence of the temporal pulse profile was found with a distinct optimum for etch rate and surface finish. The most favorable intensity at the work piece is in the range of 40MWcm^-2 to 200MWcm^-2. Lower values are not efficient, while the plasma shielding effect limits considerable increases in ablation rates for intensities above 200MWcm^-2.

The same laser was also used for cleaning of machined sample surface at much lower fluence; the technique proved successful in removing debris and was integrated within the machining operation itself.

7584-33, Session 11

Laser micromachining of metallic glasses: investigation of the material response to machining with micro-second and pico-second lasers

I. Quintana, Tekniker (Spain); T. Dobrev, Cardiff Univ. (United Kingdom); A. Aranzabe, Tekniker (Spain)

Metallic glasses have been preferred to crystalline alloys for applications in microelectronics mechanical systems and die components because of their ease of formability and excellent mechanical properties. This paper presents the machining response of amorphous and polycrystalline Ni-based alloys (Ni78 B14 Si8) and Fe alloys (Fe81 B13.5 Si3.5 C2) when subjected to micro-second and pico-second laser processing. The shape and topography of craters created with single pulses as a function of laser energy together with holes drilled and laser milled areas in both materials were studied. Focused ion beam (FIB) imaging and Electron Backscatter Diffraction (EBSD) technique were used to analyse the single craters, through holes and milled trenches in the amorphous and polycrystalline samples. The material microstructure analysis revealed that processing both materials with micro-second and pico-second lasers does not lead to crystallisation and the short-range atomic ordering of metallic glasses can be retained. When processing the amorphous sample the material laser interactions resulted in a significant ejection of molten material from the bulk that was then followed by its partial re-deposition around the craters. Additionally, there were no signs of crack formation that indicate a higher surface integrity after laser machining. This integrity is closely related to the nature of the metallic glass. A conclusion is made that laser processing both with short- and long-pulses is a promising technique for micromachining metallic glasses because it does not lead to material crystallisation, preserving the good mechanical properties of these sort of materials.

7584-34, Session 11

355nm DPSS UV laser micro-processing for semiconductor and electronics industry

F. Zhang, J. Duan, X. Zeng, X. Li, Wuhan National Lab. for Optoelectronics (China)

During the last decade, diode-pumped solid state (DPSS) lasers have been gained wider application in semiconductor and electronics industry due to the advantages of high efficiency, low operating cost, good beam quality and flexibility as well as miniature size. Owing to the ever-decreasing size of both semiconducting and electronic products, the DPSS laser with shorter wavelength will play a very important role in micro-processing the materials in order to get the higher processing quality and precision. Now, 355nm DPSS UV laser has increasingly been adopted in micro-processing application for both semiconductor and electronics industry where both micro-processing quality and precision of high-density, multi-layer and multi-material components are in a strong demand. A large numbers of works on typical applications of 355nm DPSS UV laser micro-processing both semiconducting and electronic materials have been introduced in this paper, including drilling (50 to 100µm blind holes in multi-layer FPC, 30µm through holes in thin Nickel plate), cutting (cover-layer, rigid-flex PCB, ultra-thin ceramic chips and 0.6mm silicon), and etching (ITO and FTO function film circuit). The effects of the processing parameters (pulse energy, frequency, peak power, scanning speed and focal plane position as well as processing modes) on the micro-processing quality and precision have been investigated and analyzed. By optimizing the processing parameters, the blind drilling depth to the second copper layer can be controlled accurately and the roughness Sq 1.33µm on the second copper surface can be achieved. A high quality and size precision (position precision 20µm) cutting edge without charring, burrs and micro-cracks as well as with very small heat affected zone (HAZ) can be also obtained. When etching function film, the etching width is less than 20 micron, and the etching speed is more than 500mm/s.

7584-24, Session 12

Structuring of thin film solar cells

G. Eberhardt, U. Wagner, JENOPTIK Automatisierungstechnik GmbH (Germany); T. Peschel, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

The innovative JENOPTIK-VOTANTM Solas series are mechanical scribing and laser processing systems for structuring of thin film solar cells. The universal machine base of the JENOPTIK-VOTANTM Solas series can be equipped with any laser or scribing tool according to the particular structuring process.

Laser structuring of the different types of thin film layers is a state of the art process in the photovoltaic industry. TCO layers and molybdenum are structured with e.g. 1064 nm lasers. Amorphous silicon, microcrystalline silicon or cadmium telluride are ablated with 515/532 nm lasers. Typical pulse durations of the laser in use for these material ablation processes are in the nano second range.

Up to now the common process for CIS/CIGS cells is needle structuring. Hard metal needles scibe lines with a width of 30 to 60 µm in the semiconductor material. A laser technology would have some advantages against the mechanical scribing. The precision of the lines would be higher (no chipping effects), the laser has no wear out. The dead area can be significantly smaller with the laser technology.

So we investigate the structuring of CIS/CIGS materials with ultra short pulse lasers of different wavelengths. The ablation rates and the structuring speeds against the repetition rates have been established. For the different layer thicknesses and line widths we determined the necessary energy densities. After all tests now we can calculate the possible reduction of the dead area on the thin film module. The new technology reach up to 3.5% more efficiency per module.

7584-25, Session 12

‘Green processing’ of thin film with top-hat lasers and applications in photovoltaic

K. Du, EdgeWave GmbH (Germany)

In the talk we will discuss the fundamental aspect of ablation processes by using laser beams of different intensity profiles and cross sections. For characterizing the efficiency of pulse energy for the ablation process the effective energy efficiency and the effective overall efficiency can be used. The effective energy efficiency and effective overall efficiency of laser beams with circular Gaussian profile and two dimensional top-hat profile will be given. The circular Gaussian profile with a maximum effective overall efficiency of 30% is the most inefficient beam for ablation process. Ideal two dimensional top-hat profile has 100% effective overall efficiency and is the most efficient choise for thin film ablation process. Also the lowest influence of waste energy during ablation process with two dimensional top-hat profile is expected. In the talk energy and cost effective system concepts for “green processing” at high through put and application results in photovoltaic will be discussed.

7584-26, Session 12

Productivity and flexibility, the key factors for laser processing in photovoltaic manufacturing

M. Moody, InnoLas, Inc. (United States)

The uses of lasers in photovoltaic production have become more predominate as photovoltaic technology has exponentially advanced over the last several years. Lasers are now used in many different applications such as edge isolation, emitter wrap through (EWT), laser fired contacts (LFC), contact opening and drilling. In addition to these crystalline applications the introduction of photovoltaic thin films to the

market place has created additional applications for laser scribing. The selection of the appropriate laser for each application depends on many aspects of functionality to achieve the desired productivity goals.

As photovoltaic technology is rapidly changing because of the availability of new lasers in the marketplace, laser machine tool technology is also changing rapidly to meet the upcoming demands of the industry. Photovoltaic laser machine tools must use the latest beam delivery technology along with advanced concepts in substrate handling to achieve productivity goals while maintaining the flexibility to address new applications as they emerge in the future. The machine concepts must also be feasible for scale up in order to continue the rate of photovoltic technology advances. This paper discusses the proper selection of lasers to specific applications in photovoltaic manufacturing and also includes a review of new concepts in photovoltaic laser machine tool design that can be relied upon to insure reliable scale up from research and development to full production with the flexibility to incorporate new laser technology as it emerges.

7584-27, Session 12

Microstructuring and wafering of silicon with laser chemical processing

S. Hopman, A. Fell, K. Mayer, F. Granek, Fraunhofer-Institut für Solare Energiesysteme (Germany)

Laser processing is already widely applied in the fabrication of silicon solar cells, e.g. buried contacts, laser fired contacts or edge isolation. At Fraunhofer ISE a liquid-jet guided laser is used for Laser Chemical Processing (LCP) of silicon solar cells. Both the fundamentals of material ablation using this laser system and the application of various processes to solar cell fabrication are investigated. The applications are divided into two main areas: Microstructuring and deep laser cutting (wafering) of silicon substrates.

Microstructuring includes investigation of laser induced defects in comparison to standard laser systems and ablation efficiencies depending on laser parameters and liquid properties. We will consider the laser induced damage by TEM measurements and defect etch for different laser parameters in comparison to a standard laser.

However one of the most important and industrial relevant topics at the moment is the formation of a selective highly doped emitter under the metal fingers of solar cells. In this presentation newest results concerning concentration variations of the phosphoric acid jet for the local n-type doping will be shown with regard to the obtained contact resistance. Moreover, the improvement of contact resistance and solar cell performance by introduction of the selective emitter will be shown by comparison of solar cells with and without LCP emitters.

The second working area, wafering, is another promising application of LCP in the field of silicon photovoltaics. A 70 mm deep laser cut in silicon block was already demonstrated with a long pulse laser. To reduce the damage introduced by the laser processing in the silicon crystal lattice, a laser with shorter pulse lengths was tested. The system consists of two separately controllable lasers. We will present the influence of pulse length, pulse energy and repetition rate of the laser on the ablation efficiency of silicon.

7584-28, Session 12

Advanced laser techniques from semiconductor manufacturing transition to solar PV production

M. Mendes, R. Slagle, J. Fu, X. Song, C. Porneala, M. Hannon, J. P. Sercel, JPSA (United States)

Semiconductor manufacturing, a mature industry, uses a number of laser techniques in production. Diode-pumped solid-state (DPSS) lasers are used in applications that cannot be performed by mechanical, chemical, or other laser fabrication methods and where they add value through increased throughput and/or improved process quality. Applications such as wafer scribing/dicing, via formation, blind features, surface texturing, laser doping and annealing for Semicon are being applied to crystalline silicon PV manufacture as well as research and development for the next generation of high efficiency cells. Similarly, selective material removal for exposing underlying layers without thermal damage is vital in the production of thin film PV panels.

In this paper, some of the most important applications of lasers along with experimental results will be reviewed to illustrate how laser methods can have a significant impact on the development and productivity of the photovoltaic industry.

7584-32, Session 12

Monolithic interconnection of CIGS solar cells by picosecond laser structuring

H. P. Huber, C. Hellwig, G. Heise, T. Kuznicki, S. Sarrach, C. Menhard, Hochschule München (Germany); A. Heiss, H. Vogt, J. Palm, AVANCIS GmbH & Co KG (Germany)

We report on the selective structuring of CIS (Cu(In,Ga)(S,Se)2) thin film solar cells applying picoseconds lasers at 1064 nm. The thin layers are selectively separated by so called laser patterns 1, 2 and 3 (P1, P2 and P3) for the monolithic serial inter¬con¬nection.

We demonstrate that the half micron thick Molybdenum back electrode can be structured with a P1 process speed of more than 4 m/s without detectable residues and damages by direct induced laser ablation from the back side. A ~2 µm thick CIS layer is structured by standard direct laser ablation at higher energy densities and P2 process speed up to 200 mm/s. A 1.5 µm thick ZnO front electrode layer can be line separated with P3 speeds up to several 1000 mm/s by indirect induced laser ablation.

We demonstrate that direct induced (P1) and indirect induced (P3) picosecond laser ablation are not purely thermal processes working at energy densities far below the evaporation enthalpy. The validation of the processes for the functionality within a CIS solar cell will be presented.

7584-35, Session 12

Investigation on production of highly textured Sb doped polycrystalline silicon using solid state Nd:YAG laser for photovoltaic application

P. A. Iyamperumal, Indian Institute of Technology Madras (India); N. J. Vasa, Indian Institute of Technology Madras (India) and Kyushu Univ. (Japan); S. Makaram, Indian Institute of Technology Madras (India); O. Tatsuo, Kyushu Univ. (Japan)

Efficient doping of amorphous silicon(a-Si) is a key issue in the field of photovoltaic applictaions. The laser doping of a-Si with a metalic materials like antimony will have the crystallization of amorphous silicon and subsequent diffusion of antimony. In addition to laser doping, lasers can also be used to produce a textured surface on the silicon surfaces so as to minimize the reflection from the surface. This means creating a roughened surface so that the incident light may have a large probability of being absorbed into the solar cell. Hence in this paper an attempt has been made to produce an highly textured Sb doped a-Si and the charetecteristics were analysed.

The amorphous silicon are coated with Sb to a thickness of 200nm using vacuum evaporation method and treated with an Nd:YAG laser of 355nm with a threshold fluence of 460mJ/cm2 by overlapping the laser spots to 90% of its size, so as to crystallize subsequently induce texture. The samples are retretaed with a low laser fluence of 230mJ/cm2 respectively so as to crytsallize and diffuse the Sb on to the surface and to activate the dopant. The laser doped and subequently laser textured samples were analysed through Scanning Electron microscope (SEM), X-ray diffraction (XRD) & Atomic Force Microscope(AFM). The Photoconductivity, halleffect charecteristics and absorbance are investigated.

The traces of SiSb in the XRD peak with improved surface roughness were observed on the laser doped samples. This represents that the dopants are highly diffused on the a-Si .

Conference 7585: Laser-based Micro- and Nanopackaging and Assembly IV

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7585-29, Poster Session

Thermal dissipation modeling in optical components modules for electrical power consumption optimization

G. Sabot, J. Chaudenson, F. Raulin, Supélec (France); R. Brenot, Alcatel-Thales 3-5lab (France); J. Jacquet, Supélec (France)

In a semi-conductor optical amplifier (SOA) as in any other optical devices, the performances that can be reached is strongly dependent on the chip temperature. For example, the optical output power of a laser or the optical gain in a SOA is reduced when the temperature of the junction increases. This latter can be controlled or monitored thanks to a thermo-electronic cooler (or a Peltier element) and a thermistor. In this paper, we first have calculated the thermal resistance of various semiconductor structures such as buried or ridge waveguides lasers. We then calculate the Peltier consumption necessary to maintain a given temperature. The influence of the thermistor position as well as the module conception have been investigated in these calculation. The size of the different mechanical elements, the nature and thermal properties of the material use for the module fabrication or the use of different inert gas inside the module have been found to play an important role in the thermal performance of the optical modules. The Peltier size is defined by maximizing its efficiency. It depends on the power to be dissipated as well as the temperature operation of the device. The latter depends on the performance expected by the optical devices. We discussed the optimization of the device structure associated to its packaging to find the best compromise between performance and electrical consumption.

7585-30, Poster Session

Threshold measurement of two-photon laser induced photo-polymerization via Z-scan

Y. B. Boiko, YBBR, Inc. (Canada)

A technique is suggested to measure a threshold of two-photon initiated photopolymerisation involving Z-scan of a thin film of sensitive material along the focusing axis of the laser beam. The condition of reaching the threshold when gradually increasing the light intensity by moving the film towards the focal spot of the beam is defined as that with minimal intensity at which polymerization occurs. The occurrence of the polymerization is detected by interferometric effect inside the transmitted beam itself, which is due to interference of the wave going through the polymerization area and the wave going around it. The technique is demonstrated for measurements employing Nd:YAG laser in nanosecond regime with fundamental frequency 1064 nm and its harmonic of 532 nm, as well as with pumped by its third harmonic optical parametric oscillator. Threshold data are presented for particular systems, indicating threshold of 5 GW/cm^2 for a system based on Rose Bengal exposed by 1064 nm nanosecond-pulsed radiation and 0.05 GW/cm^2 for Darocur initiators exposed to 532 nm. Suggested technique has advantages over existing approaches of threshold measurement due to the following: 1) it is wet-processing free; 2) it provides measurement of parameter directly connected to the value of threshold; 3) it is one-pulse technique. Alternative reported techniques of threshold measurement suffer from either involving wet-processing of the polymer, or requiring extrapolation beyond the measuring region, which limits the precision of the estimated threshold values. A suggested technique can offer capability of calibration of other alternative techniques via reliable direct measurement.

7585-31, Poster Session

Single femtosecond pulse nanochannel formation in glass

J. F. Herbstman, A. J. Hunt, Univ. of Michigan (United States)

Single pulse femtosecond laser damage in transparent dielectrics has been shown to occur through nonlinear damage mechanisms that can allow material removal on scales well below the classical limit of the order of the wavelength of the incident light. These mechanisms can be harnessed to allow the optical machining of devices on the nanoscale.

We observe the formation of high aspect-ratio nanochannels from single femtosecond pulses. These channels, several microns in length, can be formed at the front or rear surface of a sample, conditions under which spherical aberration is expected and where it is minimized. The presence of similar channels at both locations presents evidence that aberration does not play a critical role in nanochannel creation, but rather self focusing and microscale filamentation play a dominant role.

Applications for these long nanoscale diameter channels include nanopores, nanowells, or out-of-plane vias. The ability to generate these channels with single pulses allows rapid fabrication that complements existing techniques, thus addressing a major limitation to microfluidic fabrication.

7585-01, Session 1

Welding with brilliant lasers: prospects and limitations

S. M. Kittel, Robert Bosch GmbH (Germany); F. Dausinger, Dausinger + Giesen GmbH (Germany)

Now that high brightness laser sources are commercially available, extremely small focal diameters and high power densities can be realized leading to a high aspect ratio at low heat input. With regard to an increase in productivity this implies a deeper weld depth at higher feed rate and hence at shorter processing time.

In order to identify the prospects and limitations of the application of high brightness beam sources in laser welding, focal diameters from 195 µm down to 15 µm were generated by means of a modular optical system. An examination of the weld seam geometry and weld pool dynamics was done by conducting metallographical analysis and by observation using a high speed camera. Thus, the influence on process stability was evaluated: Through correlation of longitudinal cross-sections and high speed camera observation, an interrelationship between spiking and capillary breakdowns was derived. In addition, a dependency of the start of humping on laser power, feed rate and spot diameter could be found.

By this parametric study the influence of a minimal focus spot on the deep welding process is examined. It can be deduced that a small spot is not the best choice for every application. In dependence of the particular spot size and the beam quality of the laser source a new processing range arises. These observations are put down to theoretical beam properties and a fundamental thesis about the applicability of a high brightness laser is derived. Eventually it shows that a small beam diameter is most advantageous for micro application.

7585-02, Session 1

Compound characterization of laser brazed SiC-steel joints using tungsten reinforced SnAgTi-alloys

I. J. Suedmeyer, M. Rohde, T. Fuerst, Karlsruhe Institute of Technology (Germany)

With the help of a CO2-laser (l = 10.64 µm) a Silicon carbide (Trade name: Ekasic-F, Comp: ESK Ceramics) has been brazed to commercial steel (C45E, Matnr. 1.1191) using SnAgTi-filler alloys. The braze pellets were dry pressed on the basis of commercially available powders and polished to a thickness of 300 µm. The SnAgTi-fractions were varied with the objective of improving the compound strength. Furthermore, tungsten reinforced SnAgTi-fillers were examined with regard to the shear strength of the ceramic/steel joints.

Polished microsections of SnAgTi-pellets were investigated before brazing in order to evaluate the particle distribution and to detect potential porosities using light microscopy. The brazing temperature and the influence of the reinforcing particles on the active braze filler were determined by measurements with a differential scanning calorimeter (DSC). After brazing the ceramic-steel joints were characterized by scanning electron micrographs and EDX-analysis. Finally the mechanical strength of the braze-joints was determined by shear tests.

7585-03, Session 1

Laser-based joining for the packaging of miniature optoelectronic devices

D. P. Hand, N. Lorenz, S. Miller, Heriot-Watt Univ. (United Kingdom)

In recent years various techniques have been developed for the manufacture of microsystems and other miniature optoelectronic devices. However, one aspect where there remains significant room for improvement is the packaging process. Packaging is vital to protect the devices from the (sometimes harsh) external environment, whilst typically allowing specific environmental interactions. Standard packaging techniques involve heating whole devices to high temperatures, in some cases combined with strong electric fields. These high temperatures prevent the use of temperature-sensitive materials within the package (e.g. polymer and magnetic materials) and in particular generate problems with multi-step manufacturing processes where a number of thermal process steps are carried out in sequence; here a later heating step can cause parts joined earlier to disassemble.

We have demonstrated that it is feasible to use a laser as a highly localised heat source for hermetic bonding of micro devices. Our processes make use of an appropriate intermediate bonding layer (e.g. thermo-setting polymer; glass frit) to generate a high quality join whilst maintaining a low overall device temperature. In this paper we will concentrate on recent developments, (i) to enable hermetic packaging of devices containing an inert gas or even a vacuum, and (ii) to move from the packaging of single chip devices to wafer-level packaging, where many devices are packaged on a single wafer, before it is diced. This approach allows for simpler work-handling, reduces the time required for alignment, and protects the manufactured devices during the dicing process.

7585-04, Session 1

Submicron accuracy optimization for laser beam soldering processes

E. Beckert, T. Burkhardt, M. Hornaff, A. Kamm, I. Scheidig, C. Stiehl, R. Eberhardt, A. Tünnermann, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

Laser beam soldering is a packaging and joining technology alternative to common polymeric adhesive bonding processes in terms of stability (long term, temperature and radiation) and functionality (current and heat conduction). Nevertheless, when packaging especially micro optical and MOEMS systems this joining technology has to fulfil stringent requirements for accuracy in a micron and submicron range. Laser based solder reflow provides time and space restricted energy input and thus is a proper basis for precision assembly. But even minimized energy input by laser still affects accuracy due to phase changing effects of solder resolidification as well as negative expansion during down-cooling from liquidus to room temperature. On the other hand, when applying very precise volumes of solder this negative expansion, being very reproducible, can be used for pre- compensation of dealignment as well as accurate post bond alignment. When investigating the assembly of several laser and micro optical systems it has been shown that accuracy in the range of 2 to 5 microns and reproducibilities of ±1 to ±0.5 microns can be reached when using a design-of-experiment optimised soldering process that is based on flexibly applying liquid solder drops (“Solder Bumping”) onto joining surfaces of optical components that have been coated with wettable metallizations. Small dealignments were proven with different configuration, while the soldered assemblies were subject to thermal cycles and vibration/ shock test afterwards, too. Even components that are based on very different materials (e.g. glass and copper) can be processed using proper reflow parameters and adapted joining geometries.

7585-05, Session 2

Laser sintering of thick-film microelectronics on plastic substrate

X. Xu, Purdue Univ. (United States)

The conventional method of fabricating thick-film microelectronics involves depositing the ink or paste pattern onto a substrate via screen printing, and functionalizing it by firing the paste at high temperature in a furnace. With the industry demand moving towards smaller feature sizes and faster manufacturing at affordable costs, the conventional methods fall short in meeting these requirements. This work investigates fabrication of functional microelectronics onto a plastic substrate by laser sintering of commercial thick-film paste. The method allows simultaneous sintering, patterning, and functionalization of various conductive paste including silver, copper, and carbon. Experiments are carried out to optimize the laser processing parameters. It is shown that sheet resistance values obtained by laser sintering are close to those specified by the manufacturer using conventional sintering methods. Fabrications of a number of electronic components such as capacitors and patch antennas are demonstrated. Additionally, heat transfer analyses using numerical methods are conducted to understand the relationship between the temperature during sintering and the sheet resistance values of sintered products. The process developed in this work has the potential of producing electronic components on low-cost plastic substrates.

7585-06, Session 2

Deposition of polymer barrier materials by resonant infrared pulsed laser ablation

S. M. Avanesyan, N. L. Dygert, Vanderbilt Univ. (United States); H. K. Park, AppliFlex LLC (United States); K. E. Schriver, R. F. Haglund, Jr., Vanderbilt Univ. (United States)

One of the major challenges in the fabrication of thin-film organic optoelectronic devices is providing appropriate barrier materials to inhibit the uptake of moisture, vapor or other environmental contaminants. By definition, these barrier layers must be insoluble, so the usual routes to polymer or organic film deposition by spin coating are not effective. Here we report recent results on vapor-phase deposition of polymer barrier and protective layers by resonant infrared pulsed laser deposition (RIR-PLD). Among the materials we have deposited are cyclic olefin copolymers (COC), poly(tetrafluoroethylene), polyimide and poly(ether imide). Film deposition based on resonant infrared laser ablation proceeds by resonant excitation of a localized, intra-monomer vibrational mode of the target material, such as a C-H stretch, leading to low-temperature evaporation and deposition of molecules. Because the mid-infrared photons used in this process have energies well below those required to break the bonds that connect monomer units, RIR laser irradiation ablates polymers without photofragmentation, unlike ultra-violet pulsed laser deposition (UV-PLD). In this paper, we focus on deposition of barrier and protective materials that are potentially useful in the fabrication of OLEDs (organic light emitting diodes. The deposited films are characterized by SEM (scanning electron microscopy) and FTIR (Fourier-transform infrared spectroscopy). We also compared the properties of films deposited by various mid-infrared lasers, including the free electron laser (FEL), Er;YAG laser and picosecond optical parametric oscillator (OPO). These comparisons provide a perspective on various infrared laser ablation processes and suggest the laser parameters needed to make RIR-PLD of barrier layers a viable commercial process.

7585-07, Session 2

Growth directions of carbon nanotubes controlled by different electrical bias polarities

Y. Gao, Y. Zhou, W. Xiong, M. Mahjouri-Samani, M. Mitchell, Y. Lu, Univ. of Nebraska-Lincoln (United States)

Carbon nanotubes (CNTs) of different alignments yield applications in different fields. Growth of CNTs of different alignments on metallic electrodes was achieved by applying biasing voltages with different polarities in a laser-assisted chemical vapor deposition (LCVD) process. Surface-bounded CNTs were found to crawl out from the positively charged electrodes. In contrast, vertically aligned CNTs were found to dominate the negatively charged electrodes. Based on a tip-growth mode, the movement of catalyst-nanoparticles (NPs) under the influence of external electric field was suggested to determine the different growth directions of the CNTs on the anodes and cathodes. The surface-bounded CNTs were ascribed to the repulsive force between the catalyst NPs and the anodes, while the vertically aligned CNTs were ascribed to the joint interactions from the attractive force between the catalyst NPs and the cathodes as well as the strong interactions among the CNTs. This observation suggests a convenient approach to control the alignment of CNT arrays for applications in different fields.

7585-08, Session 2

Mode-selective excitation of propylene molecules in diamond growth using a wavelength-tunable CO2 laser

Z. Xie, Y. Zhou, X. He, X. Shen, Y. Gao, Y. Lu, Univ. of Nebraska-Lincoln (United States)

A wavelength-tunable CO2 laser was introduced to the combustion-flame deposition of diamond using propylene/oxygen (C3H6/O2) as the precursors. The wavelength of the tunable CO2 laser was tuned to match the vibrational modes of the propylene molecules. The laser beam of a particular wavelength was perpendicularly irradiate the C3H6/O2 flame during the deposition of diamond films. The related propylene vibrational mode was resonantly excited, and a new reaction equilibrium was formed. The excitations of different vibrational modes show different influence on the diamond growth. Based on scanning electron microscopic and stylus profiling measurements, it was revealed that diamond growth was improved when the CH3 rocking, C=C-C bending, C=CH2 twisting, and C-H bending modes were resonantly excited separately using the external laser source. The diamond growth was improved both in particle size and film thickness. However, if the C-C stretching mode was excited, the growth of diamond was significantly suppressed and yielded poor diamond particles. Spatial-resolved excitation revealed that the suppression of diamond growth by exciting C-C stretching mode was most obvious when the laser beam is right under the nozzle tip.

7585-09, Session 2

Optical emission spectroscopy of the C2H4/C2H2/O2 flame for diamond growth with and without the CO2 laser excitation

X. He, T. T. Gebre, X. Shen, Y. Zhou, Z. Xie, Y. Lu, Univ. of Nebraska-Lincoln (United States)

Optical emission spectroscopy (OES) measurements were carried out to study the C2H4/C2H2/O2 combustion flame for diamond deposition with and without the CO2 laser excitation. According to the OES spectra, strong emission from radicals C2 and CH was observed in the visible range. It was discovered that the flow rate and volume ratio of the gas precursors could significantly influence the emission intensity of the radicals. By adding a continuous-wave CO2 laser to irradiate the flame at a wavelength of 10.591 μm, it was discovered that the emission intensities of the C2 and CH radicals were increased due to the laser beam induced excitation. OES measurements of the C2 and CH radicals were performed using different gas combinations and laser powers. The rotational temperatures of the CH radicals in the flame were determined by analyzing the spectra of the R-branch of the A2∆ X2∏ (0, 0) electronic transition near 430 nm. Information obtained from the OES spectra, including the emission intensities of the C2 and CH radicals, the intensity ratios, and the rotational temperatures, was integrated to the study of diamond deposition on tungsten carbide substrates for mechanism analysis on the laser induced vibrational excitation and laser-assisted diamond deposition.

7585-10, Session 3

Femtosecond laser direct writing of diffractive optical elements in polymers

W. Watanabe, H. Mochizuki, National Institute of Advanced Industrial Science and Technology (Japan)

Femtosecond laser micromachining allows the integration of diffractive optical elements in three dimensions. When femtosecond laser pulses are focused inside the bulk of transparent materials, filamentation occurs as a consequence of dynamic balance between Kerr self-focusing and defocusing effects in the electron plasma generated through the ionization process. The plasma density in the filamentary volume can become high enough to induce permanent filamentary structural modifications. Femtosecond laser filamentation is used to fabricate volumetric optical elements in polymer materials.

In this presentation, we review filamentary refractive index modifications in various polymer materials and the fabrication of diffractive optical elements. The 800-nm femtosecond laser pulses at 1 kHz repetition rate were focused with an objective lens in polymers. Diffraction efficiency of the fabricated Bragg gratings in polymers was investigated in terms of polymers density. The mechanisms of the refractive index modifications are discussed. The selective modification of the refractive index in silicone is a promising method for the fabrication of photonic structures such as three-dimensional integrated optical devices.

7585-11, Session 3

Fabrication of micro-lenses using excimer laser ablation by means of laser-generated greytone-masks

T. Klotzbücher, D. Dadic, Institut für Mikrotechnik Mainz GmbH (Germany)

Micro-lenses, including Fresnel-Lenses, were fabricated by excimerlaser ablation of polymers by means of laser-generated greytone-masks. The smallest reproducible holes that could be fabricated by excimerlaser ablation (193 nm, 1 J/cm²) of chromium-on-quartz (thickness 50-100 nm) were around 3 µm, the pitch of which should be at least at the same value to ensure a reproducibility of hole-arrays. To achieve acceptable ablation times during the fabrication of the greytone-masks, on-the-fly ablation instead of step-and-repeat technique was used, operating the laser at a constant pulse repetition rate <30 Hz with a continuously moving quartz-substrate. In this way and using different encoding techniques it was possible to generate at least 11 different greytones. The available greytones were used to generate greytone-masks for ablation of Polymethylmethacrylate (PMMA) and Polycarbonate (PC). For that, fluences in the range of 0.07-0.14 J/cm² could be applied, corresponding to a value of 1.25 J/cm² on the workpiece without greytone-mask and a value lying well below the damage threshold of the chromium mask. Refractive micro-lenses fabricated in this way did not show a good imaging quality, since 11 greytones is less than required to generate a continuous surface profile over the full diameter of the lens during ablation. Sub-structures (steps) are created which degrade image quality. However, diffractive micro-lenses of Fresenel type with a quasi-continuously surface profile could be fabricated in a sufficient manner. This can be attributed to the fact that each segment of the Fresenel-lenses can be encoded by 11 greytones, leading to much smoother surface reliefs and to a sufficient imaging quality.

7585-12, Session 3

Integration of electronics and photonics in active material by fs laser for functional microdevice fabrication

Y. Cheng, Z. Xu, Shanghai Institute of Optics and Fine Mechanics (China); K. Sugioka, K. Midorikawa, RIKEN (Japan)

Recently, hybrid integration of multifunctional micro-components for creating complex, intelligent micro/nano systems has attracted significant attention. These micro/nano systems have important applications in a variety of areas, such as healthcare, environment, communication, national security, and so on. Until now, fabrication of micro/nano systems incorporated with different functions is still a challenging issue, which generally requires fabrication of micro-components beforehand followed by assembly and packaging procedures. Thus, the fabrication process is complex and costly. In recent years, the rapid development of femtosecond laser microfabrication technology has enabled direct fabrication and integration of multifunctional components, such as microfluidics, microoptics, micromechanics, microelectronics, etc., into a substrate. Particularly, in this talk, we show the use of femtosecond laser microfabrication for integrating microelectronics and microphotonics. Both microelectrodes and optical waveguides can be directly embedded in active materials after a femtosecond laser direct writing followed by electroless chemical plating. As an example, a Mach-Zehnder based optical modulator is fabricated in $LiNbO_3$ crystal and its function is demonstrated.

7585-13, Session 3

Organic random laser in an optofluidic chip fabricated by femtosecond laser

K. C. Vishnubhatla, R. Osellame, G. Lanzani, R. Ramponi, T. Virgili, Istituto di Fotonica e Nanotecnologie, CNR, Politecnico di Milano (Italy)

Optofluidics is a rapidly emerging field and it culminates the integration of optics and novel microfluidics functions onto a single platform. This combination of the microfluidics with integrated optics has given rise to a new class of optofluidic devices. These Optofluidic devices are gaining importance, owing to their advantages over other solid state photonic counterparts like; 1) ease of integration with other microfluidic elements 2) tailoring of device characteristics by simple replacement of the fluids 3) some materials like conjugate polymers have certain beneficial properties, when in solutions as compared to their solid form. To take advantage of these properties, a practical configuration like an embedded microchannel is needed to handle the fluids and also to fabricate devices. Femtosecond Laser Irradiation and Chemical Etching (FLICE) is fast becoming a useful and reliable microfabrication technology for fabrication of embedded microchannels in glasses. Moreover, since the same laser can be used to produce low loss optical waveguides, these femtosecond laser based technologies could become a single-stop solution for fabrication of microfluidic channels and their integration with optical circuits. Here, for example, we demonstrate an optofluidic random lasing from a polyfluorene solution dispersed with TiO_2 ¬nanoparticles, contained in a microfluidic chip. On optical pumping, the polymer solution provides the gain and the amplification is achieved by the multiple random scattering of the stimulated emission from the nanoparticles. The scheme for integration of the random lasing to produce an on chip laser source will be presented.

7585-14, Session 3

Integrated optical circuits in fiber cladding by tightly focused femtosecond laser writing

V. A. Maselli, P. R. Herman, Univ. of Toronto (Canada)

Femtosecond laser direct writing in glass materials represents a simple single-step approach to generate three-dimensional (3D) optical circuits that cannot be constructed with traditional fabrication techniques. Numerous optical devices such as optical splitters, directional couplers, Bragg gratings, Mach-Zehnder interferometers and amplifiers have been previously demonstrated in bulk glasses and crystal optical materials that underpin new opportunities for generating compact optical circuits for Telecom, sensing and lab-on-chip microsystems.

In this paper, we present an attractive extension of such femtosecond laser processing to the writing of optical circuits directly inside the cladding of single-mode optical fiber. To enable the formation of strongly guided and undistorted waveguide modes within the small cylindrical fused silica volume (125 um diameter), frequency-doubled (lambda = 522 nm) Ytterbium fiber-amplified femtosecond laser light at high repetition rate (500 kHz) was tightly focused with a high 1.25 numerical aperture (NA) oil immersion lens. In this way, low-loss waveguides could be arbitrarily positioned in various cladding positions without generating ablation damage. Basic components such as directional couplers were demonstrated that present a new means for dense integration of optical components that effectively couple with the nearby core fiber waveguide. Such 3D all-fiber optical circuits present a practical means to bypass tedious assembly and packaging steps such as fiber pigtailing with planar lightwave and other types of optical circuits. The paper will discuss how femtosecond laser formation of optical circuits directly within the cladding of optical fiber opens new prospects for manufacturing compact and functional optical and optofluidic microsystems for widely based Telecom, sensing and lab-on-a fiber applications.

7585-15, Session 4

Direct micro-pattern machining of metal molds using pico-second lasers

S. Fujimaki, Toshiba Machine Co., Ltd. (Japan)

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7585-16, Session 4

Scaling ablation rates for picosecond lasers using burst micromachining

R. Knappe, H. Haloui, A. Seifert, A. J. Weis, A. Nebel, LUMERA LASER GmbH (Germany)

High-precision micromachining with picosecond lasers became an established process. Power scaling led to industrial lasers, generating average power levels well above 50W for applications like structuring turbine blades, micro moulds, and solar cells.

In this paper we report, how a smart distribution of energy into groups of pulses can significantly improve ablation rates for some materials, also providing a better surface quality.

Machining micro moulds in stainless steel, a net ablation rate of ~1mm³/min is routinely achieved, e.g. using pulse energy of 200µJ at a repetition rate of 200kHz. This is industrial standard, and demonstrates an improvement by two orders of magnitude over the recent years.

When the energy was distributed to a burst of 10 pulses (20µJ), repeated with 200kHz, the ablation rate of stainless steel was 5 times higher with the same 40W average power. Bursts of 10 pulses repeated with 1MHz (4µJ) even resulted in an ablation rate as high as 10mm³/min.

In addition, optimized pulse delays achieved a reduction of the surface roughness by one order of magnitude, providing Ra values as low as 200nm. Similar results were performed machining silicon, scaling the ablation rate from 1.2mm³/min (1 pulse, 200µJ, 200kHz) to 15mm³/min (10 pulses, 4µJ, 1MHz).

Burst machining of ceramics, copper and glass did not change ablation rates, only improved surface quality. For glass machining, we achieved record-high ablation rates of >60mm³/min, using a new state-of-the-art laser which could generate >70W of average power and repetition rates as high as 2MHz.

7585-17, Session 4

Enhancement of ablation efficiency by a femto/nano-second dual-beam micromachining system

C. Lin, Z. Rao, Missouri Univ. of Science and Technology (United States); L. Jiang, Beijing Institute of Technology (China); W. Tsai, P. Wu, C. Chien, Industrial Technology Research Institute (Taiwan); H. Tsai, Missouri Univ. of Science and Technology (United States)

In this paper, a dual-beam laser micromachining system consisting of a femtosecond (fs) laser and a nanosecond (ns) laser has been developed to enhance the ablation efficiency. Experiments were conducted on different materials including the dielectric (fused silica), semiconductor (silicon wafer), and metal (aluminum alloys). The amount of material being removed was determined for a single fs pulse alone (120 fs duration), a single ns pulse alone (30 ns duration), and a pair of one fs pulse and one ns pulse with different time lags in between. It was found that the material removal efficiency increases in the dual-beam process for all materials being studied as compared to the fs alone or ns alone, particularly for dielectrics. The highest ablation efficiency for fused silica occurs when the fs pulse is shot near the peak of the ns pulse envelope. A corresponding numerical model for dual beam ablation of dielectrics was also developed by integrating the plasma model, the improved two-temperature model, and Fourier's law to understand the laser-material interaction. The theoretical predictions are consistent with the experimental results. It was found that the fs laser pulse can significantly increase the free electron density and change the optical properties of the dielectric, leading to the increase of absorption for the subsequent ns pulse energy. This study provides a fundamental understanding for the enhancement of material ablation efficiency, particularly for wide-band-gap dielectrics.

7585-18, Session 4

Precise ablation milling with ultra short pulsed Nd:YAG lasers by optical and acoustical process control

P. Weber, V. Schulze, Karlsruhe Institute of Technology (Germany)

Laser ablation milling with ultra short pulsed Nd:YAG lasers enables micro structuring in nearly all kinds of solid materials like metals, ceramics and polymers. A precise machining result with high surface quality requires a defined ablation process. Problems arise through the scatter in the resulting ablation depth of the laser beam machining process where material is removed in layers. Since the ablated volume may change due to varying absorption properties in single layers and inhomogeneities in the material, the focal plane might deviate from the surface of the work piece when the next layer is machined. Thus the focal plane has to be adjusted after each layer. A newly developed optical and acoustical process control enables an in-process adjustment of the focal plane that leads to defined process conditions and thus to better ablation results.

The optical process control is realized by assistance of a confocal white light sensor. It enables an automated work piece orientation before machining and an inline ablation depth monitoring. The optical device can be integrated for an online or offline process control. Both variants will be presented and discussed.

A further approach for adjustment of the focal plane is the acoustic process control. Acoustic emissions are detected while laser beam machining. A signal analysis of the airborne sound spectrum emitted by the process enables conclusions about process parameters like focal position or pulse intensity of the laser beam. Based on this correlation the acoustic process control is built up. The focal plane can then be readjusted during ablation.

7585-19, Session 4

Highest-speed dicing of thin silicon wafers with nanosecond-pulse 355nm q-switched laser source using line-focus fluence optimization technique

J. M. Bovatsek, R. S. Patel, Newport Spectra-Physics (United States)

Due to current and future anticipated widespread use of thin silicon wafers in the microelectronics industry, there is a large and growing interest in laser-based wafer dicing solutions. As the wafers become thinner, the laser advantage over saw dicing increases with regard to both speed and yield of the process. Furthermore, managing the laser heat input during the dicing process becomes more important with increasingly thin wafers. In this work, shaped-beam laser-cutting of thin (100um and below) silicon is explored with Newport / Spectra-Physics® Pulseo® 20W nanosecond-pulse 355nm DPSS q-switched laser system. Optimal process conditions for cutting various depths in silicon are determined, with particular emphasis on fluence optimization for a narrow-kerf cutting process. By shaping the laser beam into a line focus, the optimal fluence for machining the silicon can be achieved while at the same time utilizing the full output power of the laser source. In addition, by adjusting the length of the laser line focus, the absolute fastest speed for various cutting depths is realized. Compared to a circular beam, a dramatic improvement in process efficiency is observed.

7585-20, Session 5

Femtosecond nanomachining: theory and applications in biomedical research and analysis

A. J. Hunt, J. F. Herbstman, Univ. of Michigan (United States)

Classically, the limit for optical machining is on the order of the wavelength of the incident light. However, by taking advantage of nonlinear damage mechanisms that occur for femtosecond laser pulses, damage can be achieved on a scale an order of magnitude lower pushing the realm of optical device fabrication to allow nanomachining.

Femtosecond laser nanomachining can be carried out in a variety of dielectrics, and in a transparent substrates machining can be sub-surface, in contrast to other nanomachining techniques such as electron beam or focused ion beam. We focus on the use of glass, as it is in many ways an ideal material for use in biological applications due to its chemical, optical, electrical and mechanical properties.

Recent advances by our group and others technique have demonstrated the formation of high aspect ratio nanochannels from single pulses. These nanochannels have a wide range of applications as a standalone technique including the fabrication of nanopores and nanowells, but can also complement existing photolithographic device fabrication techniques by allowing precisely placed jumpers that can connect channels that are out of plane. We discuss applications for diagnostic microfluidic devices, and basic cell biology research.

7585-21, Session 5

Fabrication of dielectric and metallo-dielectric 3D nanostructures by direct laser writing and electroless plating

A. Radke, F. Wolff, T. Klotzbücher, Institut für Mikrotechnik Mainz GmbH (Germany); H. W. Giessen, Univ. Stuttgart (Germany)

Three-dimensional nanostructures were generated by direct laser writing via two-photon polymerisation. Ultrashort laser pulses emitted from a mode-locked titanium-sapphire laser were tightly focused into the photoresist SU 8 (MicroChem) by a high-resolution microscope objective (63x/1.40). The laser focus was scanned relative to the resist at constant speed with a computer-controlled XYZ piezo-stage to expose three-dimensional patterns. Feature sizes as small as 150 nm laterally and 400 nm vertically were achieved. To demonstrate the capabilities of this method, woodpile photonic crystals were fabricated that show a characteristic dip in transmission at near-infrared wavelengths. The spectral position of the transmission dip scales linearly with the grating period of the fabricated crystals. To investigate plasmon coupling in metallo-dielectric structures, metallised 3D nanostructures were fabricated. To obtain metallo-dielectric structures, at first dielectric templates in SU-8 were fabricated via direct laser writing that subsequently were coated with a thin silver film via electroless plating. It is demonstrated that completely closed silver films can be formed, even on convoluted 3D geometries.

7585-22, Session 5

Micropatterning and crystallization of sol-gel-derived dielectric film by laser direct writing

A. Watanabe, T. Tanase, K. Miyajima, Y. Kobayashi, M. Konno, Tohoku Univ. (Japan)

A new low-temperature process for the formation of crystalline micropatterns of dielectric materials was developed by applying the laser direct writing method to sol-gel-derived dielectric films. The beam from an Ar ion laser was focused and scanned on the sol-gel derived film, and it induced pyrolysis of the precursor film with spatially selectivity. The development of the film using an acidic solution gave crystalline micropatterns of dielectric materials with resolution of several microns. The crystallization process was investigated by micro-Raman spectroscopy. The micropatterns of crystalline lead zirconate titanate (PZT) and barium titanate (BT) were fabricated by laser direct writing method. The crystallization process was investigated by micro-Raman spectroscopy. The dielectric properties of the micropatterns were discussed.

7585-23, Session 5

Laser annealing of thin film cathode material for lithium ion batteries

R. Kohler, M. Bruns, P. Smyrek, S. Ulrich, Karlsruhe Institute of Technology (Germany); M. Przybylski, ATL Lasertechnik GmbH (Germany); W. Pfleging, Karlsruhe Institute of Technology (Germany)

The material development for advanced lithium ion batteries plays an important role in future mobile applications and energy storage systems. It is assumed that electrode materials made of nano-composited materials will improve battery lifetime and will lead to an enhancement of lithium diffusion and thus improve battery capacity and cyclability. Lithium cobalt oxide (LiCoO2) is commonly used as a cathode material. Thin films of this electrode material were synthesised by r.f. magnetron sputtering of LiCoO2 targets in pure argon plasma on silicon and stainless steel substrates. For the formation of the high temperature phase of LiCoO2 (HT-LiCoO2), which exhibits good electrochemical performance with a specific capacity of 140 mAh/g and high capacity retention, a subsequent annealing treatment is necessary.

For this purpose laser annealing of thin film LiCoO2 was investigated in detail. A high power diode laser system operating at a wavelength of 940 nm with an integrated pyrometer for temperature control was used. Different annealing temperatures (between 200°C and 700°C) and process gases (argon, oxygen, helium, nitrogen, ambient air) were applied. The grain size of the thin films could be controlled by either annealing temperature or annealing time. Additionally, laser annealing was applied to micro-structured thin films.

The as-prepared and the laser treated films were studied with Raman spectroscopy, X-ray photoelectron spectroscopy and X-ray diffraction to determine their stoichiometry and crystallinity. The development of HT-LiCoO2 and also the formation of a Co3O4 phase were discussed. The electrochemical properties of the manufactured films were investigated via electrochemical cycling against a lithium anode.

7585-24, Session 6

Structuring of thin film solar cells

G. Eberhardt, U. Wagner, JENOPTIK Automatisierungstechnik GmbH (Germany); T. Peschel, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

The innovative JENOPTIK-VOTANTM Solas series are mechanical scribing and laser processing systems for structuring of thin film solar cells. The universal machine base of the JENOPTIK-VOTANTM Solas series can be equipped with any laser or scribing tool according to the particular structuring process.

Laser structuring of the different types of thin film layers is a state of the art process in the photovoltaic industry. TCO layers and molybdenum are structured with e.g. 1064 nm lasers. Amorphous silicon, microcrystalline silicon or cadmium telluride are ablated with 515/532 nm lasers. Typical pulse durations of the laser in use for these material ablation processes are in the nano second range.

Up to now the common process for CIS/CIGS cells is needle structuring. Hard metal needles scibe lines with a width of 30 to 60 µm in the semiconductor material. A laser technology would have some advantages against the mechanical scribing. The precision of the lines would be higher (no chipping effects), the laser has no wear out. The dead area can be significantly smaller with the laser technology.

So we investigate the structuring of CIS/CIGS materials with ultra short pulse lasers of different wavelengths. The ablation rates and the structuring speeds against the repetition rates have been established. For the different layer thicknesses and line widths we determined the necessary energy densities. After all tests now we can calculate the possible reduction of the dead area on the thin film module. The new technology reach up to 3.5% more efficiency per module.

7585-25, Session 6

‘Green processing’ of thin film with top-hat lasers and applications in photovoltaic

K. Du, EdgeWave GmbH (Germany)

In the talk we will discuss the fundamental aspect of ablation processes by using laser beams of different intensity profiles and cross sections. For characterizing the efficiency of pulse energy for the ablation process the effective energy efficiency and the effective overall efficiency can be used. The effective energy efficiency and effective overall efficiency of laser beams with circular Gaussian profile and two dimensional top-hat profile will be given. The circular Gaussian profile with a maximum effective overall efficiency of 30% is the most inefficient beam for ablation process. Ideal two dimensional top-hat profile has 100% effective overall efficiency and is the most efficient choise for thin film ablation process. Also the lowest influence of waste energy during ablation process with two dimensional top-hat profile is expected. In the talk energy and cost effective system concepts for “green processing” at high through put and application results in photovoltaic will be discussed.

7585-26, Session 6

Productivity and flexibility, the key factors for laser processing in photovoltaic manufacturing

M. Moody, InnoLas, Inc. (United States)

The uses of lasers in photovoltaic production have become more predominate as photovoltaic technology has exponentially advanced over the last several years. Lasers are now used in many different applications such as edge isolation, emitter wrap through (EWT), laser fired contacts (LFC), contact opening and drilling. In addition to these crystalline applications the introduction of photovoltaic thin films to the market place has created additional applications for laser scribing. The selection of the appropriate laser for each application depends on many aspects of functionality to achieve the desired productivity goals.

As photovoltaic technology is rapidly changing because of the availability of new lasers in the marketplace, laser machine tool technology is also changing rapidly to meet the upcoming demands of the industry. Photovoltaic laser machine tools must use the latest beam delivery technology along with advanced concepts in substrate handling to achieve productivity goals while maintaining the flexibility to address new applications as they emerge in the future. The machine concepts must also be feasible for scale up in order to continue the rate of photovoltic technology advances. This paper discusses the proper selection of lasers to specific applications in photovoltaic manufacturing and also includes a review of new concepts in photovoltaic laser machine tool design that can be relied upon to insure reliable scale up from research and development to full production with the flexibility to incorporate new laser technology as it emerges.

7585-27, Session 6

Microstructuring and wafering of silicon with laser chemical processing

S. Hopman, A. Fell, K. Mayer, F. Granek, Fraunhofer-Institut für Solare Energiesysteme (Germany)

Laser processing is already widely applied in the fabrication of silicon solar cells, e.g. buried contacts, laser fired contacts or edge isolation. At Fraunhofer ISE a liquid-jet guided laser is used for Laser Chemical Processing (LCP) of silicon solar cells. Both the fundamentals of material ablation using this laser system and the application of various processes to solar cell fabrication are investigated. The applications are divided into two main areas: Microstructuring and deep laser cutting (wafering) of silicon substrates.

Microstructuring includes investigation of laser induced defects in comparison to standard laser systems and ablation efficiencies depending on laser parameters and liquid properties. We will consider the laser induced damage by TEM measurements and defect etch for different laser parameters in comparison to a standard laser.

However one of the most important and industrial relevant topics at the moment is the formation of a selective highly doped emitter under the metal fingers of solar cells. In this presentation newest results concerning concentration variations of the phosphoric acid jet for the local n-type doping will be shown with regard to the obtained contact resistance. Moreover, the improvement of contact resistance and solar cell performance by introduction of the selective emitter will be shown by comparison of solar cells with and without LCP emitters.

The second working area, wafering, is another promising application of LCP in the field of silicon photovoltaics. A 70 mm deep laser cut in silicon block was already demonstrated with a long pulse laser. To reduce the damage introduced by the laser processing in the silicon crystal lattice, a laser with shorter pulse lengths was tested. The system consists of two separately controllable lasers. We will present the influence of pulse length, pulse energy and repetition rate of the laser on the ablation efficiency of silicon.

7585-28, Session 6

Advanced laser techniques from semiconductor manufacturing transition to solar PV production

M. Mendes, R. Slagle, J. Fu, X. Song, C. Porneala, M. Hannon, J. P. Sercel, JPSA (United States)

Semiconductor manufacturing, a mature industry, uses a number of laser techniques in production. Diode-pumped solid-state (DPSS) lasers are used in applications that cannot be performed by mechanical, chemical, or other laser fabrication methods and where they add value through increased throughput and/or improved process quality. Applications such as wafer scribing/dicing, via formation, blind features, surface texturing, laser doping and annealing for Semicon are being applied to crystalline silicon PV manufacture as well as research and development for the next generation of high efficiency cells. Similarly, selective material removal for exposing underlying layers without thermal damage is vital in the production of thin film PV panels.

In this paper, some of the most important applications of lasers along with experimental results will be reviewed to illustrate how laser methods can have a significant impact on the development and productivity of the photovoltaic industry.

7585-32, Session 6

Monolithic interconnection of CIGS solar cells by picosecond laser structuring

H. P. Huber, C. Hellwig, G. Heise, T. Kuznicki, S. Sarrach, C. Menhard, Hochschule München (Germany); A. Heiss, H. Vogt, J. Palm, AVANCIS GmbH & Co KG (Germany)

We report on the selective structuring of CIS (Cu(In,Ga)(S,Se)2) thin film solar cells applying picoseconds lasers at 1064 nm. The thin layers are selectively separated by so called laser patterns 1, 2 and 3 (P1, P2 and P3) for the monolithic serial inter¬con¬nection.

We demonstrate that the half micron thick Molybdenum back electrode can be structured with a P1 process speed of more than 4 m/s without detectable residues and damages by direct induced laser ablation from the back side. A ~2 µm thick CIS layer is structured by standard direct laser ablation at higher energy densities and P2 process speed up to 200 mm/s. A 1.5 µm thick ZnO front electrode layer can be line separated with P3 speeds up to several 1000 mm/s by indirect induced laser ablation.

We demonstrate that direct induced (P1) and indirect induced (P3) picosecond laser ablation are not purely thermal processes working at energy densities far below the evaporation enthalpy. The validation of the processes for the functionality within a CIS solar cell will be presented.

7585-35, Session 6

Investigation on production of highly textured Sb doped polycrystalline silicon using solid state Nd:YAG laser for photovoltaic application

P. A. Iyamperumal, Indian Institute of Technology Madras (India); N. J. Vasa, Indian Institute of Technology Madras (India) and Kyushu Univ. (Japan); S. Makaram, Indian Institute of Technology Madras (India); O. Tatsuo, Kyushu Univ. (Japan)

Efficient doping of amorphous silicon(a-Si) is a key issue in the field of photovoltaic applictaions. The laser doping of a-Si with a metalic materials like antimony will have the crystallization of amorphous silicon and subsequent diffusion of antimony. In addition to laser doping, lasers can also be used to produce a textured surface on the silicon surfaces so as to minimize the reflection from the surface. This means creating a roughened surface so that the incident light may have a large probability of being absorbed into the solar cell. Hence in this paper an attempt has been made to produce an highly textured Sb doped a-Si and the charetecteristics were analysed.

The amorphous silicon are coated with Sb to a thickness of 200nm using vacuum evaporation method and treated with an Nd:YAG laser of 355nm with a threshold fluence of 460mJ/cm2 by overlapping the laser spots to 90% of its size, so as to crystallize subsequently induce texture. The samples are retretaed with a low laser fluence of 230mJ/cm2 respectively so as to crytsallize and diffuse the Sb on to the surface and to activate the dopant. The laser doped and subequently laser textured samples were analysed through Scanning Electron microscope (SEM), X-ray diffraction (XRD) & Atomic Force Microscope(AFM). The Photoconductivity, halleffect charecteristics and absorbance are investigated.

The traces of SiSb in the XRD peak with improved surface roughness were observed on the laser doped samples. This represents that the dopants are highly diffused on the a-Si .

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7586-20, Poster Session

Generation of extended-area femtosecond laser induced periodic nanostructures on TiO2 by moving samples through a line focus

K. Dasari, S. K. Das, A. Rosenfeld, R. Grunwald, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany)

Nanostructured titanium dioxide (TiO2) is of growing importance for applications like superwetting, photocatalysis, antifogging, photovoltaics, gas sensors and electronic devices. Because of its specific biocompatibility, this material promises to essentially contribute in the development of innovative components for future biomedical technologies. To realize the functionalities of interest, extremely small structures have to be written into extended surface areas with high precision. In comparison to alternative approaches like multistep lithography, laser-induced periodic surface structuring (LIPSS) takes advantage of exploiting self-organization processes and thus enabling for an ultrafast parallel processing. The structuring of extended regions by this method can be realized by scanning of the sample under conditions optimized for a coherent linking. In comparison to a two-dimensional (2D) scan over N2 focal positions, an one-dimensional scan with a line focus over N positions is significantly less time consuming and requires one less high-precision translation stage thus making the fabrication procedure more convenient. In our experiments, the beam of a 40-fs Ti:sapphire laser was focused by a cylindrical lens while moving the sample in one direction. The formation of both high and low spatial frequency LIPSS (HSFL, LSFL) at second harmonic of Ti:sapphire-laser wavelengths (around 400 nm) at properly chosen scanning velocity and pulse energies is demonstrated. Structured multi-mm2 areas with periods of 80 nm and 325 nm were obtained corresponding to distinct sets of optimized parameters. The results are compared to data from literature achieved by other methods. The basic technical issues are discussed with particular respect to selected potential applications.

7586-21, Poster Session

Nuclear spin polarization of 3He atoms with a frequency doubled Ti:sapphire laser toward nuclear magnetic resonance of porous media

Y. Tabata, H. Yamada, S. Maeda, H. Morioka, H. Kumagai, A. Kobayashi, Osaka City Univ. (Japan)

Nuclear magnetic resonance techniques are extensively used as non-destructive methods for analyzing samples. Particularly, NMR based on laser-polarized noble gases has been attracted as a powerful technique for characterizing physical parameters of porous media and imaging human lungs. Therefore we have investigated the nuclear polarization of 3He atoms by metastability exchange optical pumping for enhancement NMR signals. In the presentation, we report the feasibility and the advantages of the polarization of 3He atoms utilizing the 23S-33P line at 389-nm wavelength as the optical pumping transition, in comparison with the conventional 23S-23P line at 1083-nm wavelength. The 389-nm wavelength light has been readily available with a development of an indium gallium nitride light-emitting diode (InGaN LED). The optical pumping light at 389-nm wavelength as a coherent light is obtained by frequency doubling the output of a CW Ti:sapphire laser with a nonlinear crystal (BiBO). The other light source for optical pumping at 1083-nm wavelength and measurement of the nuclear polarization is based on a diode laser. It was tested in the 1-mT magnetic field at the 3He gas pressure of 1-10 Torr.

7586-22, Poster Session

Visualization of nanostructure of alpha-Se prepared by pulsed laser photodeposition

N. Mirchin, S. A. Popesku, I. Lapsker, A. Peled, Holon Institute of Technology (Israel)

We evaluated the morphology of ultrathin -Se photodeposited nanostructures obtained by photodeposition (PD) of -Se on glass substrates. PD from solutions has been used for realizing various thin film patterns, of thicknesses 5-500 nm to produce various spatially distributed components for optical applications. During PD nanometer particles appear on the irradiated (Ar+ ion laser, =498 nm or a Xenon UV-Visible lamp) zones of any transparent substrates. A new technique based on capturing the evanescent light leaking image, named Differential Evanescent Light Intensity (DELI), is used to get the information about the photodeposited -Se nanostructures profiles in the deposited zone on glass substrates serving as waveguides. The deposited particles observed on the substrates have diameters typically in the range of 100-300 nm as obtained by other microscopy methods. The morphology of the nanostructures consists of a random array of individual particles adsorbed onto the surface. The deposited material morphological profile was observed for fluencies in excess of F>Fth~25 J/cm^2 for the particular experimental conditions of this work for -Se. The highest merits found for the DELI technique are the fast and ease of measurements, comparable z-resolution to SEM and capability of large areas profiling and mean thickness measurements. We obtained that deposition fluencies of about F~300J/cm^2 were enough to produce layers up to about 340nm thickness, similar to values needed for CW Ar+ ion laser PD deposition at =498nm.

7586-23, Poster Session

Structural properties of Si and Ge nanocrystals embedded in silica

F. Djurabekova, M. Backman, Univ. of Helsinki (Finland); K. Nordlund, Univ. of Helsinki (Finland) and Helsinki Institute of Physics (Finland)

table photoluminescence has been observed in Si nanocrystals (NCs) embedded in amorphous SiO2 matrices. However, the origin of the photoluminescence is not clear, but it appears to be related to defects at the crystal-matrix interface. Hence the atomic structure of Si nanocrystals in silica is of great interest. We present our work on constructing atomic models of nanocrystals of realistic size, and show that the structural properties agree well with EXAFS experiments. We also analyze the structure with respect to optically active defects. We apply both an empirical classical many-body potential and a charge optimized many-body potential to confirm the presence of silanone bonds (Si=O), responsible for the enhancement of light amplification properties of Si - O systems. We discuss the stability of those bonds owing to the presence of the interface.

7586-24, Poster Session

Laser interactions with vertically aligned carbon nanotube arrays

C. Rouleau, D. B. Geohegan, A. A. Puretzky, J. J. Jackson, Oak Ridge National Lab. (United States); G. Duscher, The Univ. of Tennessee (United States); K. L. More, Oak Ridge National Lab. (United States)

High-intensity interactions of ultrafast laser pulses with carbon nanotubes are of both fundamental and applied interest. Here the damage thresholds and mechanisms of laser ablation of nanotubes grown in vertically aligned carbon nanotube arrays (VANTAs) have been studied in vacuum and in background gases. The arrays were a product of base-growth, resulting from conventional chemical vapor deposition on Fe/Al-catalyzed Si wafers. High-resolution TEM and Raman spectroscopy show that the nanotubes comprising the array are primarily single-wall, large (3-4 nm) diameter, and form a very porous (<10 vol.%) network. Laser interactions with the as-synthesized arrays were studied for laser polarizations parallel, perpendicular, and in the plane of the array. In addition, nanotubes removed from the VANTAs were dispersed on TEM grids prior to irradiation for high-resolution TEM investigations of damage mechanisms.

Despite the porous nature of the material, single femtosecond laser shots (800nm, 40fs) were found to be effective at machining/patterning the arrays in all three laser/VANTA orientations investigated. Electron microscopy grids were used to capture the ejecta during processing to investigate by high-resolution TEM the mechanisms of ablation, while high resolution SEM was used to characterize the microstructure on either side of the laser-induced kerf. Phase changes in the carbon nanotubes, both in the ejected material and within the machined surfaces, will be described.

Research sponsored by DOE-BES (DSUF) at the Center for Nanophase Materials Sciences and SHaRE Facilities using samples supplied by DOE-BES (DMSE).

7586-01, Session 1

Surface plasmon enhanced photoelectron emission from metals with nanostructured surfaces

C. Guo, Univ. of Rochester (United States)

In this work, we find, for the first time, that the resonant angle of surface plasmons (SPs) excited on a unique type of nanostructured metal can be significantly different from the calculated values. We believe that this SP resonant angle shift is caused by a modification of the effective refractive index at the air-metal interface. We also find that the excitation of SPs can significantly enhance photoelectron emission on the nanostructured metal surfaces.

7586-02, Session 1

Tip-enhanced Raman spectroscopy and related techniques in studies of biological materials

T. Schmid, ETH Zürich (Switzerland)

Biological materials can be highly heterogeneous at the nanometer scale. The investigation of nanostructures is often hampered by the low spatial resolution (e.g. optical microscopy/spectroscopy techniques) or very little chemical information (e.g. atomic force microscopy (AFM), scanning tunneling microscopy (STM)) provided by analytical techniques. Our research focuses on combined instruments, which allow the analysis of the exactly same area of a sample by complementary techniques, such as AFM and Raman spectroscopy.

Tip-enhanced Raman spectroscopy combines the high spatial resolution of AFM or STM with the chemical information provided by Raman spectroscopy. The technique is based on enhancement effects known from surface-enhanced Raman scattering (SERS). In TERS the enhancing metallic nanostructure is brought to the sample by an AFM or STM tip. With a TERS-active tip, enhanced Raman signals can be generated from a sample area as small as 10-50 nm in diameter.

AFM analysis of bacterial biofilms has revealed their heterogeneity at the nanometer scale. TERS measurements of the biopolymers alginate and cytochrome c have yielded spectroscopic fingerprints even of such weak Raman scatterers, which in future can allow their localization in complex matrices. Furthermore, biofilms of the bacterium H. meridiana were studied, which was found to be involved in the generation of the mineral dolomite (biomineralization). Only combined AFM-Raman analysis was able to identify the nanoglobules found in laboratory cultures of H. meridiana as dolomite nanoparticles. Our combined setups are and will be applied to the investigation of biofilms, fish spermatozoa as well as biological membranes.

7586-03, Session 1

Discovery of very narrow and intense resonances in SERS spectra of single wall carbon nanotubes

A. A. Puretzky, D. B. Geohegan, C. Rouleau, Oak Ridge National Lab. (United States)

The discovery of single molecule detection using Surface Enhanced Raman Scattering (SERS) resulted in intense research activity to understand the plasmonic properties of different nanostructures and their fabrication for ultrasensitive analysis. Although fundamental characterization of single wall carbon nanotubes (SWNTs) has been conducted extensively by Raman spectroscopy, SERS provides much higher sensitivity. Here we report the discovery of very narrow Raman lines in SERS spectra of the low frequency region of SWNTs - in some cases almost 10 times narrower compared to those measured and predicted theoretically for individual SWNTs. In this study, the disordered top layer of as-synthesized vertically aligned carbon nanotube arrays (VANTAs) was investigated. SWNTs in this layer served as templates for deposition of variably-spaced gold nanoparticles, creating numerous “hot spots” that generated very intense single lines of individual SWNTs in the low frequency region (10-300 cm-1) of the Raman spectra. Minimum linewidths of 0.3 cm-1 and maximum measured enhancement factors of ~ 2000 were observed. The corresponding electronic resonances were studied and assigned using tunable laser excitation. Interesting new features were observed in this low frequency region. Their origin and implications for new opportunities in SERS-based carbon nanotube spectroscopy will be discussed.

Research sponsored by DOE-BES (DSUF) at the Center for Nanophase Materials Sciences using samples supplied by DOE-BES (DMSE).

7586-04, Session 1

Plasmonic solar cells: status and prospects

S. Mokkapati, F. Beck, The Australian National Univ. (Australia); A. Polman, FOM Institute for Atomic and Molecular Physics (Netherlands); K. Catchpole, The Australian National Univ. (Australia)

There has been an increased interest, in recent years, on reducing the cost of electricity generation using photovoltaics. This has motivated research in the field of high efficiency thin film solar-cells to reduce the cost of silicon consumption. Light trapping becomes ever more important in thin solar-cells in order to reduce the increased transmission losses. Light trapping is especially important at longer wavelengths (~1000 nm), where silicon is an indirect band gap material. However, conventional light trapping techniques like surface texturing cannot be employed in thin solar-cells, as the active region in thin solar cells is only few μm thick.

Localized surface plasmons are charge density oscillations in isolated metal nanoparticles coupled to external light and provide an effective means of light trapping in thin solar cells. The technique is cheap, compatible with large area solar cell fabrication techniques, and can easily be tuned to target specific wavelength regions. For effective light trapping using localised surface plasmons, the scattering cross section of the nanoparticle has to be maximised. It is also important to maximise the fraction of scattered light coupled into the substrate. The scattering cross section and the fraction of scattered light coupled into the substrate depend critically on the particle size, shape and its dielectric

environment. It is essential to optimize the particle properties to obtain the maximum possible absorption enhancement inside the solar cell. We review the basic concept involved and the effect of above stated particle properties on the cell performance and provide an outlook on the current status and future prospects of solar-cells employing light trapping using localized surface plasmons.

7586-05, Session 1

Spectral modulation of single hybrid plasmonic nanostructures

K. Appavoo, Vanderbilt Univ. (United States); D. Lei, Imperial College London (United Kingdom); D. W. Ferrara, J. Nag, Vanderbilt Univ. (United States); Y. Sonnefraud, S. A. Maier, Imperial College London (United Kingdom); R. F. Haglund, Jr., Vanderbilt Univ. (United States)

We have modulated both resonance wavelength and spectral width of single hybrid plasmonic nanostructures exhibiting plasmonic effects by cycling through a metal-insulator transition in vanadium dioxide (VO2). The nanostructures under investigation were composite nanopillars of Au::VO2 and VO2::Au. Sandwich nanopillars made of VO2::Au::VO2 have also been examined. The nanostructures were fabricated on 0.13mm thin glass substrates by electron-beam lithography, pulsed laser deposition of VO2 and electron-beam evaporation of gold. We describe the first experimental observations of plasmonic modulation by the MIT in single nanoparticles using white light extinction spectroscopy in the visible and near-infrared. By varying the radial dimension of the nanopillars in a systematic way, the plasmon resonance of the gold can be tuned by as much as 275 nm. Moreover, we found a 50 fold enhancement in the electric field of the VO2::Au as compared to the sandwich nanopillars of VO2::Au::VO2. This increase in energy confinement could be attributed to symmetry breaking in the plane of incident field. Moreover, for the nanopillar exhibiting the greatest plasmon resonance modulation (radial dimension of 80 nm), a study of the confinement of the gold nanodisk has been undertaken. We found that greater confinement of the gold nanodisk resulted in a broader spectral width. Also, decreasing the thickness of the VO2 layers in the sandwich nanoparticles decreases the ability to modulate the plasmon resonance as expected. The experimental results have been compared with full-field, three-dimensional finite-difference time-domain simulations.

7586-06, Session 1

Surface plasmon effects induced by uncollimated emission of semiconductor microstructures

D. Lepage, J. J. Dubowski, Univ. de Sherbrooke (Canada)

The inherent surface sensitivity of the surface plasmon resonance (SPR) effect has made it highly attractive for biochemical analysis of processes localized on metal surfaces. Many devices have been developed commercially for that purpose within the past 20 years. However, a monolithically integrated SPR microchip, which could be easily integrated with specimen processing hardware for a wholly automated analysis, has yet to be demonstrated. We have recently proposed an innovative microstructure for a monolithically integrated SPR device comprising a metal coated SiO2 layer deposited atop a photoluminescence emitting quantum well (QW) wafer. The functioning of such a device is based on the uncollimated and incoherent emission of semiconductors. Therefore, any given point of the metal-dielectric interface is exposed to the whole range of wavevector spectra and thus, coupling of all the SPR modes supported by the architecture is expected to take place. We discuss the results of our calculations and measurements aimed at the description of SPs coupling in QW semiconductor-based SPR architectures designed for biosensing applications. Dispersion (kll) maps (angular frequency versus in-plane wavevector) of the analytical far-field dispersion relation for the investigated microstructure are studied using hyperspectral luminescence mapping. These maps determine experimentally the spectro-angular properties of studied SPR systems. Two SPs modes could be coupled in the 0th diffraction order where the injected in-plane wavevectors from the QW structures can always meet SPR conditions. This results in increasing the SPs coupling efficiency up to 100 times higher than in case of indirect SPs injection.

7586-07, Session 2

Melting mechanisms of embedded nanocrystals

K. Nordlund, Univ. of Helsinki (Finland) and Helsinki Institute of Physics (Finland); J. Pakarinen, F. Djurabekova, M. Backman, Univ. of Helsinki (Finland)

Understanding the melting mechanisms of nanocrystals embedded in solids is of great current interest, since both the synthesis and modification of such systems frequently involves use of high temperatures.

Using molecular dynamics computer simulations we study the melting mechanisms of Cu, Ag and Au nanoclusters embedded in metal matrices and Si nanocrystals in amorphous silica.

The results show that nanocrystals embedded in a solid bulk material with a higher melting temperature exhibit complex melting behavior, and can even in the same systen exhibit four distinct stages prior to full melting of the system.

These are, in order of increasing temperature,

(i) defect motion in the cluster leading to partial interface melting,

(ii) fluctuations between ordered and disordered states,

(iii) melting of the nanocrystal but not the surrounding bulk, and (iv) melting of the surrounding bulk at the interface with the nanocrystal.

While all of the mechanisms have in some form been previously reported in the literature, the current work showed that even a single system can have at least four different stages of melting.

We further argue that due to this complexity, different experimental methods may interpret the same system as either molten or crystalline due to the different ways the atomic state is measured.

7586-08, Session 2

Limits on the optical response of nano-objects: from isolated to interacting and self-organized particles

A. Castelo, Consejo Superior de Investigaciones Cientificas (Spain); C. N. Afonso, Consejo Superior de Investigaciones Científicas (Spain); U. Gupta, Univ. Antwerpen (Belgium); G. Van Tendeloo, Univ. of Antwerp (Belgium)

There is a large amount of theoretical and experimental reports addressing the optical properties of nanostructures of increasing complexity. Whereas the role of size, shape and environment on the optical properties appears well established, the role of organization of small nanoparticles (< 5 nm) as well as their interaction is less clear. This work aims to contribute to the understanding of these issues by studying the threshold separation among neighbouring nanoparticles for interaction phenomena to become important as well as the limits in which self-organization effects dominate over interaction ones.

We applied alternate pulsed laser deposition to produce metal nanoparticles layered samples the host interlayer thickness being the key parameter allowing changing the structural properties. They are studied by high resolution electron microscopy both in plan and cross-section views and compared to optical extinction. As the host inter-layer thickness is decreased, the nano-objects evolve from small isolated quasi-spheres to interacting ones, self-organised nano-nuts (indented), self-organised nanocolumns and larger objects. The optical response is

characterised by the surface Plasmon resonance (SPR) and becomes polarization dependent as the spacing thickness decreases. The SPR broadens towards the infrared and splits into two well separated resonances evidencing that oscillations of the conduction electrons along the parallel and perpendicular axis to the substrate are different and thus self-organisation has occurred. The correlation of the optical spectra and the structural analysis allows to discuss the limits for each type of optical response as well as its dependence on fine shape /structure of the self-organised nano-objects.

7586-09, Session 2

Excimer laser interactions with single crystal ZnO: unconventional nanoparticle production

J. T. Dickinson, E. H. Khan, S. C. Langford, Washington State Univ. (United States)

UV-Laser interactions with wide bandgap insulators and semiconductors has generated a number of examples of point defect production, surface and bulk modification, etching and re-deposition processes, as well as numerous PLD related applications involving the emitted particles. In metal containing compounds such as oxides and halides, aggregation of metals into nanoparticles has been observed. In this talk we examine the fundamental mechanisms required to explain the formation of such nanoparticles. In particular we examine these modifications in oriented single crystals of semiconducting ZnO with a band-gap of ~3.4 eV We first discuss results on interactions of strongly absorbing 248 nm (5 eV), 193 nm (6.3 eV), and 157 nm (7.8 eV) excimer laser light with high purity ZnO surfaces in UHV. Using time resolved quadrupole mass spectroscopy, we show examine atomic and molecular emissions (Zn, O, and O2) generated at fluences below plasma formation threshold. Although the atomic Zn emission is robust, more total oxygen is observed to leave the surface. One possible emission mechanism we are pursuing is the ejection of O by localized electron hole pair annihilation. Accompanying exposure of these single crystals to 193 nm light is coloration: i.e. gray to black spots (some preliminary evidence is showing detectable but less coloration at 248 nm); we show conclusively that this coloration is due to surface metallic zinc in the form of nanoparticles, typically 10-20 nm in diameter. We discuss formation mechanisms and the role of strong interactions of the laser with these nanoparticles.

7586-10, Session 3

Synthesis and characterization of ZnO nanocrystals by nanoparticle-assisted pulsed laser deposition

D. Nakamura, T. Matsumoto, A. Kumeda, K. Toya, K. Okazaki, M. Higashihata, Kyushu Univ. (Japan); B. Cao, Univ. of Jinan (China); T. Okada, Kyushu Univ. (Japan)

ZnO nano-crystals have been paid a great attention as building blocks for the opto-electronic devices. In this presentation, the synthesis and characterization of ZnO nanowires and nanowalls grown by a novel high-pressure nanoparticle-assisted pulsed-laser deposition (NAPLD) method will be discussed.

7586-11, Session 3

Particle ejection in pulsed laser ablation: dependence on material and laser parameters

T. K. M. Lippert, S. Heiroth, Paul Scherrer Institut (Switzerland); J. Koch, D. Günther, ETH Zurich (Switzerland); A. Wokaun, Paul Scherrer Institut (Switzerland)

Particle formation in the laser ablation process is an important issue in different fields of application. The accuracy and precision of LA-ICP-MS analysis depends on the generated particle sizes and requires ideally a conversion of the solid analyte to a fine aerosol with a narrow particle size distribution [1]. In laser-based coating techniques the transfer of particles represents a common undesired side-effect degrading the film quality which has evoked considerable efforts to eliminate the particles from the ablation plume [2-4]. On the other hand the laser ablation process can be deliberately adapted to a controlled synthesis of nanoparticles [5, 6].

In the present work we compare the ablation characteristics of different materials, Cu as a fcc metal, PMMA as an organic polymer, glassy Li2B4O7 and different polymorphs of yttria-stabilized zirconia (YSZ) as a dielectric ceramic material, using ns-UV and fs-UV/NIR laser pulses. Ejection of particles in the micron to nm range was visualized by time-resolved pump-probe imaging using shadowgraphic and light scattering techniques. Quantitative size distribution data of the generated aerosols were acquired in the particle range of 65 nm to 1µm. In the case of YSZ, a laser-induced phase transition to the monoclinic phase, as detected by Raman spectroscopy, causes a superior fracture toughness of the partially stabilized (3YSZ) phase versus higher doped fully stabilized targets (8, 9.5YSZ). It is demonstrated how the differences in the materials ablation behavior affect the morphology of PLD grown thin films for various laser conditions, resulting in particle-free 3YSZ layers for ns-UV irradiation.

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7586-12, Session 3

Nanophotonic fabrication in sub-nm scale

T. Yatsui, M. Ohtsu, The Univ. of Tokyo (Japan)

Nanophotonics, a novel optical technology, utilizes the local interaction between nanometric particles via optical near fields. The optical near fields are the elementary surface excitations on nanometric particles. Of the variety of qualitative innovations in optical technology realized by nanophotonics, this talk focuses on fabrication. To fabricate nanophotonic devices with the nanometer-scale controllability in size and position, we developed the self-assembly of a size- and position-controlled ultra-long nanodot chain using a novel effect of near-field optical desorption. A sub-100-nm dot chain with a deviation of 5 nm forms at a size based on plasmon resonance, depending on the photon energy; the resulting structure forms a high-transmission-efficiency nanoscale waveguide. Using this method with simple lithographically patterned substrates will dramatically increase the throughput of the production of nanoscale structures at all scales. A realization of an ultra-flat silica surface with angstrom-scale average roughness using noadiabatic optical near-field etching is also demonstrated. We proposed a new method of optical near-field etching where a non-adiabatic process is applied to a synthetic silica substrate using a continuum wave laser (wavelength of 532 nm) with a Cl2 gas source. Because the absorption band edge energy of Cl2 is higher than the photon energy of the light source, we preclude the conventional adiabatic photochemical reaction. An optical near-field, generated on the nanometrically rough substrate, induces the nonadiabatic chemical reaction to the Cl2 molecules and thereby selectively etches away the roughness, leaving an ultra-flat synthetic silica surface with angstrom-scale average roughness.

7586-13, Session 3

Altering the synthesis of carbon nanohorns for new hybrid nanostructures

D. B. Geohegan, A. A. Puretzky, C. Rouleau, M. Yoon, N. Thonnard, Oak Ridge National Lab. (United States); G. Duscher, The Univ. of Tennessee (United States); K. L. More, Oak Ridge National Lab. (United States)

Single-wall carbon nanohorns (SWNHs) are biocompatible hollow carbon nanostructures with high surface areas useful for energy storage and drug delivery. They are synthesized in dense, confined carbon plasmas generated by laser or arc, and their efficient self-assembly process into single-wall carbon nanostructures, without the use of metal catalyst, is of fundamental interest. Recently, we investigated the factors influencing the growth rates, size, and morphology of pure carbon SWNHs and their ball-shaped aggregates by varying the growth times, temperatures, and spatial confinement of ablation plumes using a high-power pulsed laser with tunable pulse width, repetition rate, and energy per pulse.1

Here, we explore alterations to the synthesis process of carbon nanohorns through the co-ablation of metals and the use of hydrogen-containing background gases. Metal atoms and hydrogen alter the growth kinetics of the individual nanohorn units and introduce pathways for the formation of competing carbon nanostructures, such as single-wall carbon nanotubes and graphene sheets. Co-ablation of targets containing carbon and CaH_2, for example, resulted in the formation of nanohorns with greatly altered morphologies and aggregates. Different approaches for carbon nanohorn synthesis and metal decoration (exohedral and endohedral) will be described with characterization of the samples by HRTEM, AC-Z-STEM, EELS, and Raman spectroscopy. Energy stability calculations are presented to explain the formation of resulting nanostructures.

Synthesis research sponsored by DOE-BES (DMSE), sample characterization by the Center for Nanophase Materials Sciences and SHaRE Facilities DOE-BES (DSUF), and hydrogen sorption, NMR, and neutron scattering by partners in the Hydrogen Sorption Center of Excellence (DOE-EERE).

7586-14, Session 3

Three-dimensional gold-helix photonic metamaterials made via two-photon direct laser writing

J. K. Gansel, M. Thiel, M. Rill, M. Decker, Univ. Karlsruhe (Germany); K. Bade, V. Saile, Forschungszentrum Karlsruhe GmbH (Germany); G. von Freymann, S. Linden, M. Wegener, Univ. Karlsruhe (Germany)

The large potential of chiral metamaterials to manipulate the polarization state of light has attracted increasing attention in the last few years. For example, chiral metamaterials can lead to giant gyrotropy1, circular dichroism2, and negative phase velocities3-5 at microwave4 and far-infrared frequencies5. So far, all fabricated chiral metamaterials operating at optical frequencies are based on stacking of several planar layers1,2.

Here, we introduce a chiral photonic metamaterial design composed of three-dimensional (3D) metallic helices arranged on a two-dimensional square lattice. For the fabrication, we utilize a novel approach based on direct laser writing and electrodeposition of gold. First, a positive-tone photoresist is structured by two-photon direct laser writing. Then, the resulting template is backfilled with gold using electrodeposition, where an ITO-layer below the photoresist acts as the cathode. After removal of the photoresist using plasma etching, free-standing gold nanostructures result. This overall method is very flexible and allows for the fabrication of high quality metallic metamaterial samples.

Our experiments for light propagation along the helix axis reveal that the structure transmits the circular polarization of light which has the opposite handedness than the gold helices. The other circular polarization state is blocked. The corresponding frequency range spans more than one octave. Thus, our new chiral metamaterial design can be used as a broadband circular polarizer. Numerical calculations based on a finite time integration technique are in good agreement with the experiments.

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7586-16, Session 4

Nanostructured polymers by a compact laser plasma EUV source

H. Fiedorowicz, A. S. Bartnik, Military Univ. of Technology (Poland)

In the paper application of a compact laser plasma EUV source in processing polymers is reported in which nanostructuring polymer surfaces was demonstrated for the first time. Processing is caused by direct photo-etching of polymers with EUV photons. The mechanism of the interaction is similar to the UV laser ablation where energetic photons cause chemical bonds of the polymer chain to be broken, however, the EUV interaction region is limited to very thin surface layer (<100nm). It makes possible to avoid degradation of bulk material caused by penetrating UV radiation. In the experiments a laser plasma EUV source based on a gas puff target has been used. EUV radiation in the wavelength range from about 5 nm to about 50 nm was efficiently produced in result of irradiation an xenon or krypton gas puff target with laser pulses (0.8 J/4 ns/10 Hz) from a Nd:YAG laser. The use of the gas puff target instead of a solid target makes possible to generate EUV light without debris production associated with the laser ablation. The source was equipped with a grazing incidence axisymmetrical ellipsoidal mirror to focus EUV radiation in the relatively broad spectral range with the maximum near 10 nm. The EUV fluency of about 30 mJ/cm2 was measured in the focus at a diameter of about 0.5 mm. The experiments on polymer surface modification by EUV light have been performed. Formation of self-organized nanostructures on the surfaces was observed. The results of the studies should be applicable in biomedical engineering.

7586-17, Session 4

Long-time feedback in self-organized nanostructures formation upon multipulse femtosecond laser ablation

J. Reif, O. Varlamova, Brandenburgische Technische Univ. Cottbus (Germany) and Cottbus Joint Lab. (Germany); M. Bounhalli, Brandenburgische Technische Univ. Cottbus (Germany) and Univ. Jean Monnet Saint-Etienne (France); T. Arguirov, Cottbus Joint Lab. (Germany) and IHP GmbH (Germany); M. Schade, H. Leipner, Martin-Luther-Univ. Halle-Wittenberg (Germany)

Self-organized nanostructures (ripples) on the target surface are observed

after multi-pulse femtosec¬ond laser irradiation. From numerous experimental data it appears obvious that successive pulses result in a positive feedback in the self-organization process. We report on a series of experiments on different targets (CaF2, Si) to investigate this feedback in more detail, in particular its dynamics. We study the influence of time separation between successive pulses on both the size and complexity of the nanostructures and on the size of the modified surface area. Taking into account the dependence of structure formation on the total applied irradiation dose, total pulse number and laser parameters (pulse energy, pulse duration, focussing) are kept constant throughout all experiments.

By varying the pulse separation between 1 ms and 1 s (rep. rate between 1 kHz and 1 Hz), we find that both modified area as well as pattern feature size and complexity decrease with increasing pulse-to-pulse delay. The effect is similar to a reduction of effective irradiation dose with increasing intervals. Vice versa, the coupling efficiency between laser and target increases with increasing repetition rate.

Assuming the structure formation to be the result of relaxation from surface instability induced by the laser impact, we can understand the observed behaviour in the following way: the stronger the per-turbation is from the preceding pulse the better is the coupling of the succeeding one, thus resulting in a positive feedback. Then, the decrease of coupling with increasing intervals should correspond to a decay of induced perturbation/instability.

Since we observe a change of structural features even between 0.5 s and 1 s intervals, this indicates an unexpectedly long “lifetime” of the instability, at the order of seconds.

But not only temporally do we observe such “long-range” effect of the laser induced instability. Also spatially, we see a persisting modification of the crystalline structure well beyond the ablation spot, though no apparent surface morphology can be seen. Mapping the band-to-band photoluminescence from silicon, we find a spatial modulation in a region significantly larger than irradiated. This indicates a dramatic increase of non-radiative recombination compared to unaffected material.

The atomic structure of the modified region is investigated by transmission electron microscopy of thin slices cut out by a focused ion beam.

7586-18, Session 4

Local near field assisted parallel nanostructuring of fused silica

F. Hubenthal, R. Morarescu, L. Englert, L. Haag, T. Baumert, F. Träger, Univ. Kassel (Germany)

For nearly all aspects in modern nanotechnology there is an ongoing interest in further miniaturizing of surface structures with dimensions well below the diffraction limit. Of particular interest are light induced parallel processes for submicrometer surface structuring. We have prepared such nanostructures in fused silica, exploiting the localized optical near fields of highly ordered triangular gold nanoparticles prepared by nanosphere lithography. In brief, triangular nanoparticles were irradiated with a single laser pulse with a duration of 35 fs and a central wavelength of lambda = 790 nm. After irradiation, the nanoparticles as well as the fused silica were ablated. The strongly localized ablation process creates highly ordered nanostructures with dimensions well below the diffraction limit. Depending on the fluence and the polarization of the laser light with respect to the nanoparticles, different nanostructures, such as circular and elliptical holes, grooves, and channels were generated. For example, for a polarization along the bisector of the triangular nanoparticles, nanogrooves with a depth of 14 nm, a width of 68 nm, and a length of 300 nm were generated. In contrast, changing the polarization of the laser light by 90°, nanochannels separated by several µm were created. The obtained structures can be explained by the enhanced electromagnetic near fields, which overcome the ablation threshold of fused silica locally in the vicinity of the irradiated nanoparticles. The shape of the nanostructures is influenced by the excitation of the plasmon resonance of the triangular nanoparticles.

7586-19, Session 4

Fabrication of Al2O3/TiO2 multilayer mirrors for ‘water-window’ attosecond pulses

Y. Tanaka, M. Murata, H. Kumagai, A. Kobayashi, Osaka City Univ. (Japan); T. Shinagawa, Osaka Municipal Technical Research Institute (Japan)

Multilayer mirrors for water-window wavelength region is useful in many applications such as attosecond metrology, x-ray astronomy, x-ray lithography and x-ray microscopy. However, the reflectivities of multilayer mirrors are still low in the region. As the layer thickness decreases, reflectivity is strongly affected by surface and interfacial roughnesses, so, precise control of layer thickness and suppression of these roughnesses are necessary.

We have already studied and then fabricated novel metal-oxide multilayer mirrors for water-window wavelengths by atomic layer deposition (ALD) or atomic layer epitaxy (ALE) methods which have the self-limiting nature of the surface reactions and can control thickness on an atomic scale over large are. The reason why metal-oxide multilayer mirrors are effective in the water-window wavelength is that they can prevent the formation of an alloy at the interface leading to scattering loss, and the absorption of oxygen in oxides is negligible.

In this study, high and low refractive materials were chosen to be TiO2 and Al2O3 respectively, because they can be fabricated by ALD or ALE methods and Ti L-absorption edge is located at 2.73nm. We have already examined the growth of these films and constant growth rates were obtained. In the presentation, ALE of Al2O3/TiO2 multilayer mirrors will be discussed in detail.

Conference 7587: Free-Space Laser Communication Technologies XXII

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7587-01, Session 1

Free space optical communication research at Naval Research Laboratory

W. S. Rabinovich, C. I. Moore, R. Mahon, H. R. Burris, J. L. Murphy, M. S. Ferraro, P. G. Goetz, M. R. Suite, L. M. Thomas, B. B. Xu, R. Smith, G. C. Gilbreath, C. Font, U.S. Naval Research Lab. (United States); W. T. Freeman, SmartLogic, Inc. (United States)

I will review free space optical communication work at the US Naval Research Laboratory

7587-02, Session 1

Preliminary results of the OCTL to OICETS optical link experiment (OTOOLE)

K. E. Wilson, J. M. Kovalik, A. Biswas, M. W. Wright, W. T. Roberts, Jet Propulsion Lab. (United States); Y. Takayama, National Institute of Information and Communications Technology (Japan); S. Yamakawa, Japan Aerospace Exploration Agency (Japan)

JPL has collaborated with JAXA and NICT to demonstrate a 50Mb/s downlink and 2Mb/s uplink bi-directional link with the LEO OICETS satellite. The experiments were conducted in May and June over a variety of atmospheric conditions. Bit error rates of 10-4 to 10-8 were measured on the downlink and 10-4 on the uplink. This paper describes the preparations, precursor experiments, and operations for the link. It also presents the analyzed results of the uplink and downlink data.

7587-03, Session 1

Lasercomm for interplanetary missions: Recent European activities, future possibilities, and synergy aspects

T. Dreischer, K. Kudielka, T. Weigel, Y. Tissot, F. Arnold, RUAG Space AG (Switzerland)

Science return and high bandwidth communications are key issues to support the foreseen endeavours on spaceflights to the Moon and beyond. For a given mass, power consumption and volume, laser communications can offer an increase in telemetry bandwidth over classical RF technology allowing for a variety of new options, like more raw scientific data being sent back to Earth where data processing can be performed on ground. Recent European activities in the field of laser communications have been focussing on missions for deep space and within the Earth's sphere of influence. Various link topologies have been analyzed, involving Lissajous orbits at Libration points of the Earth-Sun and the Moon-Earth system, and also Martian orbiters. Different types of lasercomm terminal concepts have been investigated, either operating fully autonomously or being attached to dedicated telecom orbiter spacecraft. Enhanced pulse position modulation formats were tested together with tailored FEC and interleaver technology in inter-island test campaigns using ESA's optical ground station on Tenerife. The paper summarises the findings from all activities, highlights the potential and describes synergy aspects of involved technologies, all in view of future possibilities of the usage of lasercomm as part of an integrated RF-optical TT&C subsystem to support enhanced science return.

7587-04, Session 1

Optical satellite communications in Europe

Z. Sodnik, European Space Research and Technology Ctr. (Netherlands)

The first technology developments for optical satellite communication systems, which started in Europe more than 30 years ago, were based on CO2 laser systems. However, CO2 laser technology is not useful in space and when reliable laser-diodes became available ESA developed SILEX (the world-first optical inter-satellite communication link experiment) a data relay link between an Earth observation satellite (SPOT-4) and a geostationary satellite (ARTEMIS). Since it's commissioning in 2001, the date relay system has been used extensively, also by external customers such as the Japanese OICETS satellite and by LOLA, a French aircraft to ARTEMIS communication experiment. However SILEX, being the first technology demonstration, was not able to compete with RF technology in terms of mass and data rate and a second generation of laser communication technology has been developed by the German Space Agency (DLR). The mass of the new optical terminals has been decreased from 160kg to 35kg and data rates increased from 50Mbps to 5600Mbps. Two such terminals have been launched on the TerraSAR-X and NFIRE satellites in 2007 into low Earth orbit and demonstrated over link distances up to 6000km. The next evolution of these terminals will have an extended range of up to 45000kg and be used for the new European Data Relay Satellite (EDRS) system first serving the Sentinel satellites of the European GMES (Global Monitoring for the Environment and Security) initiative.

The paper will give an overview of all past and future laser communication activities to be performed in Europe and discuss the results.

7587-05, Session 1

Free space quantum communications

R. E. Meyers, Army Research Lab. (United States)

No abstract available

7587-06, Session 2

Free-space gigabit laser link experiment incorporating Japan and Canada technology development

A. S. Koujelev, D. Gratton, L. Hotte, Canadian Space Agency (Canada); Y. Arimoto, National Institute of Information and Communications Technology (Japan)

This paper presents the results of technology demonstration: short distance ground to ground free-space optical (FSO) link with 2.5 Gbps data rate. Each terminal consists of a gimballed 10 cm telescope, acquisition and coarse tracking CCD and digital control system, a fine tracking system, fiber-optic interface, transceivers, beacon lasers, and bit error test set. Two different fine-tracking subsystems were set-up on two terminals: first is based on micro mechanical steering mirror [1], developed at NICT, Japan; and the second is based on liquid crystal (nonlinear spatial light modulation mechanism) [2], developed at CSA, Canada. Performance of the two systems, their compatibility and the possibility of application to future space missions are discussed.

[1] Y. Arimoto, "Multi-gigabit free-space optical communication system with bidirectional beacon tracking", IEEJ Transactions on Fundamentals

and Materials 127, 385-390 (2007).

[2] A. S. Koujelev, and A. E. Dudelzak, “Optical beam tracking and distortion compensation based on a nonlinear lens mechanism”, Optical Engineering 47, 085003 (2008).

7587-07, Session 2

Near field laser transmission with Bidirectional beacon tracking for Tbps class wireless communications

Y. Arimoto, National Institute of Information and Communications Technology (Japan)

The free space optical (FSO) communication in which diffraction limited laser beam is directly coupled to/from a single mode fiber (SMF) have been considered as an ultimate media to establish broadband point-to-point wireless link between mobile terminals such as satellites, trains and aircrafts. However, the author recently noticed that a new concept seems be required to establish a stable and robust FSO link between SMF apertures. This FSO link should be characterized as a near filed laser transmission with bidirectional beacon tracking, where the demanding factor for the stable operation is to assure and maintain not only the tracking accuracy but also the pointing accuracy of transmitting near field laser beams. This paper will discuss various types of configurations about the optical components, such as beacon transmitters, tracking sensors and fast steering mirrors, to construct the FSO terminal. It also presents one of the recent realizations of new generation optical terminals to achieve Tera-bit-per-seconds (Tbps) class optical links with less than one watt of required power supply to operate the terminal in a terrestrial link up to 1-km distance.

7587-08, Session 2

Laser communications for unmanned aircraft systems using differential GPS and IMU data

Z. Wang, M. Czarnomski, R. Spitsberg, R. R. Schultz, W. H. Semke, Univ. of North Dakota (United States)

Free space laser communications provides wide bandwidth and high security capabilities to Unmanned Aircraft Systems (UAS) in order to successfully accomplish Intelligence, Surveillance, Target Acquisition, and Reconnaissance (ISTAR) missions. This paper describes the practical implementation of a laser-based video communications payload system flown by a small Unmanned Aerial Vehicle (UAV) as a proof-of-concept. Two subsystems have been developed: a laser communications subsystem, consisting of a laser transmitter installed in the airborne payload and a photodiode array receiver positioned at a pre-determined, fixed GPS location on the ground, and a two-axis gimbal pointing subsystem used to precisely point the laser transmitter beam at the ground-based photodiode array receiver. An expander is integrated into the airborne laser transmitter for focusing the laser beam. To account for aircraft vibrations and differential GPS (DGPS) error, a 4.5cm × 4.5cm photodiode array was customized to receive the video data carried by the laser beam. The control algorithm for the two-axis gimbal pointing subsystem is executed on a PC-104 format computer onboard the payload to accurately point at the ground-based photodiode array receiver. This algorithm calculates a line-of-sight vector in real-time by using the UAV autopilot’s DGPS and IMU data, along with the known receiver GPS location. To improve pointing accuracy, a Kalman filter is used to estimate and smooth the IMU data. The two subsystems have been successfully tested in simulation, and preliminary flight tests took place in July 2009 within military-restricted airspace over Camp Grafton South, a National Guard training facility in North Dakota.

7587-09, Session 2

Precision optical ranging by paired one-way time of flight

K. M. Birnbaum, Y. Chen, H. Hemmati, Jet Propulsion Lab. (United States)

Precision ranging between planetary bodies would provide valuable scientific information, including tests of fundamental physics.

Current ranging techniques based on retro-reflectors, however, are limited to the Earth-Moon distance due to an inverse fourth power scaling. We present methods for interplanetary distances based on paired one-way ranging, which scales with a more favorable inverse square power. Corrections for clock offset, frequency error, and the Doppler effect are shown. We present the results of tabletop experiments demonstrating millimeter ranging accuracy.

7587-10, Session 2

Ground to aircraft link emulation of a planetary access link

A. Biswas, J. M. Kovalik, M. W. Regehr, M. W. Wright, Jet Propulsion Lab. (United States)

A ground-to-aircraft optical link was recently demonstrated where the concept of operations for a planetary access link were validated. System parameters monitored during the link demonstration including acquisition and tracking performance in the presence of platform disturbance will be presented. Streaming video imagery transferred over the link at 270 Megabits per second (Mb/s) and bit-error rates of 1E-5 were measured on transmitted pseudo random bit sequences will also be presented.

7587-11, Session 2

Data products for the OCTL to OICETS optical link experiment

J. M. Kovalik, K. E. Wilson, A. Biswas, M. W. Wright, W. T. Roberts, Jet Propulsion Lab. (United States)

JPL has developed a series of software and hardware tools to analyze and record data from a 50Mb/s downlink and 2 Mb/s uplink bi-directional links with the LEO OICETS satellite. This paper presents the data products for this experiment including the system architecture and actual data received.

7587-12, Session 2

Expanded laser communications demonstrations with OICETS and ground stations

Y. Takayama, M. Toyoshima, Y. Shoji, Y. Koyama, H. Kunimori, National Institute of Information and Communications Technology (Japan); M. Sakaue, S. Yamakawa, Japan Aerospace Exploration Agency (Japan); Y. Tashima, N. Kura, SED Co. Ltd. (Japan)

Ground-to-satellite laser communication experiments were successfully performed again between the optical ground station developed by the National Institute of Information and Communications Technology (NICT), and a low earth orbit (LEO) satellite the Optical Inter-orbit Communications Engineering Test Satellite (OICETS) “Kirari” in 2008 and 2009 in cooperation with the Japan Aerospace Exploration Agency (JAXA). NICT initiated the international ground-to-satellite laser communications with the optical ground stations of NASA/JPL, DLR,

and ESA in 2009. We introduce the motivation to start again the OICETS experiments and show the results.

7587-13, Session 2

Inter-satellite and satellite-ground communication laser links based on homodyne BPSK

R. Lange, F. F. Heine, M. Gregory, H. Kämpfner, Tesat-Spacecom GmbH & Co. KG (Germany); R. Meyer, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany)

Laser communication links with data rates of 5.65 Gbps are under in-orbit verification. We report on recent results on the performance of LEO-LEO and LEO-to ground links and discuss pointing items and acquisition duration.

7587-14, Session 3

Experimental demonstration of a retro-reflective laser communication link on a mobile platform

V. V. Nikulin, Binghamton Univ. (United States); J. E. Malowicki, Air Force Research Lab. (United States); R. M. Khandekar, V. Skormin, Binghamton Univ. (United States); D. J. Legare, Air Force Research Lab. (United States)

Successful pointing, acquisition, and tracking (PAT) are crucial for the implementation of laser communication links between ground and aerial vehicles. This technology has advantages over the traditional radio frequency (RF) communication, thus justifying the research efforts presented herein. The authors have been successful in the development of a high precision, agile, digitally controlled two-degree-of-freedom electromechanical system for positioning of optical instruments, cameras, telescopes, and communication lasers. The centerpiece of this system is a robotic manipulator capable of singularity-free operation throughout the full hemisphere range of yaw/pitch motion. The availability of efficient two-degree-of-freedom positioning facilitated the development of an optical platform stabilization system capable of rejecting resident vibrations with the angular and frequency range consistent with those caused by a ground vehicle moving on a rough terrain. This technology is being utilized for the development of a duplex mobile PAT system demonstrator that would provide valuable feedback for the development of practical laser communication systems intended for fleets of moving ground, and possibly aerial, vehicles. In this paper, a tracking system providing optical connectivity between stationary and mobile ground platforms is described. It utilizes mechanical manipulator to perform optical platform stabilization and initial beam positioning, and optical tracking for maintaining the line-of-sight communication. Particular system components and the challenges of their integration are described. The results of field testing of the resultant system under practical conditions are presented.

7587-15, Session 3

High energy laser testbed for accurate beam pointing control

D. Kim, Agency for Defense Development (Korea, Republic of); J. J. Kim, D. Frist, B. Agrawal, Naval Postgraduate School (United States)

Precision laser beam pointing and high-bandwidth rejection of jitters produced by platform vibrations are among the key technologies in the emerging fields of laser communications and high energy laser (HEL) systems. Undesired fluctuations in the pointing of a laser beam reduce the accuracy of the pointing at the target due to target motion and external disturbances. Furthermore, since disturbance characteristics often change with time and environment, optimal performance of a beam steering system requires an adaptive control system.

An HEL testbed has been developed to support research environments on precision beam control technology including acquisition, tracking, and pointing. The testbed incorporates an optical table, 10 inch telescope, two axis gimbal, fast steering mirrors, and servo components.

In this paper, system configurations of the HEL testbed are briefly introduced and a mathematical model is constructed to estimate system performance and to design new control algorithms. In some cases, the pointing error may be measured and used to provide feed-forward control. The advantage of feed-forward control is that corrective action is taken for a change in input before it affects the control parameter. LMS (Least Mean Square) is a liner adaptive filtering algorithm which has been successfully and widely used in signal processing applications. Based on the mathematical control model, a feed-forward controller and LMS adaptive filter are designed and applied to the HEL model. Computer simulation results on the various conditions are discussed and it is shown that the proposed algorithms can improve the pointing performance of the system.

7587-16, Session 3

Low complexity transceivers and autonomous concept of operations for optical planetary access links

A. Biswas, J. M. Kovalik, M. W. Regehr, M. W. Wright, Jet Propulsion Lab. (United States)

A ground to aircraft free-space laser communication link was demonstrated recently. This demonstration serves as a proof of concept for an optical access link that can be utilized for transferring high-definition imagery from the surface of Mars to a spacecraft orbiting Mars. The low-complexity transceiver design and concept of operations emphasizing autonomous link acquisition and data transfer will be described in this presentation. We will discuss how these elements feed forward to a future implementation on a Mars or other planetary mission highlighting technology gaps that need to be filled.

7587-17, Session 3

Modeling and measurement of effects of atmospheric turbulence and platform jitter on free-space laser communication

Z. Liu, V. V. Nikulin, R. M. Khandekar, Binghamton Univ. (United States)

Laser beam propagating through the atmosphere is distorted by atmospheric turbulence and platform jitter, which lead to reduction of the received signal, beam pointing error, and bit-error rate (BER) degradation. To analyze these issues, mathematical models of atmosphere and platform vibrations were developed. A realistic wavefront distortion, which was generated by utilizing the Kolmogorov spectrum and McGlamery algorithm, was applied with an electrically addressed programmable liquid crystal spatial light modulator (SLM). A disturbance signal with specific spectrum implemented by a two-dimensional piezoelectric steering mirror is applied to represent the platform jitter. While former studies usually focus on these effects separately, we model them simultaneously to simulate the actual laser communication. Experimental results show how SNR, BER and pointing error change with the increase of atmospheric turbulence strength and vibration spectrum bandwidth. This paper presents the modeling and measurement of effects of atmospheric turbulence and platform vibration. The distortion mitigation and correction techniques are tested based on the system.

7587-18, Session 3

Statistical characteristics of free space optical systems with spatial diversity

J. P. G. de Oliveira, Univ. Karlsruhe (Germany)

Free space optical communication has become an attractive solution for data transmission due to its cost-effective, license-free and high bandwidth characteristics. The performance of such systems, however, is highly affected by the effects of optical turbulence. Multiple laser transmitters and/or receivers can be used to mitigate the turbulence fading by exploiting the advantages of spatial diversity. In this work the statistical characteristics of free space communication signals with spatial diversity were obtained. The statistical properties of the photocurrent generated at the receiver by a Gaussian beam after propagating through the random medium were obtained by means of computer simulation. The geometrical configuration of spatial diversity at the receiver and at the transmitter was investigated and the cases where random beam misalignment took place were taken into account. The influence of the correlation among the multiple transmitted or received signals on the generated photocurrent was also investigated. The results presented here can be very helpful in designing a free space optical link with spatial diversity, since they are given in function of system configurations and impairment conditions.

7587-19, Session 3

Low voltage actuator using carbon nanotube to tilt mirror angle

Y. Takayama, M. Toyoshima, National Institute of Information and Communications Technology (Japan)

When the high data rate connection is required between satellites or satellites and ground stations, the free-space laser communications would be one of the promising candidates. To perform the acquisition and tracking of the incoming light from the counter terminal, it is important to control the mirrors reflection angle properly. Among several candidates to control the mirror angle, a piezoelectric actuator is one of the frequently used devices. The device is useful for the purpose, but it requires applying high voltage.

Recently, the idea to convert the electrical operation to mechanical movement through a material characteristic attracts attentions and an actuator using the carbon nanotube is regarded as an interesting device because of the low voltage applied to control the actuator. We consider that the actuator with the carbon nanotube has a possibility to be used in a communication terminal. Therefore, we made a trial production of the actuator and started the investigation of the characteristics.

In this work, we show the actuator as a trail production and measured some characteristics of the actuator.

7587-20, Session 3

System level designing of FSO link through VCSEL and NRZ modulation technique by using different filters

M. Irfan, Sir Syed Univ. of Engineering & Technology (Pakistan)

Free Space Optics (FSO) communication provides an attractive solution to bridge the gap between the existing fiber optics infrastructure and the end user.The paper examines the System level design link of FSO by using different filters for the reduction of noise and timing error. Transmitter consist of NRZ modulating VCSEL with a wavelength of 1550 nm and using positive intrinsic negative type photodiode as a receiver, the link range is 450 meters.The simulation results in FSO link is considered as weak turbulance approximation for geometrical model and optical noise.The result shows the response of timing error,zero crossing distortion and SNR by using different filters.

7587-21, Session 3

Transmitter and translating receiver design for 64-ary pulse position modulation (PPM)

A. J. Mendez, Mendez R&D Associates (United States); V. J. Hernandez, Lawrence Livermore National Lab. (United States); R. M. Gagliardi, The Univ. of Southern California (United States); C. V. Bennett, Lawrence Livermore National Lab. (United States)

PPM signaling has the advantages of transmitting log(base2)M bits per symbol and power efficiency while maintaining use of direct detection receivers. NASA is developing technology to implement 64-ary PPM (for relatively low data rates). In contrast, in this paper we explore the architecture and design of a 64-ary transmitter and translating receiver based on an algorithm that associates incoming bit streams with outgoing pulse positions (and vice-versa) at > 1 Gb/s data rates. The PPM transmitter is relatively straightforward (a cascade of log(base2)M asymmetric binary switches operating at the frame rate), but the receiver options for the case of higher transmission rate's shorter decision times (PPM slot times), are more complicated. In previous papers we have explored decision aids in the form of virtual array receivers in which the receiver produces M delayed versions of the input, and a set of comparison tests. In effect, it is a time-to-space mapping, functioning at the frame rate, with an associated control law as a decision aid. This paper describes a particular time-to-space mapping variant that directly reads out ("translates") the received symbol into the transmitted bit sequence it represents. We will describe the transceiver algorithms, architecture, designs, and the results of numerical simulations, including bit error rate (BER) calculations. The concept is enabled by the development of "lossless splitters", planar lightwave circuits (PLCs) that compensate for splitting losses by means of embedded erbium doped waveguide amplifiers (EDWAs). The lessons learned will be discussed for the case of high data rate 64-ary PPM.

7587-22, Session 3

A review of the information capacity of single-mode free-space optical communication

B. I. Erkmen, B. Moision, K. M. Birnbaum, Jet Propulsion Lab. (United States)

We provide a summary of the classical information capacity of single-mode free-space optical

communication, both for pure-loss channels (i.e., with no background radiation), and for thermal-noise channels (i.e., with background radiation). We compare the capacities afforded by structured transmitters and receivers to that of the ultimate communication capacity dictated by the quantum nature of light, and we draw out the following conclusions. The ultimate capacity can be achieved with classical coherent states (i.e., ideal laser light), but the capacity-achieving receiver (measurement) is yet to be determined. In photon-starved pure-loss channels, binary phase modulation in combination with the optimal receiver is near-capacity achieving, and more importantly, it is superior to on-off keying with either the optimal receiver (as yet to be determined) or with a photon-counter. Heterodyne detection approaches the ultimate capacity at high mean photon numbers. In channels with high background noise and low signal, we find that homodyne and heterodyne detection both approach the ultimate capacity, and when the mean signal photon number is high, heterodyne detection remains near-optimal. We also quantify the degradation in channel capacity that is due to multiple noise modes contributing to the output of photon-counters, and the number of noise modes needed to render the Poisson approximation to the noise photon-count valid.

7587-23, Session 4

Estimation-based optimum receiver for free space optics using pilot-aided modulation

H. Moradi, H. Refai, Univ. of Oklahoma (United States); P. G. LoPresti, The Univ. of Tulsa (United States); M. Atiquzzaman, Univ. of Oklahoma (United States)

Incoherent receivers of Free Space Optical (FSO) signals have no knowledge of instantaneous channel state. Thus, the information from a FSO channel must be estimated in order to design an optimal receiver with maximum likelihood (ML) detection. Using pilot-aided symbols, we introduce and develop a multi slot averaging (MSA) estimation technique to approximate the values of parameters required at the incoherent detector. The time-variance property of any fading channel is one of the major factors that make channel estimation more complicated. Fortunately, this property is relatively less effective in FSO channels. Given that FSO symbol period is very short, it is assumed that the channel within a period is invariant and can be estimated repeatedly in that period.

We investigate the bit error rate (BER) performance of FSO links with MSA estimation over lognormal atmospheric turbulence fading (scintillation) channels. Numerical simulation will be completed to find the optimal number of slots and the number of bits per slot while maintaining a maximum of 0.1dB in estimation error. This paper, also, proposes a design of the estimator using Xilinx system generator. The total delay of the receiver is only 84 samples which is due to the CORDIC blocks of system generator. The BER measured from the output of the implemented receiver shows acceptable matching to the simulated diagrams. More details will be provided in the full manuscript.

7587-24, Session 4

JAXA's efforts toward next generation space data-relay satellite using optical inter-orbit communication technology

S. Yamakawa, Japan Aerospace Exploration Agency (Japan)

JAXA has made an effort to build the next generation space data relay network. The inter-orbit optical links are essential segments for such networks in order to fulfill requirements of high resolution earth observation satellite applications and humaned space flight mission. In this paper, JAXA's R&D activities towards realizing advanced optical communication terminals are introduced. The target of the terminal is to establish the optical data relay link between LEO and GEO up to 2.5 Gbps of data-rate. The space data relay network with the terminals will provide seamless and high rate data downlink service for user spacecrafts in LEO.

7587-25, Session 4

Separating and tracking multiple beacon sources for deep space optical communications

K. M. Birnbaum, A. Sahasrabudhe, W. H. Farr, Jet Propulsion Lab. (United States)

We propose a solution for pointing and tracking an optical terminal using one or more beacons and a slowly varying background image. The primary application is a deep space optical communication terminal, where multiple source tracking provides robustness against beacon outage. Our solution uses optical orthogonal codes modulated on each beacon to separate the signal from each source for centroiding. This technique allows calculation of the transmit pointing vector from each beacon location as well as the background image. The latter can be used to track during beacon outages. We present a simple algorithm for performing this separation, and apply it to experimental data from a photon-counting detector illuminated by two beacons and one constant source. Our results show that the photon flux from each source can be accurately estimated even in the low signal, high background regime.

7587-26, Session 4

High-efficiency, high-power, fiber master oscillator power amplifier for deep-space communication operating at 1532 nm

D. L. Sipes, Jr., Optical Engines, Inc. (United States); A. Sugg, T. Moretti, Vega Wave Systems (United States)

There is demand for improved deep-space satellite communications links with increased data rates to accommodate new sensor technologies and increased sensor payloads on spacecraft. It is imperative that new solutions be compact in size, light in weight, be high speed, and highly power efficient. Optical links offer potential improvements in power, size and weight due to a substantially narrower beam and smaller components. Solutions using fiber-laser transmitter master-oscillator power-amplifiers (MOPA) have been investigated previously, but methods for improving the system power efficiency are needed. In this paper we will present methods for improving the wall-plug efficiency of fiber MOPAs for deep-space communications. A high-power, wavelength-stabilized, 1550 nm seed laser with an external modulator is used to reduce the number of amplifier stages. In addition, resonant pumping in the 1430 to 1530 nm band improves pump absorption and, hence, wall-plug efficiency. A double-pass first-stage amplifier is used in order to maximize extraction efficiency at high gain. The design targets a wall plug efficiency of 20% with more than 1 kW of peak power per pulse and over 10 W of average power. An amplifier operating at 1532nm also has the advantage of commercial off-the-shelf components with demonstrated reliability.

7587-27, Session 4

Free space optical communication utilizing mid-infrared interband cascade laser

A. Soibel, M. W. Wright, W. H. Farr, S. Keo, C. Hill, Jet Propulsion Lab. (United States); R. Q. Yang, Univ. of Oklahoma (United States); H. C. Liu, National Research Council Canada (Canada)

A Free Space Optical (FSO) link utilizing mid-IR Interband Cascade lasers has been demonstrated in the 3-5 um atmospheric transmission window. The performance of the mid-IR FSO link has been compared with the performance of a near-IR link under various fog conditions using an indoor communication testbed. These experiments demonstrated the potential advantages of a mid-IR FSO link over a 1550 nm FSO link.

7587-28, Session 4

Challenges of developing resonant cavity photon-counting detectors at 1064nm

S. A. Vasile, aPeak, Inc. (United States); S. M. Unlu, Boston Univ. (United States); J. Lipson, aPeak, Inc. (United States)

Deep Space Optical Communications (DSOC)) impose challenging requirements on detector sensitivity and bandwidth. The current state-off-the art of high-repetition rate, high-power lasers recommends using near-infrared (NIR) 1064nm wavelengths for DSOC. Integration of smart pixel technology for parallel data acquisition and processing is currently available in silicon. Large photonic arrays with integrated beam acquisition, tracking and/or communication capabilities, and smart pixel architecture should allow the implementation of more reliable and robust DSOC systems. Silicon has though a weak absorption at 1064nm and one elegant approach to increase its absorption efficiency is to trap the photons inside the silicon using cavity resonance tuned to 1064nm.

Easy to say, hard to do! We present in this paper the challenges of developing resonant cavity detectors arrays for single-photon detection, as well as the development of smart pixel technology to be implemented into such photon-counting detector arrays.

We conclude that such detector arrays are feasible, provided that suitable process control protocols are developed. We report a 10X performance enhancement at 1064 nm of the first resonant cavity photon-detectors prototypes and less than 150ps timing performance in photon-starved mode and 10-20ps for multi-photon hits.

7587-29, Session 4

Study of the fiber-coupling efficiency for ground-to-satellite laser communications

H. Takenaka, The Univ. of Electro-Communications (Japan); M. Toyoshima, National Institute of Information and Communications Technology (Japan)

Recently, the amount of the data measured onboard the satellites are increasing because the recent satellites have been higher performances. Therefore, the faster communication method is demanded. The solution is to use optical communication systems that have been studied in the past. When for the communication system 1.5μm technologies are used, Erbium Doped Fiber Amplifiers (EDFAs) are required. Therefore, it needs to couple laser light into a single mode fiber. It is rather difficult to couple the laser beam into optical fibers owing to atmospheric turbulence in ground-to-satellite laser propagation paths. We make a simulator for atmospheric turbulence of

We numerically evaluate the fiber-coupling efficiency for ground-to-satellite laser communications through atmospheric turbulence.

7587-30, Session 5

Stray light modeling and performance of the deep space optical communications terminal

W. T. Roberts, G. G. Ortiz, J. R. Charles, Jet Propulsion Lab. (United States)

Deep-space optical communications systems must be capable of acquiring and receiving extremely weak signals under relatively harsh conditions, and often when the sun is only a few degrees from the line of sight. As a result, stray-light control is a major consideration in the design of any deep-space optical communications terminal. This paper describes the stray-light mitigation features of the 15 cm aperture Deep-Space Optical Communication Terminal (DSOCT), and evaluates the expected effectiveness of these features through stray-light modeling. The modeled performance of the optical system is then compared with the measured performance. Technology validation and lessons learned from the effort, in light of the implications for future deep-space terminal designs, are explained.

7587-31, Session 5

Intensity distribution based space and time division multiple access technique for hybrid-LOS indoor optical wireless communication

S. Miyamoto, K. Kawamoto, S. Sampei, Osaka Univ. (Japan)

This paper proposes a novel signal discrimination scheme for the spatially multiplexed optical signals and applies it to a space division multiple access (SDMA) in hybrid line-of-sight (hybrid-LOS) indoor optical wireless communication system. In the proposed scheme, multiple terminals simultaneously transmit their optical signals to access point (AP) using on-off-keying (OOK) modulation, and the spatially multiplexed optical signals are received by a photodetectors array (PD-array), where multiple PDs are disposed to observe the spatial intensity distribution of optical signals. Because the terminals transmit their data using OOK modulation, the spatial intensity distribution observed by the AP equipped with PD-array is subject to the data transmitted from individual terminals, and the AP can identify the terminals transmitting the optical signal by determining the transmitted intensity distribution. Of course, the transmitted intensity distributions are not orthogonal and the discriminability of transmitted intensity distributions is much related to differences of intensity distributions. This implies that the number of terminals that can access to the AP will be limited. In order to enhance the discriminability of the transmitted intensity distributions, the proposed signal discrimination scheme is further applied to a space and time division multiple access (SD/TDMA). In the SD/TDMA, the discriminability required to enable SDMA is ensured by introducing a scheduling algorithm in which terminals with higher discriminatory of transmitted intensity distributions are allocated to the same time slot. Numerical results show that SD/TDMA using proposed signal discrimination scheme increases the throughput and the number of terminals that can access to the AP.

7587-32, Session 5

Toward an optimal combined FSO/RF system via an adaptive bit rate procedure

H. Moradi, M. Falahpour, H. Refai, Univ. of Oklahoma (United States); P. G. LoPresti, The Univ. of Tulsa (United States); M. Atiquzzaman, Univ. of Oklahoma (United States)

In hybrid FSO/RF (Free Space Optics/Radio Frequency) systems, the FSO link is the primary link while the RF link is the secondary (backup) link. In current hybrid systems, once the FSO signal to noise ratio (SNR) decreases above a preset threshold, the system switches from FSO to RF to maintain the communication connection. But this scenario does not provide maximum utilization of the available bandwidth in terms of spectrum efficiency. This paper proposes an adaptive FSO bit rate algorithm to maintain communication using the FSO link as long as its bit rate is greater than that can be offered by the RF, thus requiring no switching to the secondary link. The system switches to the secondary link if and only if the FSO bit rate while maintaining the system BER drops below the bit rate that can be achieved by the RF link. This paper shows the dependence of FSO bit error rate on channel bit rate using analysis and numerical simulation. We use this fact to introduce the algorithm that adaptively updates the bit rate to maintain the system BER. The receiver periodically estimates the averaged received signal and noise strength and calculates the system BER over short time intervals. Furthermore, numerical simulation is carried out and the results confirm the algorithm's effectiveness on maintaining higher bit rate communication connection using FSO link. Hence, the overall system performance achieves better throughput.

7587-34, Session 5

OTOOLE system design

W. T. Roberts, M. W. Wright, J. M. Kovalik, K. E. Wilson, Jet Propulsion Lab. (United States)

The OTOOLE project demonstrated bi-directional optical communications between the JAXA OICETS spacecraft and the NASA OCTL ground station. This paper provides a detailed description of the experiment design for the uplink optical channel, in which 3 beacon lasers and 4 modulated communication lasers were combined and projected through the F/76 OCTL main telescope. The paper further describes the reimaging optical design employed on the acquisition telescope for receiving the OICETS-transmitted signal and the design of the receiver channel. Performance tests of both systems are described along with alignment technique and communication analysis.

Conference 7588: Atmospheric and Oceanic Propagation of Electromagnetic Waves IV

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Atmospheric and Oceanic Propagation of Electromagnetic Waves IV

7588-01, Session 1

Understanding the performance of atmospheric free-space laser communications systems using coherent detection

A. M. Belmonte, Univ. Politècnica de Catalunya (Spain); J. M. Kahn, Stanford Univ. (United States)

We introduce a realistic model for the impact of atmospheric phase and amplitude fluctuations on free-space links using either synchronous or nonsynchronous detection. We compare options for atmospheric compensation, including active modal methods and diversity combining techniques. We consider the effects of log-normal amplitude fluctuations and Gaussian phase fluctuations, in addition to local oscillator shot noise. We study the effect of various parameters, including the ratio of receiver aperture diameter to wavefront coherence diameter, the scintillation index, the number of modes compensated, and the number of independent diversity branches combined at the receiver. We analyze outage Shannon capacity, placing upper bounds on the achievable spectral efficiency, and also receiver error probability, enabling the performance of specific system designs to be predicted.

7588-02, Session 1

Multi-beam transmitter geometries for free-space optical communications

J. A. Tellez, J. D. Schmidt, Air Force Institute of Technology (United States)

Free-space optical communications systems provide the opportunity to take advantage of higher data transfer rates and lower probability of intercept compared to radio-frequency communications. However, propagation through atmospheric turbulence, such as for airborne laser communication over long paths, results in intensity variations at the receiver and a corresponding degradation in bit error rate (BER) performance. It has been shown that two transmitters, when separated sufficiently, can effectively “average out” the intensity varying effects of the atmospheric turbulence at the receiver. This research explores the impacts of adding more transmitters and the marginal reduction in intensity variation while minimizing the overall transmitter footprint, an important design factor when considering an airborne communications system. Wave optics simulations are used to simulate the multi-beam propagation and its effect on pointing and tracking as well as the reduction in BER as the number of transmitters is increased.

7588-03, Session 1

The effects of phase-diffuser on scintillations of laser radiation for long-distance propagation in the atmosphere

G. P. Berman, Los Alamos National Lab. (United States); A. A. Chumak, V. N. Gorshkov, Institute of Physics (Ukraine); A. R. Bishop, B. M. Chernobrod, Los Alamos National Lab. (United States); S. V. Torous, National Technical Univ. (Ukraine)

Studies of laser beams propagating through turbulent atmospheres are important for many applications such as remote sensing, tracking, and long-distance optical communications.

Our analytical approach is based on the solution of the kinetic equation for the photon distribution function in the random medium. We consider the effects of suppression of fluctuations (scintillations) of laser light by using a random-phase modulator. Both spatial and temporal phase variations introduced by the phase modulator are analyzed. We discuss two types of the phase modulators with: (i) independent spatial and temporal phase fluctuations and (ii) spatially random-phase distribution drifted across the beam. The explicit dependence of the scintillation index on the initial correlation length and finite-time phase variations is obtained for long propagation paths. It is shown that in order to reduce significantly the scintillation index, the phase modulator with shot correlation time of phase variations is required. We also present the results of numerical modeling and simulation on the propagation of the laser beam for different parameters of the phase modulator and the turbulence strength. Our numerical model is based on the solution of the Leontovich parabolic equation in the random media, by using a Pismen-Reckford algorithm. We discuss the results on focusing of the partially coherent laser beam and optimization of parameters for applications to the high data rate communication in the frequency domain.

7588-04, Session 1

Adaptive control of laser beam with sensing of the reference source channel

V. P. Lukin, Institute of Atmospheric Optics (Russian Federation)

In problems of remote sensing, communication, and energy transmission one frequently runs up against the problem of transporting radiant energy in the form of a light beam to an object located in a random inhomogeneous medium. Here, as a rule, it is necessary to maximize the energy delivered to the object. As is well known, scattering of radiation by refractive index inhomogeneities of the medium leads to a decrease of the average intensity in the near-axial region of the light beam and to the appearance of intensity fluctuations, which taken together substantially degrade the energetic characteristics of the indicated systems.

A radical means of dealing with these undesirable effects is to use various adaptive methods which allow one at least in principle to almost completely eliminate the influence of the inhomogeneities of the medium. The essence of these methods reduces to controlling the initial distribution of the beam field on the basis of information about the instantaneous distribution of inhomogeneities of the medium in which the beam is propagating.

The dynamic features of the adaptive optical systems are researched. It is executed development of the traditional adaptive systems, having in its composition wave-front sensor, active mirrors and guide source. The efficiency of the using algorithms of phase and amplitude-phase corrections are analyzed. The schemes full and partial correction of the phase distortion are considered. It is entered in analysis the new class adaptive systems, including in itself, the “system constant delay”, as well as “speed”, “forecasting” adaptive systems and systems, using idea of “frozen” fluctuations in optical wave.

7588-05, Session 1

Improved iteratively weighted centroiding for accurate spot detection in laser guide star based Shack Hartmann sensor

V. Akondi, Indian Institute of Astrophysics (India) and Indian Institute of Science (India); M. B. Roopashree, R. P. Budihala, Indian Institute of Astrophysics (India)

Laser Guide Star (LGS) has become a part of adaptive optics for better sky coverage. LGS is often formed in the mesospheric Sodium layer. In

the case of large aperture telescopes (above 10m), the effects due to the finite altitude (90 km) and thickness (10 km) lead to elongation of the spots of a Shack Hartmann Sensor (SHS) affecting the sensing accuracy. Adopting a model with the center of SHS as the LGS launch point and a Gaussian density profile for Sodium layer, we present a simple method for simulating LGS elongated spots with photon noise and read out noise. A hybrid method involving Iteratively Weighted Center of Gravity (IWCoG) algorithm and correlation technique with the weighting functions equal to the elongated spots formed with a plane wavefront (ideal spot) at individual subapertures of the SHS is proposed and compared with Center of Gravity (CoG) and Intensity Weighted Centroiding (IWC). IWCoG algorithm iteratively corrects the weighting function in the Weighted Center of Gravity (WCoG) by shifting the center of the position of the ideal spot in the weighting function to the newly estimated centroid position. The problems associated with IWCoG are addressed including saturation, non uniform convergence of Centroid Estimation Error (CEE) and increased computational time. To overcome the saturation of CEE problem, we iteratively add a random number to x and y coordinates of the centroid. Due to non uniform convergence, the CEE after the last iteration may not be the minimum possible CEE. Correlation technique is used to identify the iteration number with minimum error. We iteratively compute the correlation between the weighting function and the actual spot image function and make the hypothesis that the iteration number with maximum correlation between the weighting function and the actual spot image function is the iteration with minimum error. The hypothesis is strengthened by estimating repeatedly. To increase the speed of convergence, the center of the weighting function in the first iteration is positioned at maximum intensity point of the actual spot pattern. The novelty of this technique is tested by comparing with other algorithms at different parameters like varying spot size and spot ellipticity, spot shift due to random spot motion, spot orientation, elongation length and noise strength. The number of iterations in IWCoG algorithm is optimized for best performance.

7588-06, Session 1

Novel approach for beacon formation through simulated turbulence: initial lab-test results

A. Khizhnyak, V. B. Markov, MetroLaser, Inc. (United States)

Optimal laser energy delivery to the remote target trough turbulent medium is a task that is difficult to achieve. For example, propagation of the laser beam through turbulent atmosphere results in increased spot size, beam jitter and substantial reduction of its power density on a remote target or detector. Mitigation of these effects can be achieved by pre-distorting the wavefront of the output beam. To be effective, this operation requires information on the inhomogeneity of the atmospheric layer along the propagation path between the laser system and the target. These data can be collected, for instance, by using a localized beacon on the target. In order to incur an adequate phase disturbance the laser beacon beam should propagate through the same turbulent atmosphere as the laser beam to corrected. Thus, formation of the diffraction limited beacon on the target is an important goal.

Early we discussed the approach for compensating phase disturbance due to atmospheric turbulence based on the target-in-the-loop (TIL) scheme. In this presentation we report the results of the laboratory realization of the proposed approach of beacon formation through turbulent medium in TIL-scheme with optical phase conjugation. The laboratory realization of the TIL-scheme includes the diffuse target, turbulent atmosphere simulator, laser amplifier and a non-linear optical phase conjugate mirror. In the current experimental setup, the turbulence simulator is made off a group of random phase screens with Kolmogorov spectrum and it enables to imitate a controlled-level strength of turbulence (scintillation index).

This presentation provides formation on experimental results of the lab-tests and operational performance of the TIL-system and comparison of these data with the results of the computer simulation.

7588-07, Session 2

Generalized atmospheric turbulence: implications regarding imaging and communications

N. S. Kopeika, A. Zilberman, E. Golbraikh, Ben-Gurion Univ. of the Negev (Israel)

It is well known that random spatial and temporal fluctuations in the refractive index of the atmosphere (optical turbulence) give rise to variations in the amplitude and phase of an optical wave propagating through it. The distortion of wavefront shape affects the image quality through image motion and blurring of the scene. It is especially important to take into account turbulence characteristics while processing images of objects obtained in the visible or infrared range. The turbulence-induced phase distortions result in intensity fluctuations (scintillations) at the receiving aperture and contribute significantly to the degradation of optical wireless communication links. Thus, understanding atmospheric turbulence statistics can provide ways to correct for degradations of optical systems operating through the atmosphere and to predict their performance. It is especially important for studies of electromagnetic radiation transfer through a turbulent medium and system design (optical communication, imaging systems, laser weaponry, adaptive optics, etc.).

To date, performance of electro-optical systems has been estimated assuming the Obukhov-Kolmogorov (O-K) model of the refractive index fluctuation spectrum in the atmosphere. In the past decade, experimental evidence has shown significant deviations from this model in certain portions of the atmosphere. As was observed, the power spectrum of turbulence in the atmospheric boundary layer and at higher altitudes may exhibit increasingly non-Obukhov-Kolmogorov (N-O-K) statistics.

In this work, on the basis of experimental observations and modeling, generalized atmospheric turbulence statistics including both O-K and N-O-K path components are discussed, and their influence on imaging and communications through the atmosphere estimated for different scenarios of vertical and slant-path propagation. The atmospheric model of an arbitrary (non-Kolmogorov) spectrum is applied to estimate the statistical quantities associated with optical communication links (e.g., scintillation and fading statistics) and imaging systems.

Implications can be significant for optical communication, imaging through the atmosphere, and remote sensing.

7588-08, Session 2

Atmospheric channel characterization for ORCA testing at NTTR

L. C. Andrews, R. L. Phillips, R. F. Crabbs, D. T. Wayne, T. Leclerc, P. Sauer, Univ. of Central Florida (United States)

The DARPA Optical RF Communications Adjunct (ORCA) program was created in an attempt to bring high data rate networking to the warfighter via airborne platforms. Recent testing of the ORCA system was conducted by the Northrop Grumman Corporation (NGC) at the Nevada Test and Training Range (NTTR) at the Nellis Air Force Range near Tonopah, NV. The University of Central Florida (UCF) conducted a parallel experiment to measure path-averaged values of the refractive-index structure parameter, the inner scale of turbulence, and the outer scale of turbulence along the ORCA propagation path from an airborne platform to the ground at Antelope Peak. This paper presents background information on expected atmospheric conditions for the channel, models that were used by UCF for the measurements, and path-averaged values of the three atmospheric parameters. In addition, weather instrumentation was set up at ground level on Antelope Peak to measure local conditions on the mountain top.

7588-09, Session 2

Real-time wind speed measurement using wavefront sensor data

M. B. Roopashree, V. Akondi, B. R. Prasad, Indian Institute of Astrophysics (India)

Wind speed has a linear effect on the temporal bandwidth of atmospheric turbulence fluctuations and a squared effect on cumulative intensity reduction. Hence, real time measurement of the effective wind speed (an integrated effect along all the turbulence layers) helps in continuous monitoring and optimization of the performance parameters, especially the integration time which controls the servo lag timescales in adaptive optics systems. It is possible to use wavefront sensor data from a Shack Hartmann sensor to measure the wind speed. In this paper, we propose a simple and efficient method for the estimation of wind speed. A small portion from the center of a wavefront arriving at time 't' is selected. This portion is mapped at all possible positions on a phase screen coming later than 't' by a time ∆tint (integration time) to form a correlation map. Correlation maps are also formed for phase screens arriving at integral multiples of ∆tint. Wind speed and direction is estimated statistically via the calculation of the vectors formed by joining the central portion and the position of maximum correlation on the correlation maps. Since the wind speed is estimated from a statistical mean of a sufficiently large ensemble, the number of realizations to be considered to arrive at a reasonably accurate estimate is optimized. If the number of realizations is small, then the linear fitting error is large and making a large number of measurements takes large amount of computational time. We applied and validated the method on simulated phase screens following Kolmogorov spatial statistics and experimental data obtained in the lab.

7588-10, Session 2

Simplified model for reduction of laser intensity scintillations in turbulent atmospheres using a partially coherent beam

G. P. Berman, A. R. Bishop, B. M. Chernobrod, Los Alamos National Lab. (United States); V. N. Gorshkov, Institute of Physics (Ukraine); D. C. Lizon, D. I. Moody, D. C. Nguyen, Los Alamos National Lab. (United States); S. V. Torous, National Technical Univ. (Ukraine)

We use a simplified experimental approach in which the atmospheric turbulence is simulated by a phase diffuser. We demonstrate experimentally and numerically that the application of a partially coherent beam (PCB) in combination with time averaging leads to a significant reduction in the scintillation index. The role of the speckle size, the amplitude of the phase modulation, and the strength of the atmospheric turbulence are examined. We obtain good agreement between our numerical simulations and our experimental results. This study provides a useful foundation for future applications of PCB-based methods of scintillation reduction in physical atmospheres.

7588-11, Session 3

A review of selected oceanic EM scattering problems

M. C. Haller, Oregon State Univ. (United States)

EM propagation and scattering in the ocean is of interest in a wide range of science problems. For example, the vertical distribution of attenuated solar radiation drives the processes of photosynthesis and photo oxidation and determines the productivity of ocean waters. Related observations of the biological and geological constituent of the water column are obtained through passive optical sensing of surface reflectance by satellite ocean color sensors. In addition, active sensors such as lidar in the optical band or radar in the microwave band are used to map the sea bottom or to image waves at the ocean surface. This paper will first present an overview of oceanic EM scattering problems and applications. Next, we will describe the current state of understanding and directions of future research. Finally, we will focus in more detail on the problem of microwave scattering from breaking waves at the ocean surface. A new model for microwave scattering from the layer of water droplets produced by wave breaking at the ocean surface will be presented and compared with observations from a recent field experiment.

7588-12, Session 3

Inverse near-critical-angle scattering as a tool to characterize bubble clouds

F. R. A. Onofri, M. Krzysiek, M. Wozniak, IUSTI (France); J. Mroczka, Wroclaw Univ. of Technology (Poland); Y. Yuan, F. Ren, Univ. de Rouen (France)

In the framework of wave optics, the far field near-critical-angle scattering (NCAS) of a single bubble can be modelled by a Kirchhoff-type approximation of the amplitude distribution of the corresponding virtual reflected wave front [1, 2]. The NCAS pattern is characterized by low angular frequency fringes, showing great similarities with the rainbow scattering pattern of an equivalent droplet. It has also been shown that from this pattern one can directly infer the bubble diameter and refractive index [3]. Nevertheless, under real flow conditions, the NCAS of a single bubble is too noisy to be analysed correctly. To solve this problem and to limit the draw back of any counting technique, it has been recently proposed to transform the critical angle refractometry and sizing technique in an inverse technique, i.e. the bubble size distribution (BSD) is deduced "instantaneously" from the collective NCAS of a bubble cloud [4]. In this paper we present: the light scattering models and the inverse methods we have developed to speed up the calculations, take into account bubble non sphericity and to retrieval the BSD. We also show experimental results demonstrating the efficiency and robustness of this new technique to characterized bubbly flows [5].

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7588-13, Session 3

Novel device for aerosol light scattering measurements including its angular and polarization characteristics and aerosol spectral absorption measurement instrumentation

G. Dolgos, J. V. Martins, Univ. of Maryland, Baltimore County (United States); L. A. Remer, A. L. Correia, NASA Goddard Space Flight Ctr. (United States); M. Tabacniks, A. R. Lima, Univ. of Maryland, Baltimore County (United States)

We designed, built and calibrated a novel device for aerosol light scattering measurements. This device is a polarized imaging nephelometer called PI-Neph that is capable of measuring the phase matrix in a wide scattering angle range, i.e. from 1.5 degrees to 178.5 degrees in the present configuration. The broad range is crucial for particle size retrievals. The current resolution is less than 1 degree near the extreme directions, and the angular range and resolution can be improved without significant costs. We calibrated the instrument

with filtered air and carbon dioxide, the raw data compares excellently with their corresponding theoretical phase matrixes. The PI-Neph has no moving parts, measures in a few seconds and is suitable for the laboratory and the field due to its high sensitivity. We are upgrading the PI-Neph to measure the full phase matrix by modulating the polarization of the illuminating light. The PI-Neph is being made portable to transition from the laboratory to aircraft field measurements.

Our complementary goal has been to measure the absorption spectra of black carbon and other aerosols from 230 nm to 1000 nm. The deep UV measurements are not important for the atmospheric radiative balance, but contain information about the chemical composition of the sample. Measuring the decrease in filter reflectance due to the collected aerosol permits the calculation of spectral absorption cross section of the aerosol particles. Our integrating sphere measurement eliminates errors due to the directional distribution of aluminized filter reflectance. The method will be validated by independent measurements.

7588-15, Session 3

Ghost imaging with partially coherent light in turbulent atmosphere

Y. Cai, Soochow Univ. (China); O. Korotkova, Univ. of Miami (United States); F. Wang, Soochow Univ. (China)

Ghost imaging, also known as quantum or correlated, or coincidence or two-photon imaging, has been studied extensively in recent years. Recent theoretical and experimental results have shown that ghost imaging can be realized with classical correlated light named partially coherent light (i.e., pseudo-thermal light) in free space, and the coherence of light play a key role in classical ghost imaging. While the most serious limitation for ghost imaging with partially coherent light in free space is that the imaging distance can't be very long because the partially coherent light becomes coherent light after long propagation in free space. In this paper, we investigate ghost imaging with partially coherent light in turbulent atmosphere. Our results show that we can realize not only short-distance ghost imaging, but also long-distance ghost imaging in turbulent atmosphere. The imaging properties are closely related to the structure constant of turbulent atmosphere. Our results provide a novel way for long-distance imaging and have great potential application in remote sensing and so on.

7588-16, Session 3

Radiation transfer in semitransparent medium containing bubbles

L. Pilon, Univ. of California, Los Angeles (United States)

This paper presents a review of recent studies focusing on theoretical predictions and experimental measurements of the radiative properties of semitransparent medium containing spherical bubbles. First, it discusses the conditions under which the absorption by the matrix surrounding a bubble must be accounted for in the calculation of the efficiency factors by comparing results from the (1) conventional Mie theory assuming that the matrix is non-absorbing, and (2) far-field and (3) near-field approximations accounting for attenuation of the EM wave by the matrix and incident on the bubble surface. Second, it uses these different models for a single bubble to estimate the effective radiation characteristics of an ensemble of polydisperse bubbles embedded in an absorbing medium. Finally, experimental techniques and associated inverse methods to measure radiation characteristics of semi-transparent medium are presented and results are compared with theoretical predictions.

It is established that the efficiency factors for a spherical particle can differ significantly from one model to another, in particular for large particle size parameter and matrix absorption index. Moreover, the choice of the absorption efficiency factor depends on the model used for estimating the effective absorption coefficient. However, for small void fractions, absorption by the matrix dominates and models for the absorption coefficient and efficiency factor are unimportant. For bubbles in water, the conventional Mie theory can be used between 0.2 and 200 microns except at some wavelengths where absorption by water must be accounted for.

7588-17, Session 4

Intensity fluctuations of incoherently superposed Gaussian beams in atmospheric turbulence

Y. K. Baykal, Çankaya Univ. (Turkey)

Intensity fluctuations of incoherently superposed Gaussian beams are formulated in weak turbulence by employing the extended Huygens-Fresnel principle. Each individual beam superposed is taken to be fully coherent. The scintillation index evaluated for different number of beams indicate that as the number of beams increase, scintillations decrease. Incoherent superposition of smaller sized Gaussian sources exhibits smaller fluctuations. Comparing the scintillation index arising from incoherently superposed Gaussian beams to the scintillation index of coherently superposed Gaussian beams of the same structure shows that incoherent superposition yields lower intensity fluctuations, thus can be advantageous in atmospheric optical communication systems.

7588-18, Session 4

Propagation of elegant higher-order Gaussian beams in turbulent atmosphere

F. Wang, Y. Cai, Soochow Univ. (China); H. T. Eyyuboglu, Y. K. Baykal, Çankaya Univ. (Turkey)

The propagation of elegant higher-order Gaussian beams including elegant Hermite-Gaussian beam and elegant Laguerre-Gaussian beam in turbulent atmosphere is investigated. Explicit and analytical formulae for the average intensity and effective beam size of an elegant higher-order Gaussian beam in turbulent atmosphere are derived based on extended Huygens-Fresnel integral. The intensity and spreading properties of standard and elegant higher-order Gaussian beams in turbulent atmosphere are studied numerically and comparatively. We find that the propagation properties of elegant higher-order Gaussian beams in turbulent atmosphere are much different from their propagation properties in free space. The elegant higher-order Gaussian beams with higher orders are less affected by the atmospheric turbulence. Furthermore, the standard high-order beams spreads more rapidly than the elegant higher-order beams in turbulent atmosphere under the same conditions. Our results will be useful in long-distance free space optical communications.

7588-19, Session 4

Profile ground impact on scintillation: 50km and 200-km slant paths from airplane to Antelope peak

I. Toselli, Florida Space Institute (United States); L. C. Andrews, Univ. of Central Florida (United States); R. L. Phillips, D. T. Wayne, Florida Space Institute (United States)

The interest for free space laser beam propagation is increased because several experiments showed recently that optical links through the atmosphere can be effectively established, even though several negative effects due to refractive index fluctuations must be kept in count. The most negative effect is the scintillation which has been widely investigated. However, it has not been yet reported what influence a ground profile has on scintillation values. In this paper we show theoretical results of the ground impact on scintillation for a specific

mountain profile of the ground. Also, we compare these results with experimental results which have been collected for two downlink paths, 50 km and 200 km, from an airplane to Antelope Peak (Nevada).

7588-20, Session 4

Fluctuations and deviation of image mass center in conditions of atmospheric turbulence and thermal blooming

G. A. Filimonov, V. V. Dudorov, V. V. Kolosov, Institute of Atmospheric Optics (Russian Federation)

The investigation of fluctuation and deviation of image mass center was performed for the case when atmospheric turbulence and thermal blooming are present. Images were built for objects in the form of a gaussian beam. The influence of turbulence on the image mass center deviation is investigated as well as the influence of thermal blooming on the image mass center fluctuations. It is shown that turbulence reduces a deviation.

7588-21, Session 4

Propagation limits for optical beams generated by diffraction

A. Carbajal-Domínguez, Univ. Juárez Autónoma de Tabasco (Mexico)

For several applications, it would be desirable to have optical beams with auto-healing and partial coherence features, mainly because they would carry information in a more stable way. For instance, partially coherent J0 Bessel beams have been proposed as possible candidate. In present work, in the angular spectrum formalism, it is shown that if optical beams are generated by diffraction then they have a propagation distance which is limited by their spectral content. In particular, high frequencies content contribute to shorter propagation distances due to dominant evanescent modes whilst low frequencies give longer propagation distances due to dominant propagating modes. This also could explain why partially coherent beams seem to outperform totally coherent beams for conveying information in atmospheric turbulence. Theoretical and numerical results are presented.

7588-22, Session 4

Comparison of fractional power of various classes of beams in turbulent atmosphere

S. Sahin, O. Korotkova, Univ. of Miami (United States); R. Malek-Madani, U.S. Naval Academy (United States); Y. Cai, Soochow Univ. (China)

Fractional power, also referred to as power in the bucket, is one of the most frequently used quiantities characterizing beam propagation in random media, together with M2 factor, divergence angle, and others. It is defined as a ratio of the power captured by the detection system to the total transmitted power. Since fractional power explicitly enters the expression for the signal-to-noise ratio of the electric current induced by the detected optical signal after propagation, it is of utmost importance for optical communications. We first compare the fractional power for several well-known classes of monochromatic beams: Gaussian, Annular, Hermite-Gaussian, Laguerre-Gaussian, Bessel-Gaussian, flattened etc. Then we extend the analysis to the corresponding partially coherent beams and calculate fractional power for Gaussian-, BesselJ- and BesselI- correlated beams. Both weak and strong regimes of atmospheric fluctuations are considered. In particular, the dependence of fractional power of the beams on inner, outer scales and on the refractive index structure parameter Cn2 will be investigated.

7588-23, Session 4

Beam wander characteristics of flat-topped, dark hollow, cos and cosh-Gaussian, J0- and I0- Bessel Gaussian beams propagating in turbulent atmosphere: a review

C. Z. Çil, H. T. Eyyuboglu, Y. K. Baykal, Çankaya Univ. (Turkey); O. Korotkova, Univ. of Miami (United States); Y. Cai, Soochow Univ. (China)

In this paper we review our work done in the evaluations of the root mean square (rms) beam wander characteristics of the flat-topped, dark hollow, cos-and cosh Gaussian, J0-Bessel Gaussian and the I0-Bessel Gaussian beams in atmospheric turbulence. Our formulation is based on the wave-treatment approach, where the source beam profiles are taken into account. In this approach the first and the second statistical moments are obtained from the Rytov series under weak atmospheric turbulence conditions and the beam size are determined as a function of the propagation distance. It is found that after propagating in atmospheric turbulence, under certain conditions, the collimated flat-topped, dark hollow, cos- and cosh Gaussian, J0-Bessel Gaussian and the I0-Bessel Gaussian beams have smaller rms beam wander compared to that of the Gaussian beam. The beam wander of these beams are analyzed against the propagation distance, source spot sizes, and against specific beam parameters related to the individual beam such as the relative amplitude factors of the constituent beams, the flatness parameters, the beam orders, the displacement parameters, the width parameters, and are compared against the corresponding Gaussian beam.

7588-24, Session 4

Propagation factor of a radial laser array beam in turbulent atmosphere

C. Zhao, Y. Cai, Soochow Univ. (China)

Laser array beams have important applications in free-space optical communications, high-power systems, inertial confinement fusion and high-energy weapons. The propagation properties (including average intensity, spreading, and intensity fluctuation) of laser array beams in turbulent atmosphere have been investigated widely. Up to now, the propagation factor of a laser array beam in turbulent atmosphere hasn't been studied. In this paper, we obtain the analytical formula for the propagation factor of a radial laser array which consists of a series of off-axis Gaussian beams in turbulent atmosphere based on the extended Huygens-Fresnel integral and the second-order moments of the Wigner distribution function. Our numerical results show that the propagation factor of a radial laser array beam in turbulent atmosphere increases on propagation, which is much different from its invariant properties in free-space, and is mainly determined by the parameters of the radial laser array beam and the atmosphere.

7588-25, Session 4

Wave optics simulation of Gaussian Schell-model vortex beam propagation in turbulence: intensity profile and scintillation analysis

X. Xiao, D. G. Voelz, New Mexico State Univ. (United States)

Vortex beams have been demonstrated to carry more information than non-vortex beams due to their orbital angular momentum characteristics. On the other hand, the use of partially coherent beams can reduce turbulence-induced scintillation in free space optical applications. Thus, the partially coherent vortex beam is of special interest. The intensity distribution of this type of beam, when propagated through the turbulence, has been investigated. Wang and his coworkers pointed out

that the spreading of the vortex Gaussian Schell-model (GSM) beam is less influenced by turbulence than the non-vortex beam. However, to our best knowledge the scintillation index of GSM vortex beam has not been investigated, most likely because the analytic calculation is extremely complicated. In this work, we examine the GSM vortex beam using a wave optics simulation. The simulation approach is described, the average intensity profiles are investigated and compared with analytic results, and the behavior of the normalized variance (scintillation index) at the receiver is examined.

7588-26, Poster Session

Laser magnetometer for planetary field measurements

G. Dekoulis, Lancaster Univ. (United Kingdom)

This paper describes the feasibility study and simulation results of a new diode laser magnetometer stabilized with an atomic vapor cell. The magnetometer depends on its well balanced and powerful self-oscillation circuitry to produce an accurate narrowband microwave output signal. The frequency of the output signal is proportional to the axial component under measurement of the Earth's magnetic field. Two magnetometer variations have been considered by varying the optical components in the path of the modulated light. The results of the noise analysis, the performance of the optical components, the stability of the overall feedback loop and the oscillator's performance are all presented. The accuracy in external fields' measurements depends on the accurate tuning of the different design parameters. The first stage of the project was to verify the validity of the model and to present major measurements of the Earth's magnetic field. Further progress to be reported is the accuracy in measuring the geomagnetic disturbances of planetary fields due to the variation in the intensity of heliospheric physics events.

7588-27, Poster Session

Propagation of spirally polarized beams in a turbulent atmosphere

J. Pu, T. Wang, Huaqiao Univ. (China)

Recently, much research has been carried out on the generation and focusing of the radially and azimuthally polarized beams due to their unique focusing properties. On the other hand, the propagation of laser beam in a turbulent atmosphere is a subject of considerable importance in connection with remote sensing, imaging, and optical communication. It is hoped that the spirally polarized beams can present some interesting characteristic as it propagate in the turbulent atmosphere. However, as far as we know, there is no research on the propagating of such a beam in the turbulent atmosphere. In this paper, the propagation of spirally polarized beams in the turbulent atmosphere has been investigated. The influence of the source parameters and the atmospheric turbulence on the intensity distribution and polarization distribution has been studied in great detail. It is shown that the spiral polarization distribution of the beam influences the intensity distribution and polarization distribution in the output plane. It is also shown that the atmospheric turbulence can influence the intensity distribution and polarization distribution in the output plane.

7588-29, Poster Session

Polarization changes in stochastic electromagnetic beams propagating in the oceanic turbulence

N. H. Farwell, O. Korotkova, Univ. of Miami (United States)

On the basis of the unified theory of coherence and polarization of light and the extended Huygens-Fresnel integral we derive the expressions for the polarization properties of stochastic light beams on propagation in the turbulent isotropic and homogeneous, clear-water ocean (no scattering by bio-particles is assumed). As the model for the source of the beam we use the electromagnetic Gaussian Schell-model source, with uncorrelated and partially correlated mutually orthogonal components of the electric field. To describe fluctuations of the refractive index in the ocean we will use a recently developed Nikishov's power spectrum which can be regarded as a linear approximation to a polynomial characterizing the cumulative effect of the temperature and salinity fluctuations. We perform investigations of the polarization changes of light beams for different regimes of oceanic fluctuations and for a wide range of beam parameters. Among the main quantities of interest are the degree of polarization and the polarization ellipse.

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7589-01, Session 1

fs-lasers in ophthalmology

T. Juhasz, Abbott Medical Optics (United States)

No abstract available

7589-02, Session 1

New developments in ultrashort pulse surgery of the cornea and the sclera

K. Plamann, Ecole Nationale Supérieure de Techniques Avancées (France); F. Aptel, Hôpital Édouard Herriot (France); C. L. Arnold, Ecole Nationale Supérieure de Techniques Avancées (France); A. Courjaud, Amplitude Systemes (France); C. Crotti, F. Deloison, Ecole Nationale Supérieure de Techniques Avancées (France); F. Druon, P. Georges, M. Hanna, Institut d'Optique Graduate School (France); J. Legeais, F. Morin, Hôpital Hôtel Dieu (France); E. P. Mottay, Amplitude Systemes (France); V. Nuzzo, D. A. Peyrot, Ecole Nationale Supérieure de Techniques Avancées (France); M. Savoldelli, Hôpital Hôtel Dieu (France)

Ultrashort pulse laser eye surgery benefits from the strongly localised nonlinear laser-interaction process. Unwanted side-effects are minimised and the surgical intervention can be performed in the volume of the tissue without damaging the surface. Clinical systems permitting to perform refractive surgery on clear corneas have been available for several years and have become very widespread. An interesting market has developed and several specialised companies are active in the field. However, clinical practice and our own experiments have shown that the advantages of ultrashort pulse laser surgery are strongly compromised when working on strongly scattering tissue. For instance, most of the indications for corneal grafting are related to an insufficient transparency of the patient's cornea which makes the application of existing clinical laser systems difficult. To date, no ultrashort pulse laser system is available permitting to perform surgery on the strongly scattering sclera. In our contribution we will summarise the state of the art in femtosecond laser surgery of the anterior segment of the eye as well as and foreseeable future developments which might overcome the present difficulties. We will discuss typical medical indications, surgical results, tissue optics, non-linear laser-tissue-interaction and the development of optimised laser sources.

7589-03, Session 1

High resolution macroscopy (HRMac) of the eye using non-linear optical imaging

J. V. Jester, M. Winkler, B. Jester, C. Nien-Shy, D. Chai, D. J. Brown, The Gavin Herbert Eye Institute (United States)

Non-linear optical (NLO) imaging using femtosecond lasers provides a non-invasive means of imaging the structural organization of the eye through the generation of second harmonic signals (SHG) specifically from collagen and two photon excited fluorescence to detect elastin. While NLO imaging is able to detect collagen and elastin fiber organization, the small field of view (FoV) limits the ability to study how these extracellular matrix components are structurally organized throughout the larger tissue. To address this issue we have used computed tomography on optical and mechanical sectioned tissue to greatly expand the FoV and provide high resolution macroscopic (HRMac) images that cover the entire tissue (cornea and optic nerve head). Whole, fixed tissues (cornea (13 mm diameter) or optic nerve (3 mm diameter) were then excised and either 1) embedded in low melting point agar for vibratome sectioning (200-300 m), or 2) embedded in LR White plastic resin for serial sectioned using an ultramicrotome (1-2 m). Vibratome and plastic sections were then imaged using a Zeiss LSM 510 Meta and Chameleon femtosecond laser to generate NLO signals to generate large macroscopic 3-dimensional tomographs with high resolution that varied in size from 9 to 90 Meg pixels per plane having a resolution of 0.88 m lateral and 2.0 m axial. 3-D reconstructions of the NLO based tomographs also allowed for regional measurements within the cornea and optic nerve to quantify collagen and elastin content, orientation and organization over the entire tissue. We conclude that NLO based tomography to generate HRMac images provides a powerful new tool to assess structural organization within ocular tissues. Biomechanical testing combined with NLO tomography may provide new insights into the relationship between the extracellular matrix and tissue mechanics.

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7589-04, Session 2

Brain plasticity and functionality explored by non-linear optical microscopy

L. Sacconi, Univ. degli Studi di Firenze (Italy)

In combination with fluorescent protein (XFP) expression techniques, two-photon microscopy has become an indispensable tool to image cortical plasticity in living mice. In parallel to its application in imaging, multi-photon absorption has also been used as a tool for the dissection of single neurites with submicrometric precision without causing any visible collateral damage to the surrounding neuronal structures. In this work, multi-photon nanosurgery is applied to dissect single climbing fibers expressing GFP in the cerebellar cortex. The morphological consequences are then characterized with time lapse 3-dimensional two-photon imaging over a period of minutes to days after the procedure. Preliminary investigations show that the laser induced fiber dissection recalls a regenerative process in the fiber itself over a period of days. These results show the possibility of this innovative technique to investigate regenerative processes in adult brain.

In parallel with imaging and manipulation technique, non-linear microscopy offers the opportunity to optically record electrical activity in intact neuronal networks. In this work, we combined the advantages of second-harmonic generation (SHG) with a random access (RA) excitation scheme to realize a new microscope (RASH) capable of optically recording fast membrane potential events occurring in a wide-field of view. The RASH microscope, in combination with bulk loading of tissue with FM4-64 dye, was used to simultaneously record electrical activity from clusters of Purkinje cells in acute cerebellar slices. Complex spikes, both synchronous and asynchronous, were optically recorded simultaneously across a given population of neurons. Spontaneous electrical activity was also monitored simultaneously in pairs of neurons, where action potentials were recorded without averaging across trials. These results show the strength of this technique in describing the temporal dynamics of neuronal assemblies, opening promising perspectives in understanding the computations of neuronal networks.

7589-05, Session 2

A novel flexible clinical multiphoton tomograph for early melanoma detection, skin analysis, testing of anti-age products, and in situ nanoparticle tracking

K. König, M. Weinigel, R. Bückle, H. G. Breunig, A. Gregory, JenLab GmbH (Germany)

High-resolution 3-D imaging systems based on two-photon induced autofluorescence and second harmonic generation have been introduced in 1990. However, CE-marked multiphoton medical systems for subcelluar resolution of human skin have first been launched by JenLab company with the DermaInspect® in 2004. The novel multiphoton tomograph (MPTflex), equipped with a flexible articulated optical arm, provides an increased flexibility and accessibility especially for clinical and cosmetical examinations. Improved image quality and signal to noise ratio (SNR) are achieved by a very short source-drain spacing, by larger active areas of the detectors and by single photon counting (SPC) technology. Shorter image acquisition time, due to improved image quality, reduces artifacts and simplifies the operation of the system. The compact folded optical design and the light-weight structure of the optical head eases the handling and thus assists the physician or user to control the multiphoton tomograph. Dual channel detectors, recently developed by JenLab, enable to distinguish between intratissue elastic fibers and collagenous structures simultaneously. Through the use of piezo-driven optics a stack of optical cross-sections (optical sectioning) can be acquired and 3D imaging can be performed. The multiphoton excitation of biomolecules like NAD(P)H, flavins, porphyrins, elastin, and melanin is done by an intense ultrashort pulse from an integrated tunable turn-key femtosescond near infrared (NIR) laser system. The ability for rapid high-quality image acquisition, the user-friendly operation of the system and the compact and flexible design qualifies this system to be used among others for melanoma detection, diagnostics of dermatological disorders, cosmetic research and skin aging measurements as well as in situ drug monitoring and animal research.

7589-06, Session 2

Temporal focusing for FLIM using a high peak power laser

C. Julien, A. Jacquart, E. Ishow, École Normale Supérieure de Cachan (France); A. Courjaud, Amplitude Systèmes (France); D. Oron, Weizmann Institute of Science (Israel); E. P. Mottay, Amplitude Systèmes (France); R. B. Pansu, CNRS (France)

Temporal focussing offers to full field microscopic techniques the possibility of depth sectioning. This has been applied to 3D resolved photoactivation and to 3D PALM. We have applied it to FLIM. Indeed depth sectioning is important for FLIM for two reasons. The lifetime information is quickly blurred by the mixing of decays. 3D sectioning by differentiating the signal originating from different depth will help the study of complex samples. In addition, when FLIM is achieved through single photon counting, the rate of the collection of photons is the limiting factor. Any background photons will consume processing time for no profit.

But temporal focussing requires very high peak power. The high intensity required to achieved two photons excitation at the focal point has now to be provide all over the focal plan. For that we chose a high peak power low repetition rate laser : the Tpulse 200 from Amplitude Systemes. 160mW/1e7Hz pulses where used to excite the fluorescence all over a 150x100µm2 plane with a NA:0.7 x40 objective.

The sample was a film 240 nm thick made of a neat fluorescent pigment with a two photon absorption cross section of 220 GM. Their fluorescent yield is of 20%. We show that we achieve a 7µm depth resolution and a 250ps time resolution. The fluorescence could be seen with naked eye.

7589-07, Session 3

Femtosecond laser based enucleation of porcine oocytes for somatic cell nuclear transfer

K. Kuetemeyer, Laser Zentrum Hannover e.V. (Germany); A. Lucas-Hahn, B. Petersen, E. Lemme, P. Hassel, H. Niemann, Friedrich Loeffler Institute (Germany); A. Heisterkamp, Laser Zentrum Hannover e.V. (Germany)

I would like to be considered in this year's student competition.

Cloning of several mammalian species has been achieved by somatic cell nuclear transfer (SCNT) in recent years. However, this method still results in very low efficiencies around 1% which originate from suboptimal culture conditions and highly invasive techniques for oocyte enucleation and injection of the donor cell. To overcome some of these problems, we present a new minimally invasive method for oocyte enucleation based on the application of fs laser pulses from a Ti:sapphire oscillator with approximately 140 fs pulse width. The fs laser based oocyte enucleation relies on focusing the laser beam onto the oocyte's metaphase plate, which was stained with Hoechst dye, via a high-numerical aperture objective. Three-dimensional scanning was achieved by lateral deflection of the beam using scan-mirrors and axial positioning of the objective. After generating a three-dimensional stack of multiphoton images containing the oocyte's metaphase plate, our self-developed software automatically detected the bright fluorescent area of the metaphase plate in each plane. Afterwards, the fs laser beam was solely scanned over these marked areas with a higher pulse energy and a slower scan speed in order to ablate the DNA molecules. We show that fs laser based enucleation followed by artificial activation of porcine oocytes inhibited pronucleus formation and the first mitotic cleavage while keeping their morphology intact. In contrast, control groups without previous irradiation of the metaphase plate were able to develop to the blastocyst stage. As a next step, experiments investigating the suitability of fs laser based enucleated oocytes for SCNT were performed.

7589-08, Session 3

Ultrafast laser interaction with plasmonic nanostructures in water

E. Boulais, R. Lachaine, G. Poulin, M. Meunier, Ecole Polytechnique de Montréal (Canada)

The irradiation of a nanostructure embedded in a biological media by a femtosecond laser could results in a highly localized plasma and heat production yielding to the nanosurgery of cells.To understand the basic mechanism of plasmonic enhanced laser nanoprocessing in cells, we performed three dimensional simulations to obtain the electromagnetic field distribution, the plasma production and transient temperature distribution surrounding a gold nanorod in water after an interaction with a 800nm 120 fs laser pulse. The electromagnetic field distribution is directly calculated from the Maxwell equations using a finite-element based method. Transient temperature distribution is determined through a two-temperature model and hydrodynamic phenomena are modeled through Navier-Stokes equations. Simulation results shows a significant temperature and pressure variation in the surrounding medium due to the presence of the nanostructure. The cavitation threshold is found to be around 20uJ/cm2 with a temperature rise of only 40K. Threshold for plasma chemical damage of the cell has also been determined to be around 20 uJ/cm2, four orders of magnitude lower than the threshold (~ 0.1 J/cm2) when no nanorods are used. The model has been validated using pump-probe experiments. Variation of the transmitted probe irradiation following the pump irradiation of the gold nanorods immersed in water were study in details as a function of laser fluence and polarization. Results allow direct measurement of electron-electron and electron-phonon relaxation time as well as nanorod melting and water cavitation threshold, all in good agreement with the model.

7589-09, Session 3

fs-laser cell perforation using gold nanoparticles of different shapes

M. Schomaker, H. Fehlauer, Laser Zentrum Hannover e.V. (Germany); W. Bintig, A. Ngezahayo, Leibniz Univ. Hannover (Germany); I. Nolte, H. Murua Escobar, Small Animal Clinic Hannover (Germany); H. Lubatschowski, A. Heisterkamp, Laser Zentrum Hannover e.V. (Germany)

The resulting effects of the interaction between nanoparticles and laser irradiation are a current matter in research. Depending on the laser parameters as well as the particles properties several effects may occur e.g. bubble formation, melting, fragmentation or an optical breakdown at the surface of the nanoparticle. Besides the investigations on these effects, we employed them to perforate the membrane of different cell lines and investigated nanoparticle mediated laser cell perforation as an alternative optical transfection method. Therefore, GNPs of different shapes were applied. Furthermore, we varied the methods for attaching the gold nanoparticles (GNPs) to the membrane, i.e. co-incubation of pure gold nanoparticles and bioconjugation of the surface of GNPs. The optimal incubation time and the location of the GNPs at the cell membrane were evaluated by multiphoton microscopy. If these GNP loaded cells are irradiated with a fs laser beam, small areas of the membrane can be perforated. Following, extra cellular molecules such as membrane impermeable dyes or foreign DNA (GFP vectors) are able to diffuse through the perforated area into the treated cells. We studied the dependence on the laser fluence, GNP concentration, GNP size and shape for successful nanoparticle mediated laser cell perforation. Due to a weak laser focusing a gentle cell treatment with high cell viabilities and high perforation efficiencies can be achieved. A further advantage of this perforation technique is the high number of cells that can be treated simultaneously. Additionally, we show applications of this method to primary and stem cells.

7589-10, Session 3

Dual-beam optical trapping of cells in an optofluidic device fabricated by femtosecond lasers

N. Bellini, Politecnico di Milano (Italy); F. Bragheri, Univ. degli Studi di Pavia (Italy); K. C. Vishnubhatla, Politecnico di Milano (Italy); L. Ferrara, P. Minzioni, Univ. di Pavia (Italy); G. Cerullo, R. Ramponi, Politecnico di Milano (Italy); I. Cristiani, Univ. di Pavia (Italy); R. Osellame, CNR (Italy) and Politecnico di Milano (Italy)

I would like this contribution to be considered in this year's student competition.

Dual-beam optical trapping and stretching of cells is a very promising tool to investigate their viscoelastic properties. This optical stretcher has the ability to deform cells without mechanical contact or bead attachment. In addition, it is the only method that can be combined with microfluidic delivery, allowing for the serial, high-throughput measurement of the mechanical properties of cells. Applications can be foreseen in biological, biomedical, and biotechnological research and industry. Current implementations rely on the use of two opposite optical fibers shining light into a flow chamber, but suffer from difficult alignment and temporal instabilities due to thermal and mechanical perturbations. Femtosecond laser micromachining can fabricate in the same chip both the microfluidic channel and the optical waveguides, producing a monolithic device with a very precise alignment between the components and very low sensitivity to external perturbations.

Femtosecond laser irradiation in a fused silica chip followed by chemical etching in hydrofluoric acid has been used to fabricate the microfluidic channels where the cells move by pressure-driven flow. With the same femtosecond laser source two optical waveguides, orthogonal to the microfluidic channel and opposing each other, have been written inside the chip. Optimization of the writing process has accomplished to obtain good quality single mode optical waveguides with low propagation losses and a mode field diameter of around 7 μm at 980 nm. Preliminary results of optical trapping of red blood cells are presented.

In this way very robust devices are fabricated which will allow highly reproducible and standardized measurements.

7589-11, Session 4

Subsurface femtosecond tissue alteration: selectively photobleaching macular degeneration pigments in near retinal contact

Z. Manevitch, A. Lewis, Hebrew Univ. of Jerusalem (Israel); C. Levy, E. Zeira, E. Banin, Hadassah Hebrew Univ. Medical Ctr. (Israel); A. Manevitch, A. Khatchatouriants, Hebrew Univ. of Jerusalem (Israel); J. Pe'er, E. Galun, I. Hemo, Hadassah Hebrew Univ. Medical Ctr. (Israel)

Many clinical disorders require subsurface tissue manipulation with ultralow collateral damage. Examples are age related macular degeneration (AMD) and fungal infections. Here we show, in an AMD animal model, non-invasive, selective manipulation of AMD associated pigments using a femtosecond laser. Most lasers used in medicine cannot address such problems of depth selective tissue manipulation since one photon based laser tissue interactions only provide a factor of two higher fluence at the laser focus as compared to the overlying surface. The advent of fsec lasers and the revolution they have caused in multiphoton microscopy and fabrication opens a new direction to address such subsurface tissue manipulation. Here we demonstrate, for the first time, the potential of applying fsec laser pulses to two photon photobleaching of AMD pigments that accumulate under and in ultra close proximity to the overlying retina.

7589-12, Session 4

OCT guidance for fs laser treatment of presbyopia

O. Massow, H. Hoffmann, M. Fromm, M. Heidrich, A. Krueger, T. Ripken, H. Lubatschowski, Laser Zentrum Hannover e.V. (Germany)

Presbyopia is the progressively diminished ability of the human eye to accommodate. Apart from wearing reading glasses there is no remedy of this impairment of vision which is caused by hardening of the aging lens.. A possible surgical treatment to regain flexibility of the lens could be the application of fs laser induced cuts to create gliding planes inside the lens. The main advantage of fs lasers is the possibility of cutting subsurface in bulk optical transparent tissue with minimal thermal damage utilizing nonlinear tissue interaction (photodisruption).

As the lens position varies strongly in different patients it is crucial to exactly locate the lens prior to laser application. A suitable tool for measuring the lens position is Optical Coherence Tomography (OCT), as the micrometer resolution of typical OCT systems is comparable with the accuracy of the fs laser micro surgery system.

We demonstrate a setup for measuring the anterior chamber depth with an OCT system integrated in the beam path of the surgical laser. The OCT imaging is used to target the lens with the surgical fs-laser focus. First results of OCT guided fs laser treatment on freshly excised animal eyes will be shown.

7589-13, Session 4

Bio-inspired titanium surfaces: formation of multi-scaled surface structures using femtosecond laser structuring for endosseous implant applications

A. Cunha, Univ. Técnica de Lisboa (Portugal); V. B. Oliveira, Instituto Superior de Engenharia de Lisboa (Portugal); R. Mário Correia da Silva Vilar, Univ. Técnica de Lisboa (Portugal)

It is generally recognized that a significant improvement in osseointegration may be achieved by multiscale surface structuring of biomedical Ti alloys surfaces. Femtosecond lasers are extremely effective tools to produce suitable surface textures with negligible contamination and thermal degradation of the substrate material. The aim of the present work is to investigate surface micro and nano-texturing of medical grade 2 titanium and Ti-6Al-4V alloy using a femtosecond laser aiming to assess the potential of the method to produce bio-inspired surfaces for osseointegration enhancement. The laser treatments were carried out in air using an Yb:KYW chirped-pulse-regenerative femtosecond laser system (= 1030 nm; 500 fs). The dependence of the morphology and chemical composition of the laser treated surfaces on processing parameters such as the average fluence and number of pulses was studied by field-emission gun scanning electron microscopy, atomic force microscopy, energy dispersive X-ray spectroscopy and X-ray photoelectron spectroscopy. The wettability of the surfaces was estimated by contact angle measurements. After 200 laser pulses with average fluence between 0.5 and 2.0 J/cm2 microcolumnar structures are produced on both materials. For fluences slightly larger the damage threshold of titanium (0.2 J/cm2) and number of laser pulses lower than 200, nano-sized periodic wavelet structures with 700 nm in periodicity, known as LIPSS (Laser Induced Periodic Surface Structures), are produced. LIPSS can be combined with micro-sized columnar structures to create a bimodal distribution surface topography. These surfaces present extremely promising characteristics for biomedical applications because the nanotopography allows controlling wetting and protein/surface interactions, while the micron-sized features should ensure implant stability and load-induced osteogenic activity at the implant/bone interface.

7589-14, Session 4

Fabrication and characterization of laser-micromachined polypyrrole-based artificial muscle actuated catheters

K. K. C. Lee, Univ. of Toronto (Canada); N. R. Munce, Sunnybrook Health Science Ctr. (Canada); T. Shoa, The Univ. of British Columbia (Canada); L. G. Charron, Univ. of Toronto (Canada); B. A. Standish, Ryerson Univ. (Canada); G. A. Wright, Univ. of Toronto (Canada) and Sunnybrook Health Science Ctr. (Canada); J. D. W. Madden, The Univ. of British Columbia (Canada); P. R. Herman, Univ. of Toronto (Canada); X. D. V. Yang, Ryerson Univ. (Canada) and Sunnybrook Health Science Ctr. (Canada) and Univ. of Toronto (Canada)

Polypyrrole (PPy) polymer is an artificial muscle actuator that possesses numerous characteristics attractive in guiding and improving functionality of biomedical catheters for surgical procedures. Ablative laser micromachining was investigated and characterized as means to enable precision fabrication of active catheters capable of two-dimensional positional control. An ArF excimer laser (193 nm, 15 ns) was applied to form electrically isolated channels on PPy-coated catheters such that active actuation of catheters could be demonstrated. However, one major drawback of PPy actuators is the slow speed of electrical actuation, which is proportional to the diffusion rate of ions in and out of the polymer-liquid surface under an applied electric potential. Employing a femtosecond fiber laser (1045 nm, 400 fs), surface texturing of microhole arrays has therefore been systemically applied to PPy films (thickness 20 to 40 μm) to increase the surface porosity, and thus increase the surface area accessible for ion transfer.

Catheters were coated with PPy, electrically isolated by laser machining, and followed with digital video camera characterization of the electrically induced bending radius. Bending characterization will be reported on both laser-textured and non-textured PPy bilayer actuators, and compared with profiles calculated from a one-dimensional variable resistance transmission line model. Contrasts between actuator efficacy with deep-UV and femtosecond laser surface processing will be discussed. Combining such catheter with optical coherence tomography, which can provide subsurface visualization of biological tissue, imaging capability using the active catheter tip is demonstrated. Such PPy actuator-enabled catheters promise new directions for biomedical imaging and diagnostics.

7589-15, Session 5

Applications of femtosecond laser induced Bragg gratings in silica and non-silica based optical fibers

S. J. Mihailov, D. Grobnic, C. W. Smelser, Communications Research Ctr. Canada (Canada)

Since its development in 2003, the technique of Bragg grating inscription using ultrafast infrared laser and a phase mask has proven to be far more versatile than the standard ultraviolet laser approach. The ultrafast IR laser-based process allows for the creation of grating structures in glassy and crystalline materials that are not typically UV-photosensitive, thereby creating new applications for Bragg gratings where the use of UV-photosensitive silica fibers is not possible. In this paper we will review the studies that have been performed at the Communications Research Centre Canada on the grating formation processes as well as applications of the ultrafast laser technique to fabricate gratings in various optical fibers and waveguides.

7589-16, Session 5

Mode selective fiber Bragg gratings

J. U. Thomas, C. Voigtländer, S. Nolte, A. Tünnermann, Friedrich-Schiller-Univ. Jena (Germany); N. Jovanovic, G. D. Marshall, M. J. Withford, M. Steel, Macquarie Univ. (Australia)

Focussing ultrashort lasers pulses allows for inscribing fiber Bragg gratings (FBG's) directly into rare earth doped fiber cores - without prior photosensitivity treatment. High reflective FBG's can be written into active Large Mode Area (LMA) Fibers with 20 μm core diameter using a phase mask scanning technique. Here, we demonstrate fiber Bragg gratings (FBG's), which cover only a fraction of the core. With this additional degree of freedom it is possible to taylor the reflectivity of individual modes. We show for example how those FBG's can be used in few mode LMA fibers to surpress reflections into higher order modes.

7589-17, Session 5

Compact 60-fs multigigawatt diode-pumped laser using postcompression technique

A. Courjaud, Amplitude Systemes (France); E. Mével, E. Constant, Univ. Bordeaux 1 (France); E. P. Mottay, Amplitude Systemes (France)

Industrial diode-pumped ultrafast lasers offer high flexibility in energy and repetition rate. For some scientific applications such as high harmonic generation, high peak powers with ultrashort pulses are required. Postcompression technique using noble gas filled hollow fibres is

commonly used with Ti:Sa lasers, and was recently demonstrated using 800fs pulse duration from a YFCPA laser.

We report on an improved architecture leading to an efficient and simple postcompression system, adapted to standard ultrafast diode-pumped lasers, and allowing a significant peak power improvement.

The whole system consisted in a commercial Ytterbium ultrafast diode-pumped laser (YUDL), a 15cm long hollow fibre, simply filled with nitrogen around 2bars, and 4 dispersive mirrors as a compressor. The injected pulse energy was 830µJ at 2kHz with a pulse duration of 500fs, and resulted in 330µJ output pulse energy with a compressed pulse duration as short as 60fs. Increasing the repetition rate to 5kHz, an injected pulse energy of 530µJ resulted in compressed pulses as short as 76fs for a 200µJ pulse energy.

The beam quality was excellent, with an M^2 of 1,1 and 1,2 on both axis, and no astigmatism, owing to the guiding property of the hollow fibre.

The overall efficiency of 40% and the compression factor higher than 8 leads to a peak power improvement of 3, leading to 5GW peak power at multi-kilohertz regime.

This system opens new opportunities for cost-effective high peak power generation, and could even be used to reach few cycle pulses.

7589-18, Session 5

Compression of idler pulses with an identical positive dispersive glass block to signal pulse stretcher in ultrafast optical parametric chirped-pulse amplification

Y. Akahane, K. Ogawa, K. Tsuji, M. Aoyama, K. Yamakawa, Japan Atomic Energy Agency (Japan)

To realize simple and robust sub-100 fs high-power femtosecond laser systems, we have focused on compression of an idler pulse in optical-parametric chirped-pulse amplification (OPCPA). Due to the phase-conjugation process, the sign of the even orders of spectral dispersion of the idler pulse is inverted from the signal. This means that the even orders of spectral dispersion can be compensated by passing through the same dispersive material as the pulse stretcher. When the transparent material such a highly-dispersive glass block is used for producing positive chirp of the signal pulse before amplification, the idler pulse having a negative chirp can be simply compressed by passing through the same material. In this research, we have demonstrated compression of the idler pulse from OPCPA by passing through an identical glass block for stretching the seed signal pulse.

An output pulse with 57 fs duration from oscillator was temporally stretched by a SF11 glass block with 50 mm length to 390 fs and overlapped with pump pulse from Yb:YLF laser in type-I BBO crystal with an internal crossing angle of 1.2 deg. Typical gain of parametric amplification was 3x10^(3). The idler pulse was collimated and sent to the identical glass block for pulse compression. The duration of compressed idler pulse was 73.9 fs, whereas uncompressed was 295 fs. With this scheme a simple, robust and efficient femtosecond OPCPA laser can be constructed, which is useful for industrials such as material processing as well as other widespread applications.

7589-19, Session 5

Broadband Yb:CaF2 regenerative amplifier for sub-100fs range

S. Ricaud, M. Delaigue, A. Courjaud, Amplitude Systemes (France); F. Druon, Univ. Paris-Sud 11 (France); P. Georges, Institut d'Optique Graduate School (France); P. Camy, R. Moncorgé, ENSICAEN (France); E. P. Mottay, Amplitude Systemes (France)

Industrial diode-pumped ultrafast lasers offer high flexibility in energy and repetition rate. For some specific applications, sub-100fs energetic pulses are required. Intensive work was done on the generation of short pulse duration with diode-pumped oscillators based on Ytterbium materials, however for millijoule range energy, efficient amplifiers suffer from gain narrowing, leading to longer pulse durations, typically >350fs. New materials are needed, with broad gain spectrum together with a high gain for good extraction efficiency.

A "new-old" laser material showed recently very promising results for short pulse generation in oscillators as for short pulse high energy amplification up to the Terawatt level.

We report on a watt level regenerative amplifier based on Yb:CaF2 laser material used at room temperature.

The crystal is a 6mm long crystal with 2,6% doping concentration, used at Brewster, pumped through a dichroic mirror by a 10W fiber coupled laserdiode centered at a wavelength of 978nm.

The regenerative amplifier, composed of a thin film polarizer and a BBO Pockels cell for Q switching, generated energy as high as 1,7mJ at 500Hz, centered at 1040nm with a bandwidth of 16nm FWHM. This laser cavity will be injected by stretched pulses from an oscillator, and indicates a good potential for sub 100fs pulse duration after compression in the millijoule range. It constitutes also an excellent candidate as a seed laser for high energy diode-pumped Ytterbium lasers.

7589-20, Session 6

Measuring complex and visible ultrashort pulses

D. Lee, Swamp Optics, LLC (United States); L. Xu, R. P. Trebino, Georgia Institute of Technology (United States)

We show that several versions of FROG can reliably measure very complex pulses with TBPs as large as 100 and likely higher. Thus FROG measurements of even very complex shaped pulses should be accurate and reliable. We also show that a highly simplified pulse-measurement device can measure nJ pulses in the visible. We believe that this simplified device is the best option available for measuring pulses in the visible, generated from commercial OPA's and tunable continuum sources. Like other GRENOUILLEs, it is also capable of quantitatively measuring the beam spatial chirp and pulse-front tilt. The key issue for the visible GRENOUILLE is the crystal thickness because, in the crystal, group-velocity dispersion (GVD) will cause the pulse to spread in time if the crystal is too thick and the crystal cannot act as a spectrometer if the crystal is too thin. In the 3.5-mm BBO crystal in our visible GRENOUILLE, the GVD introduced by the crystal is negligible (a few fs), and the crystal can simultaneously spectrally resolve pulses with narrow spectral structure. We made traces of double pulses for calibration and which further verified the device's operation. Also, while the visible GRENOUILLE described here uses transmissive optical components and hence operates best for > 100-fs pulses, an analogous all-reflective device can be designed for shorter pulses in the spirit of the analogous ~ 20-fs IR GRENOUILLE.

7589-21, Session 6

Modeling the propagation of ultrashort pulses through optical systems

F. Wyrowski, Friedrich-Schiller-Univ. Jena (Germany); C. Hellmann, R. Krieg, H. Schimmel, LightTrans GmbH (Germany)

The propagation of harmonic fields with suitable techniques through arbitrary optical components is the fundamental task in optical modeling. Unified Optical Modeling uses different techniques for different components in order to ensure the best compromise between simulation effort and accuracy. The software VirtualLab is based on the unified approach. Instead of working with one harmonic field but with a set of them allows modeling the partial coherence of stationary sources. In this talk we use the same approach to model the propagation of fully coherent ultra-short pulses through optical systems, which may include for instance lenses, gratings and micro-optical components. For that we can rely on the sophisticated propagation techniques for a single harmonic field. To this end the frequency domain of the pulse must be equidistantly sampled. According to the sampling theory, the suitable sampling period depends of the time window that is the extension of the pulse function in time. Because of the time shift of the pulse and material as well as angular dispersion during propagation, this time window is not constant during propagation and becomes very large. That makes sampling in practice impossible. Methods to overcome this problem are discussed. They allow a convenient pulse modeling in practice. Several examples are presented using pulse modeling with VirtualLab .

7589-22, Session 6

Terahertz pulsed spectroscopy and imaging in the pharmaceutical environment

P. F. Taday, TeraView Ltd. (United Kingdom)

The terahertz spectral region extends from the end of the far-IR spectral region (i.e., 1.3 cm-1 or 0.2 THz) to the beginning of the microwave spectral region (i.e., 133 cm-1 or 4 THz). Absorptions observed in this region are commonly associated with intermolecular hydrogen-bonding vibrations and crystalline structure lattice vibrations. Currently, many commercial systems use either ultrashort pulsed Ti:sapphire or Yb fibre based lasers.

Terahertz pulsed spectroscopy (TPS) measurements obtained in both transmission and reflectance modes advance the current state-of-the-art for elucidating solid state crystalline structures such as polymorphs, hydrates, and solvates by providing fundamental spectra-structure correlations for hydrogen-bonding and other organic moieties. TPS provides a unique insight into chemical/physical compatibility for product formulation.

Terahertz pulsed imaging (TPI) provides a quick and non destructive 3D mapping technique for determining the composition and integrity of intact chemical materials and coatings. TPI yields unique information for product formulation, product quality, and root cause analysis of multi-layered products and laminates.

This presentation will discuss recent development in the application of terahertz pulsed spectroscopy and imaging to the pharmaceutical industry. Moreover, due to the speed of the technique there are opportunities of the application of TPI for in-line and on-line measurements. These developments will also be reviewed in this presentation.

7589-23, Session 6

Surface-enhanced Raman scattering hot spot isolation using surface-enhanced multiphoton lithography

E. D. Diebold, P. Peng, E. D. Mazur, Harvard Univ. (United States)

We present a generalized method for extreme trace detection (<1 femtomole of analyte) using surface-enhanced Raman scattering (SERS) substrates. Utilizing surface-enhanced multiphoton-induced polymerization, we physically limit the available molecular adsorption sites to only the electromagnetic “hot spots” on the substrate. This technique prevents molecules from adsorbing to sites of weak SERS enhancement, while permitting adsorption only to sites of extraordinary Raman enhancement. In this process, we use loosely-focused, microJoule-level, 100-fs laser pulses to expose a commercial positive photoresist covering a SERS substrate. Upon development of the resist, the exposed portions are removed, leaving the electromagentic hot spots on the surface uncovered. Compared to a randomly-adsorbed sub-monolayer of analyte molecules on a pristine SERS substrate, the same number of molecules adsorbed on isolated hot spots exhibits at least a 10-fold improvement in average Raman scattering cross-section. We show that this process is scalable and applicable to multiple types of SERS substrates.

7589-24, Session 6

Detection of counterfeit U.S. paper money using intrinsic fluorescence lifetime

M. J. Levene, T. Chia, Yale Univ. (United States)

We used scanning two-photon laser excitation and the time-correlated single photon counting (TCSPC) measure the intrinsic fluorescence lifetime of genuine U.S. currency and of forgeries. Three types of counterfeit samples were tested: lower-quality counterfeits printed on a consumer-grade printer, higher-quality counterfeits made by traditional printing methods, and counterfeits made by washing ink off genuine notes. In all cases, lifetime measurement easily distinguished counterfeit from genuine U.S. Currency. This study provides evidence that intrinsic fluorescence lifetime measurements have applications for analysis of counterfeit and genuine paper money and potential for further applications in the field of forensic science.

7589-25, Session 6

Dispersive Fourier-transform spectral interferometry for ultrafast real-time axial profiling of multilayer objects

K. Goda, A. Motafakker-Fard, B. Jalali, Univ. of California, Los Angeles (United States)

Absolute metrology based on optical frequency combs is widely used for remote sensing and optical coherence tomography. Conventional laser ranging techniques can perform absolute distance measurement at high speed (~10 MHz), but are limited to ranging of single-layer objects, or axial profiling of multi-layer objects such as biological tissues, but are slow (~10 kHz) due to the use of a CCD-based spectrometer or frequency-swept laser, incapable of probing rapid dynamics or vulnerable to sample motion.

Here we present a laser ranging method that overcomes this trade-off and offers ultrafast real-time absolute metrology for multi-layer objects at wavelengths useful for biomedical applications. This technique uses dispersive Fourier transformation - an optical process that maps the spectrum of an optical pulse into a temporal waveform using group-velocity dispersion - as a real-time pulse-by-pulse spectrometer to analyze spectral interferometry based on a frequency comb. Dispersive Fourier transformation replaces a spatial disperser (e.g., diffraction grating) and detector array (e.g., CCD) with a dispersive fiber and single-pixel photodetector, greatly simplifying the system and, more importantly, enabling ultrafast real-time spectroscopic measurements.

As a proof-of-concept, we demonstrate continuous real-time axial profiling of a multi-layer sample at a record scan rate of 90.9 MHz at 800 nm. In particular, we observe the phase explosion effect - a rapid boiling process due to homogeneous nucleation in a superheated volume of liquid near its critical state. This method is expected to be a powerful tool for studying dynamics of laser surgery, laser cutting and micromachining, and laser-induced breakdown spectroscopy.

7589-26, Session 7

Curved-waveguide fabrication using femtosecond laser processing with glass hologram

J. Suzuki, Y. Arima, M. Yamaji, H. Kawashima, S. Tanaka, New Glass Forum (Japan)

Femtosecond laser processing with glass-hologram is an efficient processing method that an arbitrary three-dimensional intensity distribution produced by the glass-hologram is directly patterned into transparent materials at one laser shot. It has higher productivity of optical devices with higher accuracy, comparing to the conventional

femtosecond laser processing of translating tightly focused femtosecond laser pulses. We have demonstrated the fabrication of three-dimensional spiral structure [1] and straight-waveguides of 5 mm long [2], using this laser processing method.

In this work, we report on the curved-waveguide fabrication using femtosecond laser processing with glass-hologram. At first, we design and fabricate a glass-hologram as follows. Using the computer-generated holography method, we calculate a phase distribution that produces a curved-line beam from an input femtosecond laser beam. The phase distribution is transferred on a glass surface with electron beam lithography and reactive ion etching. Then we pass femtosecond laser pulses through the glass-hologram. The curved line beam generated by the glass-hologram is focused into a glass sample, and consequently a curved-waveguide is fabricated inside the glass. For example, its arc length is longer than 5 mm, while the width is about 5 mm. Curved-waveguides with different curvatures are fabricated, and optical property of the curved-waveguides is investigated. We also demonstrate fabrication of directional couplers consisting of the curved-waveguides.

[1] M. Yamaji, H. Kawashima, J. Suzuki and S. Tanaka, App. Phys. Lett. 93, 041116 (2008)

[2] J. Suzuki, M. Yamaji, and S. Tanaka, Proc. SPIE, Vol. 7201, 72011C (2009)

7589-27, Session 7

Direct writing of waveguides in bulk Ti3+:Sapphire with a femtosecond oscillator

S. Gross, A. Fuerbach, M. J. Withford, Macquarie Univ. (Australia)

We report on direct inscription of type-II waveguides in bulk titanium-doped sapphire with an ultrafast chirped-pulse oscillator. Ti3+:Sapphire is of particular interest due to its large emission bandwidth which enables a broadband tunability and generation of ultra-short pulses. However, its lasing threshold is high and powerful high brightness pump sources are required. The fabrication of a waveguide in Ti3+:Sapphire could thus enable the fabrication of low-threshold tunable lasers and broadband luminescence sources. The latter are of interest for optical coherence tomography where the obtainable resolution scales with the bandwidth of the light source.

The fabricated waveguides are formed in-between two laser induced damage regions. This technique has been applied to other crystalline materials (e.g. LiNbO3) but not in Ti3+:Sapphire, yet. The laser-induced structural changes are several microns long and about one micron wide. Their size is strongly dependent on the writing laser polarization. These damage regions of changed structure cause a stress field inside the crystalline lattice which consequently increases the refractive index to form a waveguide. The written structures exhibit a strong birefringence and two waveguides that support orthogonal polarized modes are formed between each pair of damage lines. Linearly polarized light parallel to the crystal's surface is guided between the two damage regions while a waveguide for the orthogonal polarization is formed underneath.

The propagation properties of the waveguides are characterized by their near field profiles and insertion loss with respect to the writing parameters. Further the fluorescence spectra of the waveguides are compared to the bulk material.

7589-28, Session 7

Soliton formation near topological defects in waveguide arrays

M. Heinrich, R. Keil, Friedrich-Schiller-Univ. Jena (Germany); A. Szameit, Technion-Israel Institute of Technology (Israel); L. Ramirez, F. Dreisow, T. Pertsch, S. Nolte, A. Tünnermann, Friedrich-Schiller-Univ. Jena (Germany)

We will report on our investigations of the influence of topological defects on the formation of discrete spatial solitons in waveguide arrays.

Periodic arrays of coupled waveguides have proven to be a versatile system for both integrated optics and fundamental research. The influence of defects within such systems, i.e. waveguides with detuned effective refractive index, is well understood. They have been shown to support linear bound states and thus influence the formation of spatial solitons in the surrounding sites.

We show how the presence of truncations, bends and junctions within the otherwise periodical system similarly may have a strong influence on the surrounding sites. These so-called topological defects are highly relevant for integrated optics, since they affect the performance of essential components such as opto-optical switches and routers based on waveguide arrays.

Experiments were carried out in waveguide arrays with various geometries fabricated in fused silica with the femtosecond laser direct inscription technique. Soliton formation was studied by launching 200fs pulses with peak powers of up to 2MW. The localization behaviour at the topological defect and surrounding guides was investigated via the resulting diffraction patterns. Our results are confirmed by numerical studies and clearly demonstrate the impact of topological defects.

7589-29, Session 7

Waveguide and microchannel fabrication in polymers with femtosecond lasers

S. M. Eaton, CNR (Italy); J. M. Pinazo, R. Suriano, N. Bellini, R. Ramponi, S. Turri, M. Levi, G. Cerullo, Politecnico di Milano (Italy); R. Osellame, CNR (Italy)

Femtosecond laser microfabrication is a promising technology for producing waveguides and channels for optofluidics in fused silica glass, but has yet to be fully explored in polymers, which offer more customizable properties at a fraction of the cost.

Smooth microchannels were formed by ablation with a 1-kHz femtosecond laser using a multiscan approach in poly(methyl methacrylate) (PMMA) and polystyrene (PS). Contact angle characterization showed the channels to be more hydrophilic after exposure followed by a partial hydrophobic recovery. After 100 hours, the contact angles were stable in time, and showed increased hydrophilicity compared to the pristine polymer, with PMMA showing the greatest improvement. The degradation mechanisms during ablation were studied using IR spectroscopy, revealing strong oxidation in PS. In contrast, PMMA did not show oxidation but a reduction in molecular weight due to unzipping of the backbone chain.

Next, the same 1-kHz femtosecond laser was applied to buried waveguide formation in PMMA, producing stable and symmetric structures using a beam reshaping technique. Such waveguides showed moderately low propagation loss at 633 nm. A high repetition rate (1 MHz) femtosecond laser, which offers the dual advantage of faster fabrication and symmetric waveguides, was next applied to PMMA but the resulting waveguides had a core of depressed refractive index and decayed with time. Future experiments exploring intermediate repetition rates will seek to uncover conditions suitable for stable, low-loss, symmetric waveguides in PMMA and other polymers.

7589-30, Session 8

Bonding of glass with femtosecond laser pulses at high repetition rates

S. Richter, S. Döring, Friedrich-Schiller-Univ. Jena (Germany); G. Kalkowski, R. Eberhardt, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); S. Nolte, Friedrich-Schiller-Univ. Jena (Germany) and Fraunhofer Institute for Applied Optics and Precision Engineering Jena (Germany); A. Tünnermann, Friedrich-Schiller-Univ. Jena (Germany) and Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

I would like to be considered for the student competition.

In the recent years the direct writing of waveguides with femtosecond laser pulses has attracted great interest. Due to nonlinear absorption processes the laser energy is absorbed at the focus within the transparent glass substrate. Breaking of bonds leads to changes in the refractive index.

Here, we apply this technology for bonding glass substrates. Therefore, the laser is focused at the interface between the two substrates, where it is absorbed. Due to the high repetition rate (> 1 MHz), heat accumulation of successive pulses and subsequent melting occurs. This way the laser acts as a local heat source directly at the interface. By moving the laser focus across the interface, a bonding area may be formed. The advantages of this technique are the flexible process, the low sample temperatures and localized bonding, which results in minimized thermal stress. Moreover, tailored bonding only in specific areas adapted to the application becomes easily possible.

In this presentation, we will discuss the influence of the processing parameters (pulse energy, rep.-rate, scanning speed etc.) on the bond strength.

7589-31, Session 8

Time dynamics of burst-train filamentation assisted femtosecond laser machining in glasses

D. Esser, Univ. of Toronto (Canada) and RWTH Aachen Univ. (Germany); S. Rezaei, J. Li, P. R. Herman, Univ. of Toronto (Canada)

In femtosecond laser machining, burst trains induce heat accumulation, thermal diffusion and transient defect effects for more gentle modification in the laser interaction volume due to a small time interval between subsequent pulses. A purpose-built optical resonator has been applied to generate high repetition rate (38.5MHz) femtosecond laser bursts tailored for filamentation-assisted laser machining of high aspect ratio holes in transparent glasses. Single Ti:Sapphire laser pulses (lambda=800nm, tau=50-5000fs, Ep=2mJ, f=1kHz) were trapped in a passive resonator and released into controllable burst profiles by computer generated delays to a fast Pockels cell switch. A time-gated intensified-CCD camera has been integrated with the laser processing station for recording temporally resolved optical images of laser-generated filaments, photoluminescence, ablation plumes, and hole profiles in both top and side views as they evolve on nanosecond time scales with each burst train. The temporal characterization reveals the build-up of heat accumulation and other transient effects that mitigate shock-induced microcracks. The data further reveal the formation of self-focusing filaments that guide the excision of high aspect ratio holes only when driven at high repetition rate. The filamentation-guided machining appears to be a new phenomenon for excising high aspect ratio holes in transparent media. Physical insights on how thermal accumulation and filamentation processes play together at high repetition rate will be examined.

7589-32, Session 8

Dynamics of femtosecond laser modification in glass

J. J. Witcher, L. B. Fletcher, N. Troy, D. M. Krol, Univ. of California, Davis (United States)

The use of femtosecond lasers to modify the bulk of transparent materials has proven to be an important method for the fabrication and integration of optical components, such as waveguides, splitters, Bragg gratings, and amplifiers. Despite the advances in device design there is still much to be understood about the mechanism responsible for the femtosecond laser modification of transparent materials. A better understanding of the modification process is integral to the creation of better and more diverse optical devices.

Characterization of the structural changes in glass after fs-laser radiation has provided information on defect formation, densification, and thermal stability of fs-laser modification, but more information on the dynamics of the process needs to be obtained to understand the physical processes that lead to the structural modification.

In this study fused silica glass was irradiated using an amplified Ti:sapphire fs-laser system. Using a pump-probe setup with the fs-laser we studied the dynamics of the modification. The transmission of a broadband probe was measured as a function of pump-probe delay time. By comparing the transmission results with theoretical modeling of plasma properties the electron density created by the absorption of the fs-laser pump pulse was determined. Peak electron densities and plasma lifetimes were also measured for various writing conditions. We will discuss the results in relation to the morphology and structural changes in the glass after fs laser-induced modification.

7589-33, Session 8

Three-dimensional silica surfaces fabricated using femtosecond laser lithography

H. Nishiyama, M. Mizoshiri, Y. Hirata, Osaka Univ. (Japan); J. Nishii, Hokkaido Univ. (Japan)

Three-dimensional (3D) surfaces of inorganic optical materials were created by a combined process of fs-laser nonlinear lithography and plasma etching. Hybrid diffractive-refractive optical elements are promising candidates for various photonic applications. However, the fabrication of 3D surfaces still remains a challenging task for the current semiconductor technology. In this paper, we report the fs-laser lithographic properties, and demonstrate the formation of silica diffractive-refractive hybrid microlenses by the combined process.

We used a femtosecond fiber laser system. This system delivers laser pulses at 780 nm wavelength with a pulse duration of 127 fs and repetition rate of 100 MHz.

MicroFresnel lens patterns were written directly inside resists on convex lenses by femtosecond laser-induced nonlinear optical absorption. The patterns were transferred to the underlying lenses by CHF3 plasma etching after development and baking processes. We could obtain well-defined patterns even inside the resists on the lens, which were deformed by surface tension, because nonlinear absorption occurs only near the focal volume. The surfaces of hybrid lenses were smooth and there were no thermal damage and cracks. When He-Ne laser light of 632.8 nm wavelength was coupled to the hybrid lens, the shift of focal length by 200 um was confirmed by CCD camera observation. This shift amount agreed well with theoretical values. Our combined process is effective for the fabrication of highly functional optical devices.

7589-34, Session 8

Multimodal laser spectroscopic microscopy during ultrafast laser nanofabrication

J. Li, P. R. Herman, Univ. of Toronto (Canada)

In-situ and real-time diagnostics during ultrafast laser material processing offers fundamental insights into laser-material interaction physics by collecting and analyzing temporally and spatially resolved laser excited light emissions. Our objective is to exploit such tools towards more reliable and efficient on-the-fly process control as spectral emissions become definitively correlated with the quality and performance of devices as they are formed under laser exposure. In this paper, we present an optical system that combines ultrafast laser micro/nanofabrication with multimodal spectroscopic microscopy for 5-dimensional characterization (space, time and wavelength spectrum) of laser-formed optical devices inside transparent media. Both fundamental and frequency-doubled output of an amplified fiber laser (1045 nm, 300 fs) with variable repetition rate (0.1-5 MHz) were used in dual roles of material modification and spectroscopic excitation. Computer controlled exposure and characterization tools encompassed beam positioning tools, a time-gated intensified CCD camera, an imaging spectrograph, and a single-photon-counting module for broad UV to near-IR optical recordings on various modalities of time-resolved spectroscopy, spatial imaging, and multiphoton laser scanning microscopy. Characteristics of multi-photon photoluminescence, fluorescence, plasma emission, second and third-harmonic generation, and other processes are reported for in-situ real-time evaluation of the relaxation dynamics evolving during ultrafast laser direct writing of optical waveguides in bulk silicate glasses. The results have been further coupled with cw UV laser (244 nm) photoluminescence and time-resolved deep-UV laser (157 nm) excited photoluminescence study to help unravel a comprehensive understanding of the laser glass interaction physics. The onset of heat accumulation effects with high repetition rate (> 100's of kHz at sub-uJ energy) pulses are definitively identified in the spectral recordings and correlated with the waveguide quality and defect formation mechanisms. Finally, we report on prospect for using such in-situ and real-time spectroscopic microscopy for evaluating and directing of laser nanofabrication of high quality optical waveguides and other 3-D optical devices.

7589-13, Session 9

Holographic femtosecond laser processing

Y. Hayasaki, Utsunomiya Univ. (Japan)

Femtosecond laser processing inside transparent materials has advantages of high spatial resolution due to multi-photon absorption and reduced thermal destruction of the target due to the extremely short pulse duration. Therefore, the femtosecond laser processing has been used to develop three-dimensional (3-D) optical devices. To fabricate the 3-D optical devices composed of a huge number of processing points, parallel femtosecond laser processing with high throughput is indispensable.

Holography gives the features of high throughput, high light use efficiency, and material-dependent light distribution ser to the femtosecond laser processing. Especially, computer-generated holograms (CGHs) are very useful and powerful tool, because the CGH can generate a desired arbitrary beam, such as a spatially-shaped beam, a split beam, a focused beam, and a wave-front corrected beam, with low loss of light. The CGH is variably displayed on a liquid-crystal spatial light modulator (LCSLM). A key requirement in the design of the CGH is a precise control of the diffraction peak intensity. Some methods for the control have been applied.

In this paper, we demonstrate recent progresses in our study of holographic femtosecond laser processing, including two- and three-dimensional parallel processing, line processing, and adaptive optimizations of hologram for higher uniform processing.

7589-36, Session 9

Micromachining of metal and silicon using high average power ultrafast fiber lasers

E. P. Mottay, Y. Zaouter, Amplitude Systemes (France); C. Loumena, M. Faucon, J. Lopez, ALPhANOV (France)

Ultrafast laser micromachining has been widely proven to be a high quality, high flexibility process, with numerous potential industrial applications.

The ultrashort pulse duration (< 10 ps) and the very high intensity on the target (up to 1014 W/cm²) lead to a complete ionization of the irradiated volume by non-linear effects. Since pulse duration is below the heat diffusion time, the irradiated volume is ejected before any heat diffusion or thermal damage, and consequently side-effects are significantly reduced compared to longer pulses. Hence, reduced side-effects enable to preserve the functionalities of the material and to perform fine and accurate microfabrications such as drilling , cutting, engraving, and internal marking. Low pulse energy is generally required for micromachining (<100µJ).

Until recently, a main drawback was the low processing speed due to the limited average power available from ultrafast lasers. Recent advances in commercial ultrafast lasers have significantly increased the average power available to the user. However, parallel advances in process development are required to take full advantage of these new capabilities.

We report on micromachining and engraving of metal and silicon using a variety of high average power ultrafast lasers. We used both crystal-based systems and fiber lasers, operating in the picosecond and femtosecond regimes. We will present comparative results on the influence of pulse duration, of laser wavelength and ambiant pressue on the ablation rate and processing speed. Processing speeds greater than 5 m/s are reached with smooth sidewalls and no burr.

7589-37, Session 9

Ultrafast laser-based tools enable advanced silicon solar cell efficiency enhancement processes

F. Colville, Coherent, Inc. (United States)

The recent availability of industrial-grade turn-key short-pulse (picosecond and sub-picosecond pulse-width) solid-state lasers offers new opportunities within next-generation crystalline-silicon solar cell production: specifically, for multi-c-Si types based upon standard front/back contact cells operating with average efficiencies in volume in excess of 17%. As new applications for short-pulse lasers are transitioned from solar research institutes to pilot cell production lines, an established equipment supply chain is now required to ensure laser-source and application qualification (marking the switch from non-laser based tooling to laser-based processes for solar cell production).

This paper examines first the process windows associated with applications such as laser-assisted selective-emitter formation and mask-writing for diffusion/plating during cell manufacture; how these demand both the use of both short-pulses and short-wavelengths from advanced solid-state lasers; and why legacy industrial-grade lasers (in particular nanosecond and long-wavelength options) failed to meet production acceptance criteria. The requirements then on laser-based process tools are outlined, with a direct comparison to the solar industry roadmaps being discussed currently; including the additional constraints from cell producers which impact on laser-tool design, performance, throughput, and return-on-investment.

Finally, the applications in question here for short-pulse lasers will be used as a representative case-study for the generic industrial adoption of state-of-the-art solid-state lasers; in particular, where they enable research-proven work to be taken into a production environment (hitherto laser-source limited) with a well-defined market pull.

7589-38, Session 9

Picosecond laser patterning of NiCr thin film strain gauges

O. Suttmann, J. Duesing, U. Klug, R. Kling, Laser Zentrum Hannover e.V. (Germany)

I would like to paticipate in the studen competition.

Strain measurement of technical components is realised by strain gauges based on polymer foils. Conventional strain gauges suffer from creeping and swelling through alternating ambient humidity as well as a low positioning accuracy.

A new approach for strain measurement is the integration of sputtered thin film strain gauges. These are often based on a sensing NiCr film. The sensing film is electrically isolated from the component to be measured by an insulating Al2O3 film. Both films are deposited by means of high rate PVD processes. In the next step the sensor is patterned by picosecond laser pulses. The use of laser radiation for the patterning allows the realization of sensors on 3D surfaces. This paper presents results of experiments on patterning of NiCr thin films with thicknesses ranging from 23nm to 246nm on Al2O3 substrates with picosecond laser pulses. Laser ablation with picosecond laser pulses enables thin film patterning with low thermal load and reduced risk of electrical shortcuts. Investigated parameters are fluence, number of pulses, film thickness and substrate roughness. The influence of the parameters on the ablation rates, thresholds and morphology as well as on the incubation factor is analyzed. The incubation factor describes changes of the ablation threshold after irradiation of multiple pulses below the ablation threshold. All investigated film thicknesses show a decrease of the ablation threshold with increasing number of irradiations. The ablation thresholds increase with a growing film thickness. This correlation is stronger for substrates with a higher roughness.

7589-39, Session 9

High repetition rate femtosecond laser processing of metals

J. Schille, U. Loeschner, R. Ebert, Univ. of Applied Sciences Mittweida (Germany); P. Scully, N. Goddard, Univ. of Manchester (United Kingdom); H. Exner, Univ. of Applied Sciences Mittweida (Germany)

(I would like to be considered in this year’s student competition.)

In this study a high repetition rate femtosecond fibre laser source (IMPULSE; Clark MXR) has been applied in 3D laser micro structuring of metals. We are going to discuss the investigated significant laser material interaction mechanisms in high repetition rate laser processing such as heat accumulation and particle shielding. Laser machining with repetition rates in the range of 500 kHz has shown interaction effects of the incident laser beam with the ablated particles and clusters induced by the foregone laser pulse. At higher repetition rates heat accumulation causes a higher energy input which locally leads to a temperature rise and results in better absorption conditions and lowered ablation thresholds of the irradiated material. In this machining regime energy losses forced by particle shielding have been overbalanced and a considerable increase of the ablation depth has been detected. Additionally due to a high laser energy input the formation of laser induced periodical micro structures have been observed. We found that the origin, shape and density of these conical structures can be influenced by processing parameters. However, the formation mechanism is still under discussion.

Finally we are going to present machining examples to discuss possibilities and limits of high repetition rate laser processing in 3d micro structuring. By using innovative scanning systems a high machining throughput can be reached which attract interest of the novel laser technology in Rapid Micro Tooling. Furthermore efficient fabricated laser induced micro structures can be applied in novel application due to enhanced material surface behavior.

7589-14, Session 10

Gold nanorods enhanced femtosecond laser nanoablation of silicon

M. Meunier, P. Desjeans-Gauthier, E. Boulais, Ecole Polytechnique de Montréal (Canada)

When an electromagnetic wave hits a metallic nanostructure of a size less than its wavelength, the wave’s energy is absorbed and locally reemitted as near field in close proximity to the nanostructure, but with a multiplied intensity. This local field enhancement is mainly attributed to the surface plasmon resonance of the nanostructures and can be used to perform nanoprocessing of the substrate surface on which the nanostructures are deposited. Actually, if the field enhancement is high enough, it is possible to send a femtosecond pulse below the ablation threshold of the substrate that will be powerful enough, once amplified, to locally perform nano-ablation under the nanostructures. In this research, we investigate the use of gold nanorods as an efficient nanostructure for plasmonic enhanced fs laser nanoprocessing. The field enhancement AF value can be experimentally determined by comparing the lowest laser fluence for which sample surface ablation is observed to the normal sample surface ablation threshold. In this study, we used a Ti-Sapphire femtosecond pulse laser at 800 nm wavelength irradiating a Si substrate. Values for AF was determined to be ~ 2.3 for a 25 nm diameter x 75 nm long gold nanorod. Comparison with gold nanospheres with diameters ranging from 20 to 200 nm has been made. While for gold nanoparticles, single nanoholes are usually produced, double nanoholes separated by few tens of nm could be fabricated, all oriented in the polarization directions of the irradiation beam when gold nanorods are used. In order to understand the basic mechanism of plasmonic enhanced laser nanoablation of silicon, we performed three dimensional simulations to obtain the electromagnetic field distribution surrounding the gold nanorod after an interaction with a 800nm 120 fs laser pulse. Calculation of the electromagnetic field distribution by a finite-element based method clearly shows a double lobe field enhancement, in agreement with experiments.

7589-15, Session 10

Efficient femtosecond laser nanohole processing on substrate surface using high dielectric constant particles with small size parameter

Y. Tanaka, G. Obara, A. Zenidaka, M. Obara, Keio Univ. (Japan)

We present the experimental and theoretical results on the nanohole processing using high dielectric particles with small size parameter. Nanohole processing mediated with the dielectric particle exhibits the smaller features than the diffraction limit. The use of dielectric particles has attracted much attention for industrial applications, because fabrication of the monolayer 2D particle arrangement seems much easier than the metallic ones. Based on Mie scattering theory, the enhanced near-field is determined by the size parameter x=pi*D/lambda, defined as pi* particle diameter D divided by optical wavelength lambda. The clear nanohole is obtainable with x~pi but not with the smaller size parameter x<pi/2 due to the weak enhanced near-field for frequently used particles like polystyrene particle. Therefore, the shorter wavelength is required for downsizing the processed nanoholes, which needs the sophisticated wavelength up-conversion in ultrashort time domain and vacuum UV (lambda<200 nm). Using dielectric particles having high dielectric constant, the strong enhanced near-field is generated even with small size parameters due to the strong scattering cross-section of the particle. The resonant refractive index of the particle depends on the size parameter, meaning that the used material should be selected as a function of size parameter. In the ablation processing with 2D arrayed particles, the optical field interaction such as inter-particle multiple scattering should be considered and then the optimal spectral condition is different from the single particle case. The obtained results indicate that the use of high dielectric particles becomes a promising technique for downsizing the produced nanoholes.

7589-16, Session 10

Effect of target structure on interfering femtosecond laser processing

Y. Nakata, T. Hiromoto, N. Miyanaga, Osaka Univ. (Japan)

Interfering ultra-short pulse laser processing was applied to induce nanostructures on metallic thin films. The nanostructures are nano-waterdrop, nanocrown, and nanobump. They are generated by thermally process with nano-period, and basic structure can be controlled by target structure, such as film thickness, base substrate, etc.. Peaked structure has curvature radius smaller than 10 nm, and the value was beyond the resolution of ordinal ultra-short pulse laser processing.

7589-40, Session 10

Brighter light sources from the black metal

A. Y. Vorobyev, C. Guo, Univ. of Rochester (United States)

No abstract available

7589-17, Session 11

Femtosecond laser processing of hybrid micro- and nano-structures in silicate glasses

P. Mardilovich, J. J. Witcher, L. B. Fletcher, S. H. Risbud, D. M. Krol, Univ. of California, Davis (United States)

I would like to be considered in this year's student competition.

Ultrafast laser processing had been used to induce structural modifications in the bulk of transparent dielectric materials, such as glass. This has enabled a creation of several optoelectronic device-oriented structures, such as waveguides, splitters and couplers, Bragg gratings, amplifiers etc. So far most of these structures have been homogeneous on a nanometer scale. Manufacturing heterogeneous structures of micro-scale domains with nano-scale inclusions will greatly expand the toolbox available for optoelectronic device design.

In certain doped glasses it is possible to nucleate and grow metal or semiconductor nanocrystals under certain thermal conditions. Using a focused femtosecond laser it has been shown possible to manipulate the nucleation process, allowing sufficient control to define where nanocrystal precipitation will take place.

In this work, we explored a range of processing parameters, a combination of tightly focused femtosecond laser irradiation and heat treatment, in the context of nucleation control in several silicate glass compositions. We studied the resultant structures using absorption measurement, optical and electron microscopy, and characterized structural modifications of the glass matrix using fluorescence and Raman spectroscopy.

We will discuss the results and how the processing parameters, such as laser pulse power, repetition and scan rates, and heat treatment temperature, affect the structure properties. We will specifically address these effects with respect to corresponding phase separation dynamics.

7589-18, Session 11

Structure modification of glass-ceramics thin films and layers by ultrashort laser action

V. P. Veiko, St. Petersburg State Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

Glass-ceramics (GCs) usually have glass structure doped with microcrystalls that are responsible for main properties: mechanical, chemical, optical etc. Different laser technologies for modification of structure of GCs has been developed. The most important thing is that optical transparency of GC drastically increases in visible and near IR range due to the appearance of new glassy structure. Variation of laser treatment conditions (power, exposure, wavelength from IR to UV) as well as selection of composition of GCs allows to control mentioned characteristics. Most interesting now is local structure modification of GC under short pulses laser action - from nanosecond to pico- and femtosecond. All 3 types of these lasers on different wavelengths have been used for experiments (2 - 10.6 mcm, 200 ns; ArF - 193 nm, 10 ns; Nd-YAG - 266 nm, 355 nm, 532 nm, 30 ps, Ti-sapphire -0.8 mcm,100 fs). We used two compositions of GCs with crystalline phases of TiO2-SiO2 (Sitall ST-50) and Li2O-SiO2 ("Fotoform"). As a result of above mentioned research mini- and micro-optical components based on two GCs have been fabricated and demonstrated: lenses and lens arrays, modulators, waveguides and other waveguiding components, gratings, integrated diaphragms etc.

Veiko V.P., Novikov B.Yu.. Shakhno E.A., Yakovlev E.B. Physical Mechanisms of Fast Structure Modification and the Appearance of Waves of Optical Bleaching in Glass Ceramics. Laser Physics, Vol. 18, No. 4, pp. 1-11, 2008.

7589-19, Session 11

Two-photon lithography and nanoprocessing with picojoule extreme ultrashort 12 femtosecond laser pulses

K. König, M. Schug, H. Zhang, S. Saremi, D. Feili, H. Seidel, Univ. des Saarlandes (Germany)

A novel ultrashort femtosecond laser scanning microscope with 12 femtoseconds pulse width at the focal plane has been employed in material nanoprocessing. The laser system is based on a 10 fs 85 MHz laser resonator in combination with a precompensation unit with chirped mirrors. The near infrared laser beam was focused with an objective of high numerical aperture.

A variety of photoresists could be activated via a two-photon excitation process with microwatt mean powers based on the broad emission spectrum (maximum 780 nm) of the 12 femtosecond near infrared pulses. 3D two-photon lithography was realized via beam scanning and stage scanning.

Nanoprocessing (drilling, cutting, ablation) was performed with sub-20 mW mean powers due to multiphoton ionization and plasma formation. We report on the nanostructuring of polymers, glass, and silica.

7589-20, Session 11

Individually controlled multi-focus laser processing for two-photon polymerization

K. Obata, J. Koch, B. N. Chichkov, Laser Zentrum Hannover e.V. (Germany)

Two-photon polymerization (2PP) of photosensitive polymer materials using femtosecond (fs) lasers is one of the unique techniques for true three-dimensional micro- and nano-scale structuring. Femtosecond laser induces two-photon absorption at local volume leading to precise microfabrication with structural dimensions much smaller than the diffraction limit of the incident laser beam. Recently, the increasing 2PP process resolution requiring much longer processing time became a problem for practical use. To overcome this problem, some groups have demonstrated unique 2PP setup with beam separation techniques such as parallel process with a fly's eye type lens, or diffractive optical elements (DOE). However these techniques can realize an efficient mass production, they are not suitable for the fabrication of single complex structures and unsymmetrical array structures in rapid prototyping. In this study, a novel beam separation technique with spatial light modulator (SLM) is demonstrated for acceleration of two-photon polymerization process.

In this experiment, fs laser pulses are illuminated onto the reflective type liquid crystal SLM displaying a computer generated holographic (CGH) pattern to modulate the phase of the incident laser beam. The reflected laser beam forms multi-focus spot pattern at the Fourier plane and is projected into the liquid phase inorganic/organic hybrid polymer (Ormocer) sample with a 100x immersion microscope objective (NA=1.4). These multi-focus beams can induce 2PP at each focus position. In addition, each focus spot can be independently controlled in position and laser intensity with SLM.

7589-21, Session 11

Up-conversion of crystal oscillator frequency in silicon package by near infrared, ultra-short laser

Y. Ito, R. Tanabe, F. Sato, Y. Shinohe, Nagaoka Univ. of Technology (Japan); K. Tada, Citizen Finetech Miyota Co., Ltd. (Japan)

Crystal oscillators are key component in electronic equipments. They are contained in ceramic or metal packages and sealed off after adjusting their frequencies to designated values by adding or removing small mass from the crystal. Lasers are widely adopted as tools for it. The process has, however, risks of contamination before sealing and of frequency changes stimulated by sealing processes. If the frequency adjustment could be done after packaging, these risks are avoidable. The adjustment after sealing has made possible by adopting glass lid, which is transparent at laser wavelength used. Recently, packages made of silicon have been developed. The silicon package has several advantages compared to ceramic or metal packages. To adjust the frequency after sealing, however, laser irradiation must be done through the silicon lid.

Using a laser with photon energy smaller than the band-gap of silicon, machining of substances located at back of a silicon substrate should be achievable. To demonstrate this, machining of a silicon substrate as well as machining of gold film on it was carried out using femtosecond lasers, wavelength of which lay between 1.5 to 2.5 micrometer.

It is demonstrated that the rare surface of the silicon and the gold film placed at the back of the substrate can be machined with no detectable change on the front surface of the substrate. Frequency adjustment of the silicon-packaged crystal oscillator is tried. Up-conversion of the frequency is achieved by removing small amount of thin gold film on the crystal by irradiation of 1.5 micrometer laser through the silicon lid.

7589-22, Session 12

Femtosecond laser fabrication of birefringent directional couplers in fused silica

L. A. Fernandes, Univ. of Toronto (Canada) and INESC Porto (Portugal); J. R. Grenier, P. R. Herman, J. S. Aitchison, Univ. of Toronto (Canada); P. V. S. Marques, INESC Porto (Portugal)

The fabrication of integrated polarization splitting directional couplers is demonstrated in a bulk fused silica substrate with femtosecond laser direct writing. The laser writing system consists of a Yb:fiber chirped pulse amplified system, with a center wavelength of 1044 nm operating at 300 fs, 150 nJ and 500 kHz repetition rate. The laser was frequency doubled to 522 nm to drive stronger refractive index contrast in fused silica glass.

The waveguide birefringence was controlled by the writing beam polarization, being perpendicular or parallel to the waveguide axis. By fabricating a single step Bragg grating waveguide, a peak birefringence of 2 x 10-4 was measured from the spectral splitting of the Bragg reflection peak with respect to the polarization state of the inserted broadband light. This birefringence was then used to develop polarization splitting directional couplers with various spectral responses designed for the C and L Telecom bands. Birefringent directional couplers designs are presented for broadband and WDM polarization beam splitting application that present very stable components for new applications such as differential polarization phase-shift keying in optical communication and quantum encryption receivers.

7589-41, Session 12

A frontier in optical data storage: five-dimensional optical data storage

M. Gu, Swinburne Univ. of Technology (Australia)

In this presentation, I will give a review on our recent progress on the utilisation of nanoparticles including quantum dots/rods and metallic nanorods in multi-dimensional optical data storage [Peter Zijlstra, James W. M. Chon, Min Gu, Nature, 459 (2009), 410-413; Xiangping Li, James W. M. Chon, Richard A. Evans, Min Gu, Opt. Express, 17 (2009), 2954-2961]. We have introduced a new concept of multi-dimensional optical storage based on multi-photon excitation of nanoparticles. In this new technology, the information can be stored not only in different positions of a thick medium but also in polarisation and spectral domains. The tuneability of optical properties of the nanoparticles provides the various erasable and non-erasable polarisation and spectral encoding mechanisms in the same spatial position to break the data density limit imposed by the 3D optical storage technology. This nanophotonic approach will lead to a horizon of the new-generation 5D optical data storage technology that is of a potential toward a data storage capacity of Petabytes.

7589-42, Session 12

The influence of glass structure on femtosecond laser waveguide writing in erbium-doped phosphate glass

L. B. Fletcher, J. J. Witcher, D. M. Krol, Univ. of California, Davis (United States); R. K. Brow, Missouri Univ. of Science and Technology (United States)

Permanent structural changes induced by fs lasers can be used inside active glasses to fabricate waveguide lasers, with applications in three-dimensional photonic circuits. Phosphate glasses are excellent glass host systems for achieving high rare-earth oxide concentrations with low luminescence quenching effects, and are ideal for fabricating compact high gain waveguide lasers that operate in the C-band.

Previous research with zinc phosphate glasses has demonstrated that the bulk glass structure is important to determining the resulting morphological changes after femtosecond laser waveguide writing. Glasses with shorter average phosphate chain lengths exhibited local structural densification inside the irradiated area that can be used to fabricate single mode waveguides. In the present study, we have investigated how the addition of erbium to zinc polyphosphate glass affects the response of the glass structure to modifications by femtosecond laser pulses.

Waveguides have been fabricated using a regenerative amplifier Ti:sapphire (Merlin-Spitfire Spectra Physics) 1 kHz, 180 fs laser system with pulse energies ranging from 0.2 μJ - 4 μJ. The femtosecond laser beam was directed through a 20x (0.4 NA) microscope where the glass sample was translated parallel to the femtosecond laser beam at a constant scan speed of 50 μm/s. In this study we have written waveguides in a variety of erbium doped zinc polyphosphate glass compositions. Near field guiding profiles and white light images as well as insertion losses were measured after waveguides were written. Laser-induced structural changes in the glass were characterized using confocal fluorescence and Raman microscopy.

7589-43, Session 12

Birefringent elements based on femtosecond laser-induced nanogratings

L. Ramirez, M. Heinrich, S. Richter, F. Dreisow, R. Keil, Friedrich-Schiller-Univ. Jena (Germany); A. V. Korovin, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany); U. Peschel, S. Nolte, A.

Tünnermann, Friedrich-Schiller-Univ. Jena (Germany)

We will report on the fabrication of birefringent optical components based on femtosecond laser induced nanogratings.

In recent years, the femtosecond laser processing technique has been established as a versatile method for the fabrication of three-dimensional structures within the bulk of transparent materials. In a certain range of processing parameters so-called nanogratings, i.e. self organized periodic structures with sub-wavelength dimensions, are formed within the focal region of the writing objective. As a result, the induced structures feature a characteristic birefringent behaviour. This type of modification is of great interest for a wide field of practical applications, since it promises the opportunity for the rapid fabrication of three-dimensional birefringent elements of arbitrary shape and position-dependent retardation.

We will present the results of our experiments on the formation process of such nanogratings in fused silica. We studied the influence of various fabrication parameters, thereby identifying possible ways to systematically control the grating properties such as orientation, pitch and effective refractive index. Based on our work, we were able to fabricate nanograting based birefringent optical elements with various retardations and orientations, demonstrating the practical applicability of this approach.

7589-44, Session 12

Femtosecond laser written embedded diffractive optical elements and their applications

J. Choi, M. Ramme, T. P. Anderson, M. C. Richardson, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

Femtosecond laser direct writing (FLDW) has been widely employed to create volumetric structures in transparent materials that are applicable as various photonic devices such as active and passive waveguides, couplers, gratings, and diffractive optical elements (DOEs). The advantages of fabrication of volumetric DOEs using FLDW include not only the ability to produce embedded 3D structures but also a simple fabrication scheme, ease of customization, a clean process, etc. We present DOE fabrication techniques using FLDW as well as the characterization of laser-written DOEs by various methods such as refractive index change measurement and diffraction efficiency measurement. Gratings and Fresnel zone plates were fabricated in oxide glasses using various femtosecond laser systems in high and low repetition rate regimes. The diffraction efficiency as functions of fabrication parameters was measured to investigate the dependence on the different fabrication parameters such as repetition rate and laser dose. Furthermore, we demonstrate several integration schemes of DOE with other photonic structures for compact photonic device fabrication.

7589-45, Poster Session

Observations of the intense soft x-ray emissions from ultra thin Au films irradiated with high contrast laser pulses

M. Ishino, M. Kado, M. Nishikino, Japan Atomic Energy Agency (Japan); K. Shinohara, Waseda Univ. (Japan); S. Tamotsu, K. Yasuda, Nara Women's Univ. (Japan); N. Hasegawa, M. Kishimoto, T. Ohba, T. Kawachi, Japan Atomic Energy Agency (Japan)

Soft x-ray microscopes operating in the water window are capable of imaging living hydrated biological specimens. Laser produced plasmas are attractive soft x-ray sources, because of their short duration time enough to freeze the movement of living nature, the Brown motion, and to avoid radiation damages. To obtain high spatial resolution in soft x-ray microscopy, one must adopt bright soft x-ray sources as possible. Based on the minimum dose calculation, soft x-ray photons more than 10E5 photons/um^2 at the sample surface are needed to acquire an image of the biological specimens with spatial resolution up to 100 nm. The observations of soft x-ray emissions from laser produced plasmas using ultra thin film targets have been carried out. Au thin films with nano-meter order thicknesses evaporated on silicon nitride membranes were irradiated by a high contrast Nd:glass laser pulses with OPCPA system having a wavelength of 1053 nm, a duration time of 600 ps and an intensity of about 2E14 W/cm^2. The spectral properties of emitted soft x-rays were monitored by an x-ray spectrograph from the rear side with respect to the surface of laser irradiation. The observed emission intensities had an obvious dependence on the film thickness, and the most intense emissions were obtained at the thickness of 28 nm. The experimental results have suggested that the most of the laser energy irradiated is absorbed by the film target, and it is resulted an efficient energy deposition from laser to x-rays.

7589-46, Poster Session

New nanohole processing by backside irradiation of femtosecond laser with enhanced localized near-field mediated with gold particles

G. Obara, Y. Tanaka, T. Miyanishi, M. Obara, Keio Univ. (Japan)

We will present a new enhanced near-field nanohole processing by backside irradiation of femtosecond laser. Novel features in experimental results are well explained by numerical analysis based on 3D FDTD simulation. As for the processing with arrayed particles, we found that the near-field enhancement on the substrate is quite low when the gold particles are aggregated. This phenomenon is a crucial technical issue to achieve the precise nanohole array by closely packed nanoparticles. The BACKSIDE irradiation of femtosecond laser is found to be an effective technique to solve the technical issues. The gold particles with 200 nm in diameter are deposited on the different substrates and an 800 nm ultrashort pulse laser is irradiated. The field enhancement factors become quite strong on semiconductor and metallic substrate due to the image charge effect, whereas that on dielectric substrate is quite low. The experimental results of nanohole ablation verify this simulation results. Because of the image charge effect, the strong near-field enhancement is found to be obtainable on the Si semiconductor substrate even with the irradiation from the backside of the substrate. The backside illumination provides the effective nanohole processing technique which is not affected by the deposition parameters of the particles and unwanted small dusts above the substrate. The obtained results demonstrated the backside irradiation technique will open up a new surface nano-plasmonic nanohole processing.

7589-47, Poster Session

Application of high intense laser interaction with plasma in radiotherapy by using the soliton fiber medium

P. Zobdeh, Amirkabir Univ. of Technology (Iran, Islamic Republic of); R. Sadighi-bonabi, A. Alizadeh-Bagheri, Sharif Univ. of Technology (Iran, Islamic Republic of)

By chirped pulse amplification technique in the new generation of table-top lasers, the intensity of laser beam could be increased. In the high gradient fields electrons can be accelerated. In order to interaction of this high intense laser with plasma, Laser is transmitted by vacuumed tubes and guided to a vacuumed chamber. Interaction of laser with plasma target is observed in this vacuumed chamber. In this work for the first time, we have presented using the soliton fiber medium for transmission of high intense laser in contrast with vaccume tube. Using the felexible fiber medume caused to improvment electron or other particle therapy metodes. The stable spatial soliton propagation is possible. Better relative dose is evaluated in this technique. In this method direction and influence of electron beam can be controled effectively than the previous radiation treatment.

7589-48, Poster Session

Nonlinear lithographic properties by femtosecond laser pulses using a low-NA lens

M. Mizoshiri, H. Nishiyama, Osaka Univ. (Japan); J. Nishii, Hokkaido Univ. (Japan); Y. Hirata, Osaka Univ. (Japan)

(I would like to be considered in this year's student competition.)

Refractive indices of a chemically amplified photoresist were changed by femtosecond (fs) laser irradiation. We have proposed a combined process of fs nonlinear lithography and plasma etching for the fabrication of functional photonic devices with 3-D surfaces of inorganic materials. In this study, we report the nonlinear lithographic properties using fs laser pulses focused by a low-NA objective lens, and also demonstrate the fabrication of SiO2-based microfluidic lenses. Diffraction gratings were written directly inside the pre-baked resists by fs laser nonlinear absorption. From diffraction efficiencies using He-Ne laser light, refractive indices were changed by 2.0 - 6.0 × 10-3 without post-baking treatment which was required for cross-linking reaction. In contrast, no changes of refractive index were observed in the case of ultraviolet light exposure (i-line). Considering this large refractive index change and the threshold intensity of nonlinear absorption of the resist, self-guiding of fs laser pulses can occur due to the optical confinement in the radial direction. In fact, filamentary patterns longer than the focal depth could be obtained without translating the focal spot using this lithographic property. Micro-Fresnel lens patterns with 3-D surfaces were written inside the resist at the bottom of microchannels under the lithographic condition that refractive index changes were not induced. SiO2-based fluidic lenses with smooth surfaces could be created in the channels by pattern-transfer of the resist by reactive plasma.

7589-49, Poster Session

Ultrashort pulsed laser induced cavitation bubbles mediated by plasmonic gold nanospheres

S. Haering, D. Eversole, F. Bourgeois, A. Ben-Yakar, Univ. of Texas at Austin (United States)

In this paper, we characterize the optical properties of femtosecond laser irradiated gold nanoparticles as a potential therapeutic agent, by studying their near-field enhancement. To accomplish this goal, we measure the reduction in laser energy required to induce a given cavitation bubble size in water. Specifically, we use a pump-probe technique to measure bubble oscillation times induced by 784 nm, 200 fs single laser pulses focused in water. We then deduce the maximum bubble radius from measured oscillation times using the Gilmore model for bubble expansion and collapse. Measuring bubble radii generated in a solution of 36 x 46 nm gold nanoparticles, we found a large reduction in the average intensity threshold that can induce the smallest detectable bubble creation (300 nm radius) when compared to distilled water alone. Measurements show a wide distribution of bubble sizes for a given fluence, resulting from particle orientation with respect to beam polarization and the random location of particles within the focal volume. The extent of possible mechanical damage to surrounding media caused by high strain rates is then correlated to these measured bubble sizes and oscillation times. These results may be used to tune the desired effects of nanoparticle/light-based therapeutics.

7589-50, Poster Session

Laser microsintering of tungsten in vacuum

R. Ebert, F. Ullmann, L. Hartwig, T. Suess, S. Kloetzer, A. Streek, J. Schille, P. Regenfuss, H. Exner, Hochschule Mittweida (Germany)

Laser microsintering is currently the only one process for direct fabrication of micro¬structured components from metals and ceramics with achievable resolutions better than 30 µm and free-formed undercuts. By using short, high-intensity pulses, even metals with a high melting point such as tungsten can be machined. Generally tungsten is difficult to work and laser microsintering of tungsten has been carried out in protective gas environments.

In this work laser microsintering of polyhedral tungsten powder supplied by Goodfellow was investigated as a function of laser output power, pulse interval and vacuum level. An existing laser microsintering facility was used for the investigations consisting of a Nd:YAG laser, a modulator for pulse controlling, a scanner system for beam deflection and focusing, and a vacuum sinter¬ing chamber for performing the experiments under defined pressure conditions. Furthermore the powder absorption, evaporation thresholds, and the resulting layer thicknesses are calculated for tungsten powder particles of various sizes considering powder abrasion behaviour.

Polished sections and REM images were prepared in order to analyse the experimental outcomes. The results show a dependence of particle vaporisation during laser microsintering on particle size, applied laser power and residual gas pressure. The sinter structure can be influenced by the variation in chamber pressure. At 500 mbar higher laser power leads to greater abrasion and higher sinter density; in vacuum higher laser power leads to slightly greater abrasion and correspondingly higher sinter density but higher pulse density does not lead to greater abrasion nor to higher sinter densities.