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Conferences and Courses: 21–26 January 2012
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Conference 8235: Solid State Lasers XXI: Technology and Devices

Sunday-Wednesday 22-25 January 2012

Part of Proceedings of SPIE Vol. 8235 Solid State Lasers XXI: Technology and Devices

8235-04, Session 1

High-efficiency diode pumped Er:YLF laser with multi-wavelength generation

M. V. Inochkin, V. Y. Khramov, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); G. B. Altshuler, A. Erofeev, S. W. Wilson, Palomar Medical Technologies, Inc. (United States); F. I. Feldchtein, Dental Photonics, Inc. (United States)

Strong line of water absorption determines efficient applications of laser sources nearby 3-um spectral range. Conventional Er-doped crystalline lasers are a good candidate for generation of powerful radiation in 2.6-3.0 spectral range where absorption of human tissue may be varied in several orders of magnitude depending on exact lasing wavelength. Compact diode-pumped Er-doped laser systems are of particular interest for medical applications because they can deliver powerful laser radiation directly from a handheld device used by the physician without the need or the cost implied by using of still less robust IR-fibers.

The goal of current activity was to design a compact diode-pumped Er-laser with the highest possible efficiency, peak output power and brightness. To overcome low-gain disadvantages of Er-media we used a custom designed and internally manufactured high peak power diode laser bar stack for pumping of active crystal. The compact design stipulated the implementation of a coaxial configuration for the diode stack radiation and active rod. In this paper we describe an optimized Er:YLF laser generating in 2.66 - 2.85um spectral range while selective pumping in the upper Er-laser level by 0.97um diode laser array. The custom designed and internally manufactured diode laser array stack consisted of four 10 mm-wide diode laser bars having a pitch of approximately 1mm. The combined optical power for the diode array was close to 1 kW. Each bar was individually collimated on the fast axis. The diode radiation was collected by specially designed prism system for efficient absorption of pump radiation in active rod in a combined end-pumping and side-pumping configuration. Over 70% optical coupling efficiency was achieved.

We observed sequential switching of lasing wavelength in 2.66, 2.71, 2.81, 2.83 and 2.85 um during pumping pulse depending on pumping power, repetition rate and output coupler spectral characteristics. We developed a simple theory which explains such dynamical spectral switching.

For an optimized laser cavity we achieved greater than 17% laser optical efficiency % for the generation at 2.81 um. Maximal output energy was 11 mJ at 250 us and more than 40 mJ at 1 ms pumping pulse duration at up to 50Hz repetition rate (average output power in infrared up to 2 W). Output beam spatial distribution was smooth gaussian-like and beam divergence was about 3 mrad.

8235-05, Session 1

Fabrication and optical properties of single-crystal YAG fiber optics

B. T. Laustsen, J. A. Harrington, Rutgers, The State Univ. of New Jersey (United States)

No abstract available

8235-06, Session 1

Mid-IR Laser oscillation via energy transfer in the Co:Fe:ZnS/Se co-doped crystals

J. M. Peppers, The Univ. of Alabama at Birmingham (United States); N. Myoung, The Univ. of Alabama at Birmingham (United States) and Samsung SMD (Korea, Republic of); V. V. Fedorov, S. B. Mirov, The Univ. of Alabama at Birmingham (United States)

Room temperature iron doped II-VI lasers have demonstrated broad band tunability between 3.5 and 6 um with efficiency ~40%. However, these lasers require pump sources with a wavelength ~3 um which could be selected only from a few available. Cobalt ions in the II-VI materials have strong broad absorption bands at 4A2-4T1(4P) and 4A2-4T1(4F) transitions located at ~0.75 and 1.5 um, respectively. Therefore, a number of different laser sources (including diode lasers) could be potentially used for cobalt excitation followed by energy transfer to iron ions. Here we report co-doped materials fabrication and study of energy transfer in the Co:Fe:ZnS(ZnSe) crystals at 14-300K temperature range. Iron-cobalt co-doped samples were prepared using a two-stage post-growth thermal diffusion procedure with Fe concentration range between 8.5 and 19x10^18 cm^-3. Kinetics and photoluminescence spectra reveal energy transfer from cobalt to iron under cobalt excitation at 4A2-4T1(4F) transition by 1.56 um radiation. Analysis of the experimental data show that effective energy transfer occurs from 4T1(4F) and 4T2 Co2+ energy levels to 5T2 excited level of Fe2+ ions and results in the first realization of Fe2+ ions lasing at 3.6 um via Co-Fe energy transfer. Demonstrated effective Co2+→Fe2+ energy transfer process could result in utilization of a more convenient laser pump sources for the iron doped II-VI lasers. Different mechanisms of iron excitation will be also discussed.

8235-07, Session 1

3-µm wavelength-tunable compact light source with 805/1064-nm differential frequency generation using intracavity photon-reuse and spectrum shaping techniques

N. Yamamoto, K. Akahane, T. Kawanishi, National Institute of Information and Communications Technology (Japan); H. Sotobayashi, Aoyama Gakuin Univ. (Japan)

Mid-infrared (MIR) light sources operating in the 3-µm waveband are useful photonic devices for the spectroscopic detections of trace gases and biomaterials. In order to achieve efficient MIR light emissions with small footprints, we propose an attractive technique to develop a compact intracavity system that enables the reuse of the photons emitted by the pump source. Periodically poled congruent $LiNbO_3$ (PPCLN) and Nd-YVO_4 crystals were both set in the intracavity. An 805-nm waveband GaAs-based laser diode was used as the signal and pump light sources for differential frequency generation (DFG) since GaAs-based device technology enables the construction of high-power high-efficiency lasers operating in this waveband. We have successfully demonstrated that a 3-µm wavelength-tunable light source using the photon reuse technique is the most effective and compact intracavity system, and it possesses useful broadband wavelength tunability characteristics up to approximately 90 nm and a small footprint (15 × 30 cm). We obtained high output power of around few mW from the developed light source. In addition, since the optical spectrum shape of the MIR light is also important, we have proposed a useful spectrum shaping technique using a Fabry-Perot (FP) etalon filter included in the intracavity system; we obtained a fine single peak spectrum in the 3-µm waveband. The developed wavelength-tunable compact intracavity MIR light source using the photon reuse and spectrum shaping techniques will become attractive light sources for optical communications and bio-medical applications.

8235-08, Session 1

Efficient, high-energy 2-micron solid state laser transmitter for NASA's space-based CO2 measurements

U. N. Singh, J. Yu, M. Petros, NASA Langley Research Ctr. (United States); Y. Bai, Science Systems and Applications, Inc. (United States)

This technology development was initiated during NASA Earth Science Technology Office (ESTO) funded Laser Risk Reduction Program (LRRP) with the objective to develop a Thulium (Tm) fiber laser pumped Holmium (Ho) solid-state laser that generates laser pulses in the 2µm wavelength for pulsed CO_2 DIAL/IPDA instrument. The key performance characteristics of this laser, such as energy, pulse repetition rate, pulse width, efficiency, frequency accuracy and stability, will meet or exceed the needs of the NASA Active Sensing of CO_2 Emissions over Night, Days, and Seasons (ASCENDS) transmitter as currently envisioned. This space qualifiable laser architecture utilizes fiber laser and solid-state crystal laser technologies. One of the outstanding properties of the fiber laser is its efficiency. However, it inherently has low damage threshold at high energy pulses. On the other hand, the solid state laser has the capability to produce Joule-level energy at 2µm wavelength. The proposed laser combines the advantages of both lasers to provide the desired energy with high efficiency.

8235-123, Session 1

3-µm optical fiber laser based on guided mode resonance filter

Y. Li, R. H. Woodward, M. K. Poutous, The Univ. of North Carolina at Charlotte (United States); R. Shori, Naval Air Warfare Ctr. Weapons Div. (United States); E. G. Johnson, Clemson Univ. (United States)

No abstract available

8235-72, Session 2

Effect of Si-induced defects on 1 µm-absorption losses in laser-grade YAG ceramics

R. Gaume, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States) and Stanford Univ. (United States); Y. He, A. S. Markosyan, R. L. Byer, Stanford Univ. (United States)

High-sensitivity optical absorption at 1 µm was measured in forty undoped and Nd-doped YAG ($Y_3Al_5O_{12}$) transparent ceramics and single crystals using photothermal common-path interferometry (PCI). Concurrently, chemical trace analysis was performed on those samples by glow discharge mass-spectroscopy (GDMS). Silicon and calcium were found to be the major impurities with concentrations up to 250 wt ppm. A univocal linear correlation between the Si content and the absorption loss at 1 µm is revealed and a possible mechanism for the formation of Si-induced color centers based on a bound polaron model is discussed. Solutions to reduce this optical absorption in ceramics are also proposed.

8235-73, Session 2

All ceramic Nd:YAG waveguide laser element with perfect bonding condition

A. Ikesue, Y. L. Aung, World Lab Co., Ltd. (Japan); T. Kamimura, Osaka Institute of Technology (Japan)

This paper reports on fabrication of all ceramic, high quality Nd:YAG waveguide cladded with undoped YAG. To date, over 250 W output power with slope efficiency of ~50 % has been achieved.

8235-74, Session 2

Processing control for high quality RE:YAG laser

J. Zhang, H. Yang, D. Luo, H. Lin, C. Xu, D. Y. Tang, J. Ma, Nanyang Technological Univ. (Singapore)

Various oxide laser ceramics have been developed during the past ~40 years. However it is still a challenge work to fabricate the transparent ceramic YAG with optical quality close to its single crystal. In this talk, we will present our recent progress on processing control for fabricating high optical quality transparent YAG ceramics. Their applications as the gain media for 2.0 micron mid-infrared solid state laser applications will also be demonstrated.

8235-75, Session 2

Overview of ceramic laser technology

J. Sanghera, W. Kim, G. R. Villalobos, L. B. Shaw, C. Baker, U.S. Naval Research Lab. (United States); M. Hunt, Univ. Research Foundation (United States); B. Sadowski, R. E. Miklos, Sotera Defense Solutions (United States); J. Frantz, U.S. Naval Research Lab. (United States); I. Aggarwal, Sotera Defense Solutions (United States)

The field of transparent ceramic laser materials has seen significant improvements since the first demonstration of lasing in Dy3+:CaF2 ceramic in 1964. Considerable effort has gone into powder synthesis and purification, along with better sintering processes. Consequently lasing has been demonstrated in halide, oxide and chalcogenide ceramics. The efficiency and laser output power has been steadily increasing, especially within the last decade, to the point where 100 KW output power has now been demonstrated using Nd:YAG. In addition, the ceramic technology enables fabrication of novel architectures, including undoped claddings and graded doping profiles, as well as high doping levels which are not very practical using traditional single crystal technology.

I will present an overview of the history and current status of ceramic laser technology, including recent developments from the author's lab.

8235-01, Session 3

Er3+-doped laser ceramics for resonantly-pumped eye-safe lasers

M. Dubinskii, N. E. Ter-Gabrielyan, V. Fromzel, T. V. Sanamyan, U.S. Army Research Lab. (United States)

A brief overview of spectroscopy and laser performance of Er3+-doped laser ceramics as it pertains to power scalable eye-safe lasers is presented. The benefits of ultra-low quantum defect operation for power scaling are discussed. Experimental data are presented for Er-doped sesquioxides as well as for gradient-doped YAG. Laser performance efficiencies close to quantum-defect-limited were obtained even for underdeveloped ceramics. Er-doped Y2O3 laser operation results are presented with significant emphasis on Mid-IR applications.

8235-02, Session 3

Refractive indices and thermo-optic coefficients of Erbium doped Yttria

D. E. Zelmon, N. Haynes, Air Force Research Lab. (United States); R. Shori, Naval Air Warfare Ctr. Weapons Div. (United States)

Erbium doped glasses and crystals are commonly used in the manufacture of lasers and laser amplifiers. Recently, new materials, such as sesquioxides, are being increasingly employed as laser hosts due to their superior thermal conductivity and fabricability when compared to conventional materials such as silica and YAG. However, little data is available concerning important optical properties required for amplifier design such as the refractive index and the thermo-optic coefficient. We have measured the refractive indices and their temperature dependence for a variety of concentrations of erbium in Y2O3. These results are discussed in terms of their implications for thermal lensing.

8235-03, Session 3

Spectroscopic properties of Er-sesquoxides

S. Sharma, R. Shori, Univ. of California, Los Angeles (United States) and Naval Air Warfare Ctr. (United States); J. K. Miller, Naval Air Warfare Ctr. Weapons Div. (United States)

No abstract available

8235-76, Session 3

Processing and fabrication of lanthanide sesquioxide transparent ceramics

J. Ballato, B. Kokouz, J. W. Kolis, C. D. McMillen, Clemson Univ. (United States)

This talk will focus on the fabrication of transparent ceramics of various lanthanide oxides (Sc2O3, Y2O3, Lu2O3) and several doped analogs. The purification of the feedstock and the importance of processing temperature profiles in maintaining small grain size will be emphasized. Thermal conductivity aspects of doped ceramics will also be discussed.

8235-09, Session 4

1-kHz rep rate, mode-controlled, and passively Q-switched Nd:YLF laser operating at 1053 nm

A. M. Deana, Univ. Nove de Julho (Brazil); N. U. Wetter, Instituto de Pesquisas Energéticas e Nucleares (Brazil)

Lasers that supply short, high power Q-switched pulses with high repetition rate and TEM00 mode are still a major goal in the laser cavity design field. The most common designs are the longitudinal-pumped laser that shows restrictions with respect to the power scaling of the TEM00 mode due to the thermal stress fracture limit and very short thermal lens, and the side-pumped laser, which usually has a poor beam quality and lower efficiency. Achieving at the same time power scalability and high beam quality has been the subject of intense research and finds in the technically very complex thin-disk laser its most well-known effort. Here we present a new power scalable designs that permit good beam quality and high efficiency using a side-pumping technique. Different from other designs, this technique does not achieve Gaussian mode by gain guiding but through a different type of mode- controlling using a special three mirror cavity. In a side-pumped, passively Q-switched Nd:YLF laser we achieve Gaussian pulses of 9 ns duration and hundreds of kilowatt with less than 1% pulse-to-pulse amplitude fluctuation over a 30 min period. In this set-up, a 34 W TM-polarized pump diode operating at 797nm and was focused into the crystal slab of dimensions 13mmx13mmx3mm with a spot size of 5mm x 0.1mm. A Cr:YAG saturable absorber with initial transmission of 50% was used for passive Q-switching.

8235-11, Session 4

High-gain and high-power Nd:YVO4 single-pass amplifier

X. Délen, F. Balembois, P. Georges, Lab. Charles Fabry (France)

Picosecond laser emitting pulses in the tens of microjoule regime and working at hundreds of kHz repetition rates are in high demand in fields such as material processing and harmonic generation. In this work, we present a Nd:YVO4 MOPA system based on a long cavity mode locked oscillator (9.2 MHz repetition rate) followed by a high gain amplifier. The 16 m cavity is built using a 1 m long Herriot Cell with 12 passes and a SESAM to ensure passive mode locking. The output energy per pulse is 550 nJ and the pulse duration is 22 ps for an absorbed pump power of 18 W. Pulse picking is achieved with an acousto-optic modulator allowing to choose from single shot to 1 MHz repetition rate. The amplifier is working in a single pass configuration for both the pump and the signal in a longitudinal pumping scheme. In order to achieve high gain, we use a high brigthness laser diode (60 W fiber coupled 100µm NA 0.22). Moreover, we paid a particular attention on the crystal cooling since the temperature increase has a dramatic influence on the emission cross section in Nd:YVO4. For an input average power of 35 mW at a repetition rate of 200 kHz and an absorbed pump power of 40 W, a gain of about 285 is obtained. It corresponds to an energy of 50 µJ per pulse and an average power of 10 W. The beam quality factor M^2 of the output beam is lower than 1.4.

8235-12, Session 4

1.34 µm Nd:YVO4 laser mode-locked by a single-walled carbon nanotube saturable absorber

H. L. Iliev, I. Buchvarov, Sofia Univ. St. Kliment Ohridski (Bulgaria); S. Y. Choi, K. Kim, F. Rotermund, Ajou Univ. (Korea, Republic of); V. P. Petrov, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany)

Passive mode-locking of 1.3 µm lasers is problematic for semiconductor saturable absorber mirrors (SESAMs) not only because of difficulties in their fabrication process but also in relation to the achievable parameters and damage resistivity. In contrast, single-walled carbon nanotube saturable absorbers (SWCNT-SAs) exhibit broadband absorption which is controllable by varying the nanotube diameter and chirality, and require relatively simple manufacturing processes. Here we report on steady-state mode-locked operation of a diode pumped Nd:YVO4 laser operating on the 4F3/2→4I13/2 transition at 1.342 µm using a transmitting SWCNT-SA.

The SWCNT-SA used in the present work was fabricated by SWCNTs grown by high-pressure CO conversion technique, showing broad absorption around 1.3 µm. The linear transmission at the laser wavelength was about 99%. The Nd:YVO4 laser was longitudinally pumped by the unpolarized radiation of a 808 nm fiber-coupled laser diode. The ~1.2-m long cavity was optimized for large fundamental mode size.

Above threshold the laser operated first in the CW mode, then had a range of Q-switched mode-locked operation before reaching the regime of stable steady-state mode-locking. With an output coupler of 90% reflectivity the average output power in the steady state mode-locked regime reached 0.8 W at a slope efficiency of 14.5% with respect to the incident pump power. At a repetition rate of 127 MHz this corresponds to single pulse energy of 6.3 nJ. Such pulse energies are comparable to the best results obtained using SESAMs but the pulse duration of 16.5 ps measured in the present experiment is substantially shorter.

8235-13, Session 4

Performance of 100-J cryogenically cooled multi-slab amplifier with respect to pump beam parameters and geometry

M. Divok?, M. Sawicka, J. Novak, B. Rus, T. Mocek, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

We present advanced 3D ray-tracing code for calculation of amplified spontaneous emission (ASE), stored energy, amplification and heat generation in laser active material. New results are obtained for spectrally resolved absorption and amplification and super-Gaussian pump beam profile.

We performed a parametric study on how wavelength drift and bandwidth of pump diodes influence the performance of Yb:YAG multi-slab amplifier consisting of 8 slabs with dimensions of 60 x 60 x 8 mm3 at 170 K. According to calculation, the best results were obtained for pump wavelength of 938 nm and were insensitive (< 2 %) to common values of the wavelength drift (± 3 nm) and bandwidth (3-7 nm). The highest stored energy reached 190 J for the pump energy of 360 J.

Additionally, for 8th order of the super-Gaussian beam the stored energy decreased by roughly 16 % in comparison to homogenous beam.

Then we simulated beams propagating through the amplifier either on-axis or under a small angle. For the on-axis propagation we could amplify the 10 J input pulse up to 170 J according to Frantz-Nodvik formula with no losses.

Finally, the 8 slabs in one amplifier were compared to the case of 16 slabs (45 x 45 x 8 mm3) in two amplifiers. The smaller aperture decreased ASE and the stored energy increased to 200 J for 360 J of pump energy. Consequently, the input 500 mJ pulse was amplified to 182 J with better energy efficiency.

8235-14, Session 4

Comparative design study of 100-J cryogenically cooled Yb:YAG multi-slab amplifiers operating at 10 Hz

P. Sikocinski, M. Divok?, M. Sawicka, B. Rus, T. Mocek, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

We present a comparison of alternative optical layouts for 100 J cryogenically cooled Yb:YAG multi-slab laser system operating at 10 Hz for HiLASE and ELI Beamlines projects. The first layout consists of preamplifier and main amplifier, while the second layout uses only single two-stage amplifier. These concepts are compared with respect to output energy, B-integral and energy efficiency.

Both layouts amplify 200 mJ super-Gaussian (4th order) input beam with a pulse of square shape and duration of 2 ns. Distributed losses in the amplifiers are assumed 1% per slab, the two reversers in the amplifier have losses 7% and 14%, and the transport loss between amplifiers or stages is 10%.

In the first scheme, the pulse is amplified to 10 J in 6-pass configuration in the preamplifier consisting of 4 slabs (20 x 20 x 5 mm3). Then in the main amplifier consisting of 8 slabs (60 x 60 x 8 mm3) the pulse is further amplified to 105 J in 4-pass configuration. The total pump energy is 40 J and 360 J, respectively. The maximum B-integral reaches 0.5 (accumulated 2.5) and optical to optical efficiency is 26%.

In the second scheme, the pulse is amplified to 125 J in 4-pass configuration in the amplifier consisting of 2 x 8 slabs (45 x 45 x 8 mm3) in two amplifier heads. The total pump energy is 360 J. The maximum B-integral reaches 1.5 (accumulated 3.5) and optical to optical efficiency is 35%.

While the two-stage amplifier offers higher energy efficiency, the two amplifier design operates under safer conditions with less modulated beam.

8235-15, Session 5

3.5-ps pulses from a compressed passively Q-switched microchip laser employing nonlinear temporal cleaning

A. Steinmetz, A. Martin, D. Nodop, R. Lehneis, J. Limpert, Friedrich-Schiller-Univ. Jena (Germany); A. Tünnermann, Friedrich-Schiller-Univ. Jena (Germany) and Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

We report on cleaning and shortening methods of the temporal intensity profile of compressed, passively Q-switched pulses from a fiber-amplified microchip laser in the sub-10ps domain. The nonlinear pulse compression, which is usually acquired by means of self-phase modulation (SPM) induced spectral-broadening and subsequent pulse compression, inherently results in a compressed pulse shapes containing a pedestal and/or side pulses, which might contain a considerable amount of the pulse energy and can be disadvantageous for some applications, e.g. material processing. The content of the background and side lobes can be reduced using methods based on nonlinear optical processes such as frequency conversion employing e.g. a nonlinear crystal and the nonlinear absorption in a saturable absorber mirror.

The experimental setup consists of a passively Q-switched microchip laser based on Nd:YVO4 and semiconductor saturable absorber mirror (SESAM) producing 130ps pulses and pulse energies of ~100nJ. The pulses are amplified in a two-stage ytterbium-doped fiber amplification system. The main amplifier employs a 2.2m long 40µm core photonic crystal fiber. The resulting pulse energy is as high as 28µJ and the spectrum is SPM-broadened to 0.7nm. The pulses are compressed using a chirped volume-Bragg-grating (CVBG) leading to a FWHM-duration of 5ps. Frequency-doubling in a LBO crystal to 532 nm shortens the pulses to a duration of 3.5ps and leads to a significant reduction of pulse pedestal. In the presentation we will discuss the trade-off between SHG conversion efficiency, cleaning and pulse shortening results, as well as alternative approaches such as saturable absorbers.

8235-16, Session 5

High-power VCSEL array pumped Q-switched Nd:YAG lasers

R. Van Leeuwen, Y. Xiong, L. S. Watkins, J. Seurin, G. Xu, A. Miglo, Q. Wang, C. L. Ghosh, Princeton Optronics, Inc. (United States)

Solid-state lasers pumped by high-power two-dimensional arrays of vertical-cavity surface-emitting lasers (VCSELs) were investigated. Both end-pumping and side-pumping schemes of Nd:YAG lasers with high power kW-class 808 nm VCSEL pump modules were implemented. For one application 10 mJ blue laser pulses were o

btained from a frequency-doubled actively Q-switched VCSEL-array dual side-pumped Nd:YAG laser operating at 946 nm. For another application 10 mJ green laser pulses were obtained from a frequency-doubled passively Q-switched VCSEL-array end-pumped Nd:YAG laser operating at 1064 nm. High-energy UV pulses were obtained by frequency doubling the green output. These lasers were operated at a low repetition rate (mJ) at a lower repetition rate (kHz). We will report on our findings and discuss the merits of VCSEL pumping of solid-state lasers.

8235-17, Session 5

24-picosecond pulses from a spectrally filtered passively Q-switched microchip laser

R. Lehneis, A. Steinmetz, 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 simple and robust technique for pulse duration reduction of passively Q-switched microchip lasers approaching the 10ps-domain. The technique bases on self-phase modulation (SPM) induced spectral broadening in a waveguide structure and subsequent spectral filtering to shorten the pulse duration. This approach is possible as long as the propagation in waveguide is dominated by SPM and the filter bandwidth is smaller than the broadened spectrum and larger than the transform-limited bandwidth of the initial pulse. This inexpensive and simple way appears very suitable to passively Q-switched microchip lasers possessing pulse durations between 50 and 200ps in order to reduce their pulse duration by more than one order of magnitude.

The setup of a proof-of-principle experiment consists of a fiber-amplified passively Q-switched microchip laser followed by a passive single-mode fiber (2.5m long, 7µm core diameter) in which SPM acts to broaden the spectrum and a reflective volume-Bragg-grating (VBG) as band-pass filter. This Nd:YVO4 microchip laser provides pulse durations of 140ps at 310kHz repetition rate with a spectral bandwidth smaller than 20pm at 1064.3nm. The spectral bandwidth of the pulses is increased to 1.2nm by SPM. The subsequent band-pass filter has a spectral reflection window of 240pm. With this setup the reduction of the pulse duration from 140ps down to 24ps is realized. Further investigations on the experimental parameters, e.g. spectral bandwidth of the pulse or adaptation of the filter selectivity can lead to pulses shorter than 15ps as already predicted by numerical simulations.

8235-18, Session 5

Compact VCSEL pumped Q-switched Nd:YAG lasers

B. J. Cole, C. McIntosh, A. D. Hays, J. E. Nettleton, L. Goldberg, U.S. Army RDECOM CERDEC NVESD (United States)

Recent advances in the brightness of 808nm Vertical Cavity Surface Emitting Laser (VCSEL) arrays have enabled their use for pumping of Q-switched Nd:YAG lasers. At NVESD, we have explored using these VCSEL arrays for end-pumping of Nd:YAG rods for both active and passively Q-switched lasers. Compared with diode stack pumping, VCSELs offer the advantages of a more homogenous pump intensity profile and about a 5X reduction in wavelength shift with temperature. The reduced wavelength shift of the pump source allows a reduction in resonator length while maintaining the same performance over temperature. The uniform spatial profile of the VCSEL pump results in a more uniform laser near-field intensity profile and improved output beam divergence characteristics.

This paper will describe our results for end pumping Nd:YAG lasers using VCSEL arrays that generated peak powers approaching 1 kW in 0.3 ms pulses. A compact , 7cm x5 cm footprint, actively Q-switched laser based on a folded cavity design was assembled to test the performance of VCSEL pumping. The laser was fabricated using a “Monoblock” construction, with all of the optical components directly bonded to a common optical bench, that matched the thermal expansion coefficient of Nd:YAG. Output energies exceeding 40 mJ were demonstrated over a wide range of temperatures and PRFs. The uniform spatial profile of the pump eliminated hot spots that were observed when the same device was end pumped using a diode stack and a light-duct pump concentrator. Low beam divergence and beam-pointing stability were achieved using unstable resonators with a optimized graded reflectivity mirror (GRM) output couplers. Similar construction techniques were used to fabricate compact passively Q-switched lasers generating pulse energies exceeding 20 mJ. For this device it was found that the output energy of the passively Q-switched laser was adjustable by changing the drive current to the VCSEL array.

8235-19, Session 5

Laser amplifiers for high-energy pulse train applications

G. J. Doster, Northrop Grumman Cutting Edge Optronics (United States)

This paper discusses the use of standard commercially available laser amplifier modules for amplification of pulse trains. Typical pulse trains are described as a series of laser pulses, generally tens of picoseconds in length, repeating at a rate of 100MHz or more. This train of pulses lasts one to five milliseconds and the entire series of pulses may repeat at a few Hz.

Laser amplifier strategies in this operational regime are discussed. Using PowerPULSE laser amplifiers and standard architectures, standard mode-locked laser outputs of 1mJ can be amplified to outputs greater than one Joule per pulse. The wide range of available PowerPULSE laser amplifiers allows the creation of a complete amplifier solution. Laser gain medium with diameters from 2mm to 15mm and stored energies of over 4J are available. Techniques for reduction in thermal loading, equalization of pulse energy throughout the series of pulses, and gain uniformity are presented. Operation of the laser amplifiers in Quasi-CW mode reduces unwanted thermal loading effects and allows preservation of the source beam quality. In multi-module and multi-pass systems, management of pulse to pulse energy stability by careful control of pump pulse timing is discussed. Data on gain homogeneity of the laser amplifiers is presented. Several examples of amplifiers systems and operational parameters are included

8235-20, Session 6

Yb:CaGdAlO4 thin disk

S. Ricaud, Lab. Charles Fabry de l’Institut d’Optique (France); A. Jaffres, P. Loiseau, B. Viana, Ecole Nationale Supérieure de Chimie de Paris (France); B. Weichelt, M. Abdou-Ahmed, A. Voss, T. Graf, Univ. Stuttgart (Germany); D. Ritz, FEE GmbH (Germany); M. Delaigue, E. P. Mottay, Amplitude Systemes (France); P. Georges, F. Druon, Lab. Charles Fabry de l’Institut d’Optique (France)

The thin-disk laser design allows the generation and the amplification of ultrashort pulses with very high efficiency, high output power and good beam quality. This configuration is well-mastered with Yb:YAG crystal, SESAM mode-locked oscillator generates energy pulses of 30.7 µJ at 3.516 MHz in an active multipass configuration. To generate even shorter pulses, there is a search for new materials with larger bandwidth, among them, Yb:CALGO seems to be a good candidate.

In fact, this crystal combines interesting spectroscopic and thermal properties. First, its atypical broad and flat emission bandwidth permits to demonstrate the generation of 47-fs pulses in a bulk configuration. Nevertheless, considering the good thermal properties of Yb:CALGO, the full potential of this crystal has not been exploited yet.

In this work, we present the first demonstration of laser operation with a thin-disk Yb:CALGO laser. The laser experiment was performed with 350µm-thick Yb^{3+}:CaGdAlO4 crystal. A 90 W fiber-coupled diode emitting at 980 nm has been used for the pump module. We obtained with a 2%-doped crystal, in a slightly multimode configuration, an output power up to 30W, corresponding to a slope efficiency of 41% and an optical-to-optical efficiency of 32%. Furthermore we observed a large tunability band from 1018 to 1050 nm, which shows the potential for the generation of ultrashort pulses. Finally, in a Q-switch regime, we obtain more than 1 mJ at 100 Hz repetition rate, and 4.5W at 10 kHz repetition rate.

8235-21, Session 6

Numerical modeling of a joule level thin-disk laser system

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A 3D numerical model for high energy thin-disk diode pumped quasi-three-level Yb based lasers operating at room temperature is presented. To improve the accuracy of the simulations, an influence of amplified spontaneous emission (ASE) and temperature dependence of crystal parameters such as thermal conductivity or refractive index are considered. The output of the model will be used for designing and optimizing a thin-disk diode pumped Joule level amplifier chain with multi-kHz repetition rate that is planned for the project HiLASE. First results are obtained for a regenerative amplifier with 100 mJ pulse energy output.

In the first step of the iterative approach, spectrally-resolved absorption of a Gaussian pump beam in multipass configuration is simulated by Monte-Carlo ray-tracing. Then the three-dimensional temperature distribution inside the crystal is calculated by a use of heat conduction equation, taking into account the temperature dependent quantities. Finally, the amplified spontaneous emission is calculated by ray-tracing. Simulation results have been verified by comparing with experimental data or numerical outputs of other models.

Details of our numerical approach, the latest results and their analysis will be presented. Optimal working parameters, such as temperature, Yb-ions concentration, dimensions of the pump beam and of the crystal, the output energy, and optical efficiency will be evaluated.

8235-23, Session 6

Initial testing of edge-pumped Yb:YAG disk laser with multi-passed extraction

J. Vetrovec, D. A. Copeland, A. S. Litt, Aqwest, LLC (United States); D. Du, General Atomics Aeronautical Systems, Inc. (United States)

We report on initial testing of a Yb:YAG disk laser in the kW range. The laser uses two laser disks having a composite ceramic construction with undoped perimetral edge designed to channel pump light while efficiently outcoupling amplified spontaneous emission (ASE). The disks are edge-pumped [1], thus allowing for reduced doping of crystals with laser ions, which translates to lower lasing threshold in Yb:YAG material. In addition, edge-pumping uniquely enables tailoring of gain profile by varying the arrangement of pump diodes. Thermal management of the disk is provided by a novel microchannel heat sink offering 1) ultra-low thermal resistance, 2) uniform extraction of waste heat from the disk, and 3) unparalleled dimensional stability (critical for low optical distortions).

This work presents results of testing the laser with two Yb:YAG laser disks and relay optics configured for power extraction with multiple passes through the disks [2]. Data on optical distortion and the thermal performance of the disk and the heat sink are also included. This work was in part supported by the US Army ARDEC Contract Number W15QKN09C0156.

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

2. J. Vetrovec et al., “Ytterbium-based disk amplifier for an ultra-short pulse laser,” SPIE vol. 7578 (2010)

8235-24, Session 6

Gain tailoring model and improved optical extraction in CW edge-pumped disk amplifiers

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The effect of gain tailoring upon the optical extraction and OPD in a CW edge-pumped disk amplifier is examined using a two-dimensional model of diode pumping coupled with a two-dimensional, geometric model of optical extraction by a Gaussian profile beam from a Yb:YAG medium [1]. The gain medium is described by the well-known quasi-three level model of Beach [2]. Gain tailoring is accomplished by focusing the diode pump beam using cylindrical lenses. The diode pump beam, gain medium, and optical extraction models are described after which the pump absorption efficiency, energy deposition uniformity, output energy, and maximum peak-to-valley (PV) OPD are examined as a function of the pump lens focal length and output aperture radius as well as amplifier input seed energy, number of roundtrip amplifier passes, and diode pump power. It is shown that using pump beam focusing to tailor the gain radially deposits more energy in the central region of the disk and thus results in improved optical extraction because a Gaussian input optical beam preferentially accesses the central region of the disk. With gain tailoring one can achieve the same amplifier output energies as without gain tailoring but using less pump power and/or amplifier seed energy, resulting in reduced disk heating and diode-pump waste heat. Although the maximum PV OPD is larger, the central region of the thermally-induced OPD remains relatively uniform, allowing one to increase the output energy with only modest increases in the effective OPD. This work was supported in part by US Army contracts W15QKN-09-C-0007 and W15QKN-09-C-0156.

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8235-77, Session 6

Yb:YAG thin-disk laser performance at room and cryogenic temperatures

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At cryogenic temperatures, Yb:YAG behaves as a near- ideal 4-level laser, its absorption and emission cross-sections increase, and its thermal conductivity improves. Yb:YAG thin disk laser performance at room and cryogenic (80K) temperatures will be presented. The Yb:YAG gain media is cooled using either a pressurized R134A refrigerant system or by a two-phase liquid nitrogen spray boiler. Interchangeable mounting caps allow the same Yb:YAG media to be switched between the two systems. This allows direct comparison of lasing, amplified spontaneous emission, and temperature performance between 20C and -200C.

8235-25, Session 7

High-power disk and fiber lasers: a performance comparison

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The Performance of High Power Disk Lasers and Fiber Lasers along with their rapid development to the high power cw regime have been of great interest throughout the last decade.

Both technologies are still in the focus of several conferences, workshops, and papers and represent the “state-of-the-art” of industrial high power solid state lasers for material processing. As both laser concepts are considered to be the leading 1µm light-source, this presentation gives a fair comparison of the two different technologies from a manufacturer who pursued both.

From the geometry of the active material through the resonator design, cooling regime, and pumping method to the point of beam quality and power scaling, the different approaches associated with the advantages, challenge, and limits of each technology will be highlighted.

Based on ROFIN’s substantial industrial experience with both laser concepts, an outlook into future trends and chances, especially linked to fiber lasers, will be given.

8235-26, Session 7

High-power disk lasers: advances and applications

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Though the genesis of the disk laser concept dates to the early 90's, the disk laser continues to demonstrate the flexibility and the certain future of a breakthrough technology. On-going increases in power per disk, and improvements in beam quality and efficiency continue to validate the genius of the disk laser concept. As of today, the disk principle has not reached any fundamental limits regarding output power per disk or beam quality, and offers numerous advantages over other high power resonator concepts, especially over monolithic architectures.

Fast approaching 2,000 high power disk lasers installations, with demand upwards of 1,000 lasers per year, the disk laser has proven to be a robust and reliable industrial tool. With advancements in running cost, investment cost and footprint, manufacturers continue to implement disk laser technology with more vigor than ever.

This paper will explain recent advances in disk laser technology, including the introduction of the new 6 kW power at the work piece from 1 cavity product, and process relevant features of the laser, 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.

8235-27, Session 7

Ultrafast disk lasers and amplifiers

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Disk lasers with multi-kW CW output power are widely used in manufacturing, primarily for cutting and welding applications, notably in the automotive industry. The disk technology combines high power (average and/or peak power), excellent beam quality, high efficiency and high reliability with low investment and operating costs.

Additionally, fundamental mode picosecond disk lasers are well established in micro machining at high throughput and precision. Since the worlds first market introduction of industrial grade 50 W ps lasers (TruMicro 5000) at the Photonics West 2008, their second generation now provides twice the average power (100W IR, 60W green) at significantly reduced footprint.

Mode-locked thin-disk oscillators achieve by far the highest average power of all un-amplified ultrafast lasers, significantly exceeding the 100W level in laboratory set-ups. With robust long resonators their pulse energy approaches that of typical ultrafast amplifiers.

In recent times much interest in thin disk technology has come from the ultra-high peak power, petawatt laser community.

This presentation reviews the state of the art of ultrafast disk lasers and amplifiers.

8235-44, Session 7

Multi-kW single fiber laser based on an extra large mode area fiber design

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The quality of Yb-doped fused bulk silica produced by the sintering of Yb-doped fused silica granulates made tremendous progresses within the past five years. In particular the refractive index and doping level homogeneity of such materials are excellent. By the material improvement we achieved excellent background fiber attenuation values of the active core material below 20 dB/km at 1200 nm. The improvement of the Yb-doped fused bulk silica enables multi-kW fiber laser systems based on a single very large multimode laser fiber.

We have produced different extra large mode area (XLMA) fiber concepts by jacketing and filament stacking. The advantage of the stacking technique is that even very complex fiber structures can be set easily. The utilization of a single active fiber in combination with the XLMA multimode fiber concept with fiber diameters of 1000 µm and above enables simple and robust high power fiber laser setups without complex fiber couplings.

We will present the current improvements of the core material development. Yb-doped fibers with different core compositions, based on the Yb-doped bulk silica, have been characterized in detail. In particular the laser efficiency and photodarkening performance of such fibers were studied. We will report on the excellent laser performance of a multi-kW fiber laser based on a single XLMA-fiber.

8235-45, Session 7

1.2-kW single-mode fiber laser based on 100-W high-brightness pump diodes

D. A. Kliner, H. Yu, J. Luu, K. Liao, J. Segall, M. H. Muendel, J. Shen, M. K. Kutsuris, D. K. Holdener, J. Franke, K. Nguyen, D. L. Woods, D. Meng, D. L. Vecht, R. Duesterberg, L. Xu, J. A. Skidmore, J. Guo, J. Cheng, J. Du, B. Johnson, N. Guerin, B. Huang, P. Cheng, R. Raju, K. W. Lee, J. Cai, V. V. Rossin, E. P. Zucker, JDSU (United States)

We have demonstrated a monolithic (fully fused), 1.2-kW, Yb-doped fiber laser with near-single-mode beam quality. This laser employs a new generation of high-brightness, fiber-coupled pump sources based on spatially multiplexed single emitters, with each pump providing 100 W at 915 nm within 0.15 NA from a standard 105/125 fiber. The fiber laser is end pumped through the high-reflector fiber Bragg grating using a 19:1 fused-fiber combiner. The laser power can be modulated at a frequency of up to 10 kHz by modulating the drive current of the pump diodes. The output wavelength is 1080 nm with a linewidth of 0.5 nm FWHM; the lack of amplified spontaneous emission and stimulated Raman scattering indicates that further power scaling is possible with increased pump power. Multiple lasers can be combined with a fused-fiber output. The system architecture has several advantages for practical applications:

1. The use of single-emitter diodes provides high reliability, high efficiency, and graceful system degradation in case of diode failure.

2. The end-pumped design minimizes loss of pump brightness and eliminates the need for complex pump/signal combiners that can cause loss and beam-quality degradation for the signal beam.

3. The system is monolithic (no free-space beams) for high reliability and environmental stability.

4. The output power can be varied by varying the diode drive current or by varying the duty cycle (pulse duration or repetition rate) in modulated operation.

5. The laser modules are field replaceable with a simple splicing procedure to the output combiner.

8235-46, Session 7

65 W of average power and 6-MW peak power generation from a mode-locked fiber oscillator

M. Baumgartl, Friedrich-Schiller-Univ. Jena (Germany) and Helmholtz-Institute Jena (Germany); C. Lecaplain, A. Hideur, Univ. de Rouen (France); J. Limpert, A. Tünnermann, Friedrich-Schiller-Univ. Jena (Germany) and Helmholtz-Institute Jena (Germany) and Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

The development of powerful ultrashort pulse laser sources opens the door for a large variety of applications. Both high-average powers and high pulse peak-powers are required to initiate nonlinear processes and to allow for a reasonable detection procedure. Energy scaling of ultrafast Yb-doped fiber oscillators has experienced rapid progress and has reached the levels that traditional solid-state lasers offer. The revolution arises from the discovery of new pulse shaping mechanisms in combination with the emergence of large-mode-area (LMA) photonic crystal fiber (PCF) technology.

We report on the generation of femtosecond pulses from an all-normal-dispersion fiber laser featuring a LMA ytterbium-doped large-pitch PCF. The 1.2m long fiber has two rings of air holes with a pitch of 44µm and a relative hole size of 0.2. Nonlinear polarization evolution assisted by passive spectral filtering in combination with the large-pitch fiber design enables a significant peak power enhancement with the generation of multi-megawatt pulses. 65W of average power at a 76.5MHz repetition rate, corresponding to 850nJ pulses are generated in a compact oscillator setup. The output pulses are extra-cavity dechirped down to 111fs with 6MW of peak power. To the best of our knowledge, these are the highest average and peak powers ever reached by a mode-locked fiber laser.

8235-47, Session 7

800-W CW near diffraction limited beam delivery through a 100-m long multi-mode fiber

A. Austerschulte, M. M. Vogel, T. Rataj, J. Negel, A. Voss, M. Abdou Ahmed, T. Graf, Univ. Stuttgart (Germany)

We present the efficient propagation of 800 W of near diffraction limited cw laser power through a 100 m long fiber delivery system. This is an important advance with regard to high-power material processing applications where the fiber-optic beam delivery of high-brightness beams is typically limited to a few meters. The presented all-fiber system consists of an oscillator, two amplifier stages and a passive fiber comprising a tapered region.

Behind the passive fiber a M2 value of 1.35 was measured using a Spiricion M2-200 at a total power of 800 W. A minor spectral content was observed at the Stokes-shifted wavelength (1139.5 nm) at output powers above 780 W, indicating the onset of Stimulated Raman Scattering (SRS).

The passive fiber and the tapered region were drawn at the IFSW from the same step-index preform supplied by CeramOptec GmbH, having a cladding-to-core diameter ratio of 20 and a numerical aperture (NA) of 0.056. The approximately 500 mm tapered fiber region was utilized to match the 20 µm core diameter of the MOPA system with the 30 µm core diameter of the passive transport fiber.Since the SRS-gain scales to the inverse of the effective area of the propagating mode, we could show an efficient solution to scale power handling limits.

Additional experiments are in progress to further explore the power handling limits of this delivery fiber and various other fiber designs, e.g. due to the massive increase of SRS.

8235-28, Session 8

A multi-wavelength variable-pulsewidth diode-pumped laser system for laser temporal diagnostics testing

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Testing and calibrating temporal laser diagnostics (fast photodetectors, oscilloscopes, and streak cameras) are important for characterizing short-pulse laser systems. Temporal laser diagnostics with different spectral sensitivities and bandwidths require various test wavelengths and pulsewidths. An all-solid-state diode-pumped laser system that provides low energy 165-fs FWHM pulses at 1053/527 nm, and 10/100-ps FWHM pulses at 1053/527/263 nm with energies that significantly exceed those required for testing is described.

The laser system consists of a commercial femtosecond laser, a highly stable diode-pumped Nd:YLF regenerative amplifier (regen), and frequency-conversion crystals. About 5% of 225-mW fs-laser output is launched into a single-mode PM fiber and seeds the regen after pulse picking. Most of the output power after 2nd harmonic generation and harmonic separation is launched into multimode fibers and used for fast photodetector impulse response-measurements. The regen seed (165-fs, ~100-pJ pulses at a 5-Hz repetition rate) is also used for characterizing single-shot photodetector-oscilloscope systems. We have tested the combination of a 55-GHz InGaAs photodetector and a 45-GHz digital oscilloscope.

When seeded with 165-fs pulses the regen produces ~10-ps FWHM pulses caused by gain narrowing in the active element. After inserting a 0.5-mm etalon in the regen resonator, the output pulse broadens to 100-ps. These pulses and their 2nd and 4th harmonics are used for calibrating and testing ROSS streak cameras (Sydor Instruments, Rochester, NY) with various photocathodes. A train of 10-ps pulses with a 100-ps spacing is generated by an etalon to calibrate the streak camera sweep. Single pulses of 10 ps and 100 ps are required for dynamic-range measurements.

Detailed system design and measurement results will be presented.

8235-29, Session 8

Power scaling of an Yb:LuScO3 thin disk laser to 23 W and 235 fs

C. J. Saraceno, O. H. Heckl, C. R. E. Baer, M. C. Golling, T. Südmeyer, ETH Zurich (Switzerland); K. Beil, C. Kränkel, K. Petermann, G. Huber, Univ. Hamburg (Germany); U. Keller, ETH Zurich (Switzerland)

Modelocked thin disk lasers achieve higher output powers and pulse energies than any other oscillator technology. Using the well-established gain material Yb:YAG, >30 µJ in 1-ps pulses were demonstrated in a cavity with multiple passes on the disk. The highest average power obtained up-to-date is 141 W in 738 fs pulses using the sesquioxide material Yb:Lu2O3, where a single pass on the disk lead to an oscillator with a footprint comparable to that of a low power oscillator. However, it is still a challenge to obtain shorter pulses at these high-power levels. Such sources with high peak powers and high repetition rates would have a high impact for many areas such as high-field science or high-speed micromachining.

One important challenge is to find suitable gain materials for short pulse generation in the thin disk geometry. They need to combine the requirements in terms of laser properties (broad emission bandwidth, high cross-sections) with excellent mechanical properties required for manufacturing of high-quality thin disks. Another important challenge is to design high-damage theshold SESAMs with reduced two-photon absorption for operation at high intracavity peak powers.

Here we demonstrate the suitability of the broadband mixed sesquioxide material Yb:LuScO3 for power scaling. We obtained the shortest pulses from a modelocked thin disk laser with 195 fs at an average power of 9.5 W. Furthermore, we were able to power scale our thin disk laser to 23 W and 235 fs by designing an optimized SESAM with multiple quantum wells and a dielectric topcoating with reduced two-photon absorption and increased damage threshold.

8235-30, Session 8

Pulse-on demand regenerative amplifier

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Regenerative amplifiers (RA) are a standard method to generate ultrashort pulses exceeding micro-Joule energies. Due to the interplay between the energy stored in the laser material and the energy extracted during the amplification process they show bi- or multistable behavior for some repetition rates. We demonstrate a method to build a freely triggerable RA with constant output energy. We implement this system by adding an intracavity modulator (AOM) to the RA. The AOM is controlled by a digital signal processor that adjusts in real-time the necessary loss to keep the total round-trip gain constant. The gain itself is estimated by measuring the fluorescence emitted from the upper laser level. The fluorescence is collected with a 600 µm core multimode fiber, spectrally filtered to isolate the 4F3/2 - 4F9/2 transition and then detected using a photodiode. The signal is converted to a digital signal at a sampling rate of 927 kHz. We determined a relation between the fluorescence and the necessary loss prior to pulse-on-demand operation by fixing the repetition rate and manually adjusting the loss to give a pulse energy of 6.5 µJ. The necessary control signal for the RF-driver supplying the AOM was stored in a lookup-table inside the DSP. In freely triggerable mode, the DSP adjusted the loss with the full sampling rate and a time-delay of about 2.5 µs between signal acquisition and intracavity loss adjustment. The system is able to keep a constant pulse energy of 6.5 µJ for a linear change of the repetition rate from 0 to 100 kHz within 50 ms.

8235-31, Session 8

Sub-100-fs pulses with 12.5 W from Yb:CALGO based oscillators

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We investigated ultrafast oscillators based on the new attractive Yb3+:CaGdAlO4 (Yb:CALGO) material. Its uniquely broad and flat emission spectra together with its very high thermal conductivity (>6 Wm-1K-1 for 2%-doped crystals) makes it extremely attractive for the development of high average output power sub-100-fs laser oscillators. In this paper we report on the generation of 94-fs pulses with 12.5-W average output power from an 80-MHz oscillator with corresponding pulse energy and peak power higher than 150-nJ and 1.45-MW respectively. To the best of our knowledge this is the highest average power ever reported for a sub-100-fs bulk oscillator.

Average output power levels higher than 10-W were achieved also in lower repetition rate oscillators (20-40 MHz) with pulse duration ranging between 140-fs and 320-fs and corresponding energies as high as 0.42-µJ. In all the experiments stable and self-starting mode-locking with transform-limited pulses and beam quality factor better than M2<1.1 were achieved. Single pulse operation was verified monitoring the pulse train with a fast photodiode (bandwidth :25-GHz) coupled to a 50-GHz sampling oscilloscope and by employing a 50-ps long-range autocorrelator. Continuous tunability of the mode-locking operation between 1026-nm and 1052-nm was also demonstrated. During the tests we were primarily pump power limited and no sign of saturation effects or thermal degradation were observed so far. We therefore believe that even shorter pulses at higher average output powers should be possible and combined with extended cavities such laser systems could reach the µJ pulse energy level with peak powers in the 10-MW regime.

8235-32, Session 8

Cryo-Yb:YAG lasers for next-generation photoinjector applications

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Advanced, high-brightness photoinjectors are required for the next generation of linear accelerators and free-electron lasers. Current photoinjector lasers suffer from complexity due to the use of multiple amplifier stages to achieve the desired pulse energy and have issues with power scaling. In this work, we used a liquid-nitrogen-cooled, Yb:YAG, mode-locked laser master-oscillator/power-amplifier as a high-average-power laser source for laser photoinjector applications. Such a laser can provide average powers in excess of 100 W with repetition rates of 100 kHz to 1 MHz.

The nominal repetition rate of the SESAM mode-locked cryo-Yb:YAG amplifier was 61.9 MHz and the oscillator produced 10-ps pulses at an average power of 10 W. The output wavelength was 1030 nm. The repetition rate of the laser was reduced to 1 MHz using an electro-optic pulse picker followed by a resonant saturable absorber mirror.

A four-pass amplifier was used to amplify the output power to ~100 W. The amplifier was pumped with two 250-W fiber-coupled pump diode lasers. The amplifier used both angle and polarization multiplexing to multipass the beam. As is typical of cryo-Yb:YAG lasers, the beam quality was near TEM00. The measured ratio of the pulses transmitted by the electro-optic pulse picker to the residual pulses was greater than 2400:1 at the output of the amplifier. Conversion of the 1030-nm output to wavelengths of interest in photoinjector applications (515 or 343 nm) would increase the contrast ratio further.

8235-33, Session 8

High-energy 1-Hz titanium sapphire amplifier for PetaWatt class lasers

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Ultra high intensity laser pulses are required by researchers for a growing number of applications like laser-based particle acceleration, generation of ultrafast energetic electrons and ions, etc...

Some applications like the laser wakefield acceleration require at the PetaWatt level significantly higher repetition rates than available today. This is the reason why a 1.3 PetaWatt laser operating at 1 Hz is currently under construction by Thales Optronique for Lawrence Berkeley National Laboratory

This 1 Hz 1.3 PetaWatt laser is based on a double CPA configuration with a XPW filter between the two CPA for temporal contrast enhancement.

The two final amplifiers A2 and A3 are pumped by 12 new high energy flashlamp-pumped YAG lasers delivering stable flat-top green pulses of 14 J at 1 Hz. ASE and transverse lasing are disabled through the use of a melt of a refraction index matching liquid and a fluorescence absorber surrounding the amplifying crystals of A2 & A3.

The laser system has been now built, up to the A2 amplifier included. Energy per pulse of 22.7 J at 1 Hz has been achieved for an input energy of 1.7 J from a 2 pass amplifier pumped by 56 J. No sign of ASE & parasitic lasing have been observed.. A spectral width of 41 nm has been measured suggesting that, if compressing a such amplified output, a peak power of 600 TW at 1 Hz could be achieved, which is a level never obtained up to now at this repetition rate or above.

8235-34, Session 9

Er-doped Tellurite glasses for planar waveguide power amplifier with extended gain bandwidth

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With concern growing over the effects of excess CO2 in our atmosphere, new techniques are required to determine its concentration, distribution and the complete carbon cycle during all times of the night and day throughout the year. In this presentation we detail characteristics of Er-doped tellurite glasses made as part of a study for new glasses with extended gain bandwidth suitable for planar waveguide power amplifiers (PWA) operating at wavelengths beyond the conventional C-band. These PWA could be used to amplify pulsed narrow-linewidth diode-lasers, wavelength swept through absorption peaks of CO2 around 1572nm, providing the source for DIAL or LIDAR measurements from space.

Tellurite glass compositions doped with erbium and erbium/ytterbium optimised to support extended gain bandwidth with significant amplification have been fabricated, and their thermal, optical absorption, excitation and luminescence properties investigated. Each rare-earth dopant concentration was set at 1x1020cm-3. Broad emission cross-section bandwidths up to 50nm FWHM were observed, with fluorescence lifetimes of ~3ms. Collinear pump probe measurements on ~4mm thick bulk samples revealed peak gains of up to 2.1dB/cm at a wavelength of 1535nm in the co-doped material, with an incident pump intensity of only Iinc~8kWcm-2 at a wavelength of 974nm. At equivalent absorbed pump powers between co-doped and single doped materials the relative gain was 1.25dB/cm (Iinc~4kWcm-2) and 0.9dB/cm (Iinc~8kWcm-2) respectively, demonstrating efficient energy transfer from the ytterbium to erbium ions. Excited state absorption at longer wavelengths was observed and characterised and its implication on realising sufficient gain in the wavelength band of interest is discussed.

8235-35, Session 9

Optimized heat extraction geometry for resonantly diode pumped Er3+:YAG lasers

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A new heat extraction geometry for resonantly-diode-pumped Er3+:YAG lasers is proposed. With this approach heat extraction from the laser rod has been symmetrised and improved significantly. As a result thermal lensing effect and all thermo-induced aberrations of the generated beam have been reduced, providing a much better beam quality and symmetric beam shape. For proposed approach more than 10 W of average power has been generated both in CW and QCW (4 ms pump) mode of operation at comparable pumping conditions with a diffraction limited beam. Investigations on diffraction effects inside the fiber-like laser rod have been performed and theoretical background of observed phenomena is analyzed. The study has been performed for rods with different dopand concentrations varying from 0.5 % to 0.25 % and different diameters, as well as for different pumping conditions. The results of further investigations on actively Q-switched laser will be presented.

8235-36, Session 9

Resonant diode-pumping of Er:YAG single crystal fiber operating at 1617 nm

A. Aubourg, I. Martial, Lab. Charles Fabry de l'Institut d'Optique (France) and Fibercryst SAS (France); J. Didierjean, Fibercryst SAS (France); F. Balembois, P. Georges, Lab. Charles Fabry de l'Institut d'Optique (France)

One way to increase the range and the efficiency of Er:YAG Lidar systems (or any Er:YAG laser systems requiring kilometer range propagation in the atmosphere) is to use the 1617 nm emission line which is free of absorption, instead of the 1645 nm emission line, absorbed by methane. Even if its emission cross section is higher, laser operation at 1617 nm is more difficult to obtain since the population inversion needed to reach the transparency is 14% of the total population (at 300 K) whereas it is only 9% at 1645 nm. Without any selective element in the cavity, the line competition is generally won by the 1645 nm transition. We demonstrate for the first time that multiwatt output power at 1617 nm is possible with a resonant diode-pumped Er:YAG system. For that, we investigate the potential of single crystal fibers for pump confinement and consequently for high inversion population ratio. We obtained cw output powers of 5,5W at 1617 nm for 65 W of incident pump power at 1532 nm with a measured M2 less than 1.8. In Q-switched operation, we achieved a maximum energy of 0.5 mJ at 100 Hz with a pulse duration of 28 ns at 1617 nm. This short pulse duration can be attributed to the high gain available thanks to the pump confinement offered by the 600 µm diameter single crystal fiber. The Er :YAG single crystal fibers have the potential for simple, compact and efficient eye-safe lasers at 1617 nm.

8235-37, Session 9

Ho:KRE(WO4)2, RE=(Y, Gd, Lu), CW laser performance near 2.1 micron under resonant pumping by a Tm:KLu(WO4)2 laser

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Eye-safe infrared solid-state lasers based on Ho3+ (Ho) ions operating slightly above 2 µm have potential applications in the fields of medicine, remote sensing and as pump sources for mid-infrared OPOs. In-band pumping of such lasers has been demonstrated with different crystalline hosts. In this work we compare the CW laser performance of the monoclinic double tungstates with general formula KRE(WO4)2 (KREW), RE=(Y, Gd, Lu), which are known as very efficient laser hosts for Nd-, Yb-, and Tm-ions at intermediate power levels. Room temperature operation is studied under identical conditions in a simple hemispherical two-mirror cavity using in-band pumping by a diode-pumped Tm:KLuW laser. The crack and inclusion free crystals of 3at.% Ho:KREW were grown by the Top Seeded Solution Growth - Slow Cooling method (TSSG-SC) using K2W2O7 as a solvent. The crystals were first characterized in terms of structure, composition and spectroscopy and then CW laser operation was obtained using output couplers with 50 mm radius of curvature and different transmission (1, 3, 5 and 20%).

The best results were achieved for an output coupling of 3% and the three hosts performed equally well. The maximum output power obtained with Ho:KY(WO4)2 was 406 mW at 2075 nm with slope efficiency of 59.9%. With Ho:KLu(WO4)2 the maximum power reached 392 mW at 2079 nm but the slope efficiency was slightly higher, 61.6%. Ho:KGd(WO4)2, for which the ionic radius difference between dopant and substituted ions is maximum, generated an output power of 368 mW at 2072 nm with slope efficiency of 53.2%.

8235-38, Session 9

Crystalline fiber Ho3+:YAG laser resonantly-pumped by high-spectral-brightness laser diodes

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Recent advances of high power and narrow bandwidth laser diodes emitting at 1.9 µm opens the path to direct diode pumping of Ho:YAG lasers. The usual method to pump such laser is to use thulium fiber laser which has an excellent beam quality with high power and narrow bandwidth emission. The draw back of this system is the low efficiency of this fiber laser and the increased overall complexity. In this paper we present first results of resonantly diode pumping of a Ho3+:YAG laser with fiberlike geometry. The fiber coupled diode module (BrightLock™ Ultra-500) produces 25 W at 1.91 µm with 3 nm FWHM. The fiber has a core diameter of 600 µm with 0.22 numerical aperture. The Ho3+:YAG crystal has a diameter of 1.2 mm, a length of 60 mm, a doping concentration of 0.75 at.% and is symmetrically pumped by two diode modules from both ends. Total internal reflection on the polished rod barrel allows a high pump intensity along the rod length. The Ho3+:YAG laser cavity is composed of a high reflective flat mirror and a concave output coupler with a radius of curvature of 500 mm. With an output coupler of 30 % (respectively 50%) we measured a threshold of 10.5 W (12.5 W). The maximum output power was 3.6 W (3.4 W) with a wavelength of 2.12 µm (2.09 µm). The incident power to output power slope efficiency was 0.25 (0.26) at currently 7 % of internal losses, which are subject to further investigation.

8235-39, Session 9

A coherent laser Doppler wind profiler for active control of wind turbine

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Due to a significant increasing of amount of electricity generated from wind energy, WTs become larger and move to more inaccessible locations like offshore. The classical Wind Turbine (WT) sensor and control systems have limit the power efficient and high dynamics loads which results in reducing life time of system. These disadvantages lead a high Operation and Maintenance (O&M) cost that causes the high price of electricity. A design of low cost fiber based coherent laser Doppler wind profiler for active pitch control of WTs is presented. The system is based on a 1.55µm Continuous-Wave (CW) Single Longitudinal Model (SLM) semiconductor laser source with an erbium-doped fiber amplifier (EDFA) to gain an output power of 1W. A comparable low coherence (several meters) laser is used to avoid the high laser source prices. In order to achieve a multi-distance measurement, a focus shift mechanics together with a combination of Arrayed Waveguide Grating (AWG) and a couple of multi-length fiber delay lines are used. A 2D surface scanning system and the multiple distance measurement allow us to achieve the 3D area wind measurement. A fiber based coherent (heterodyne) detection method is used for the wind Doppler frequency detection. The sensor system is validated by a mathematical model simulation, and the experiment result based on a lab setup with a wind tunnel. Together with the sensor system, we introduce a concept of wind turbine predictive pitch control system in order to overcome the influence from wind fluctuations.

8235-40, Session 10

Potential of the Eu:LYB crystal as a laser material for DPSS lasers emitting at 613 nm

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Materials for visible laser emission are highly demanded in display technology as well as for medical applications. Rare-earth doped materials have proven to be attractive laser media for the near infrared and have achieved established application in compact industrial laser systems thanks to their absorption spectra that perfectly match the wavelength of commercially available diode lasers. The development of GaN-based laser diodes emitting in the blue-UV range opens the door for diode puming of Europium or Praseodymium doped laser crystals as their absorption spectra correspond to the wavelengths of these new diodes. Different Praseodymium-doped crystals have already proven to be suitable for visible light generation, especially in the red.

In this contribution we will show the spectroscopic properties of a europium-doped borate compound. The studied host crystal has the structure Li6Yx(BO3)3, a host that has already shown good performances as laser material in the NIR when doped with Yb ions. The compound was grown by the Czochralski method, and the doping concentration is about 25%. We studied the absorption and emission spectra and calculated the gain cross sections. The compound shows a strong emission peak at 613 nm and absorption at 396 nm, which is compatible with pumping by GaN-based laser diodes. These features make the Eu:LYB crystal a very interesting candidate for the development of DPSS lasers emitting in the visible range.

8235-41, Session 10

Progress in the development of a pulsed UV laser system for an LDMS instrument on Mars

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A pulsed UV laser system will be used as excitation source in a laser-desorption mass spectrometer (LDMS) on ESA and NASA's ExoMars mission. This instrument (MOMA - Mars Organic Molecule Analyzer) has the objective of identifying organic molecules on or up to 2 meters of depth below the surface of Mars. The laser is based on a passively q-switched Nd:YAG oscillator and frequency-quadrupling to 266 nm at a UV pulse energy of about 300 µJ and a 1 ns pulse duration. Flight-near prototypes have been developed in a compact, lightweight and ruggedized design. Current activities involve the optimization of the laser design and performance with respect to new or changed requirements and operation conditions.

We present the progress and results of the current development activities. The operation of the laser system will be based on pulse bursts at fairly high repetition rates, leading to a dynamic thermal behaviour of the laser crystal and the oscillator. One of the main topics is the stabilization of the pulse energy fluctuations caused by the thermal dynamics. Further issues involve the rugged design of the laser system, mounting, and joining techniques. Results of tests in space-relevant environment, e.g. in a thermal vacuum chamber, are presented.

8235-42, Session 10

High average power sub-picosecond pulse generation at 515 nm by extracavity frequency doubling of a mode-locked Innoslab MOPA

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More than 350 W average power at 515 nm were achieved by frequency doubling of sub-picosecond pulses of an Innoslab based Yb:YAG MOPA system. The achieved conversion efficiency was 65%, while the pulse duration of 680 fs in the infrared was maintained in the green. For the highest output powers exceeding 350 W the beam quality slightly decreased from $M^2 < 1.5$ in the infrared to $M^2 < 1.7$ in the green, while at 280 W $M^2 < 1.4$ was measured in the green. At 50 MHz the pulse energy is up to 7 µJ, resulting in more than 10 MW pulse power. For conversion an extracavity single-pass setup containing a temperature-stabilized LBO crystal cut for Type-I conversion was chosen. To provide a temporally stable laser source the LBO crystal was temperature-stabilized with $\Delta T < 0.01$ K. To achieve damage-free operation of the laser, the crystal surfaces were irradiated with rather moderate pulse intensities. This requires LBO crystal lengths exceeding 10 mm, which is possible for sub-ps pulses due to LBOs low group delay dispersion. A suitable configuration of beam radius and crystal length still resulting in nearly transformation-limited pulses was found by extensive use of numerical modeling of the conversion process. These simulations take into account group velocity effects as well as thermal phase mismatch and deliver a very precise prediction of the experimental results. The contrarily developing impact of thermal and temporal effects with increasing average power could be studied by examining both issues separately.

8235-43, Session 10

Development and optimization of single-mode green solid state microchip laser

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In this paper the development and optimization process of monolithic single mode solid state laser is presented. The plane - plane laser resonator consist of three crystals: Nd:YVO4, YVO4, KTP with mirrors directly deposited on gain and SHG crystals. The undoped YVO4 crystals act as spatial polarization discriminator and in conjunction with KTP form birefringent filter. The crystals were bonded together with UV adhesive. The initial dimensions of monolithic laser resonator were 2x2x10.5mm. In this configuration for particular temperatures the laser operated on two frequencies and two beams (in direction of o- and e-ray of YVO4). That effect caused reduction of the output power (85mW@532nm). The laser optimization was realized through limitation of laser resonator cross section (elimination of the laser oscillations in the direction of e-ray). This was done in two ways:

- partially removed of the output mirror from the KTP crystals (resonator dimension: 2x2x10.5mm),

- realization of the laser resonator with total dimension 1x1x10,5mm.

As a result of the optimization the output power of the laser pumped with 1W@808nm increased up to 160 mW@532nm in single frequency regime. The power stability was at the level of ±0,75%. The laser generate Gaussian beam with M2<1.2. The linewidth was measure in the heterodyne set-up and it was at the level 87kHz. The passive frequency stability was at the level of 10-8.

8235-44, Session 10

Stability enhanced high average power green lasers for precision semiconductor processing

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Laser stability is critical to many industrial applications but is often a source of confusion when specifying and comparing different laser systems. This can be due to the variety of parameters characterised, the range of measurement techniques available and the many alternative methods that can be employed to analyse and present the stability data. High throughput semiconductor applications with sensitivity to individual pulse variations require high average power systems with optimised pulse energy stability. We report stability characterisation and optimisation for a range of frequency doubled Q-switched Nd:YAG laser systems with average power up to 500 W and peak power up to 0.8 MW. The techniques used to refine the stability of the lasers are described and the stability of the lasers is compared before and after optimisation. Stabilised industrial 532 nm laser systems are presented with pulse energy up to 50 mJ and peak to peak pulse energy variation reduced by more than a factor of two compared to standard systems at 10 kHz repetition rate.

8235-16, Session 11

Coherent quasi-CW 153-nm light source at high repetition rate

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Narrowband lasers in vacuum ultraviolet regions have a diverse range of applications in various scientific fields such as photoelectron spectroscopy and high precision spectroscopy. Although such radiation with 7 eV of photon energy has been already demonstrated, even higher photon energy is desired in fields such as angle-resolved photoelectron spectroscopy, where higher photoelectron energy would allow the observation of a broader region in the momentum space.

Here we demonstrate generation of coherent quasi-cw VUV radiation at 153.4 nm (8 eV) at 33 MHz repetition rate, which is the shortest wavelength generated through phase-matched processes in nonlinear optical crystals to our knowledge. This is achieved through successive frequency conversion of the infrared pulses from ytterbium (Yb)-fiber laser system using two LBO crystals and two $KBe_2BO_3F_2$ (KBBF) crystals.

Our Yb-fiber-based laser system consists of an oscillator and three amplifier stages, which delivers 7 W of output with 20 ps pulse duration at the center wavelength of 1074 nm at the repetition rate of 33 MHz. The infrared beam is frequency-converted by two LBO crystals into the third harmonic (TH) beam. The TH beam is focused onto a KBBF prism-coupled device (KBBF-PCD) to generate the sixth harmonic (6H) beam of the original IR beam through a second harmonic generation process. The 6H beam and the remaining fundamental IR beam are focused onto another KBBF-PCD to generate the seventh harmonic (7H) radiation through sum-frequency generation process. A clear 7H signal is observed with a phototube and a lock-in amplifier.

8235-17, Session 11

Designable nonlinear optical device: QPM quartz for VUV spectrum

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Ferroelectrics-based nonlinear optical devices have been attracting much attention since quasi-phase matching is satisfied by reversing spontaneous polarization. QPM nonlinear optics, enabling arbitrary setting of phase-matching point at desired wavelength and temperature, produces designable phase-matching properties by elaborating lithographic patterns. The QPM concept can be even combined with a waveguide technology, where >100 times higher efficiency is expected by strong confinement and extended interaction length of lights.

A novel technology called twinning, brings the possibility to introduce QPM to non-ferroelectric crystals. Twinning in quartz breaks ferroelectrics' limit: large absorption in UV region and low damage threshold to laser pulse. Crystal quartz also exhibits excellent chemical- and thermal stability, together with wide transparent window from mid-IR to vacuum UV (~150 nm). Pressure-induced twinning allows us to flip the sign of the crystallographic X axis, leading to QPM by nonlinear coefficient of d11 (=d12). Twin aspect ratio (depth /width) around several hundred allows a deep and fine QPM structure applicable to short wavelength generation with a mm-scale aperture. Walk-off-free collinear SHG was achieved at 193 nm wavelength by 5th order QPM with 9.6 um periodicity. Vacuum UV (VUV) NLO finally acquired a new degree of freedom, phase control by twinning. History and progress of QPM quartz will be reviewed, with demonstration of SHG ranging from visible to VUV.

This work is partially supported by Ministry of Science and Education, Japan (Project #: 23360037).

8235-45, Session 11

Frequency-doubled diode laser for direct pumping of ultrashort Ti:sapphire lasers

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In this work, we present a simple and robust diode laser system emitting 1.28 W in the green spectral range, suitable for pumping an ultrafast Ti:Al2O3 laser. To classify the results, our laser is compared to a commercially available diode pumped solid-state (DPSS) laser system pumping the same oscillator.

Due to their absorption characteristics, Ti:Al2O3 laser crystals are directly pumped mostly by frequency doubled solid state lasers. These pump lasers offer multiple watts of green light but very often increase both dimensions and costs of Ti:sapphire laser systems. As high power diode lasers have become available, more than 1.5 W of green light could be generated by single-pass frequency conversion, enabling competitive direct optical pumping.

Using our laser for optical pumping of a Ti:sapphire laser reduces the optical conversion efficiencies to 75 % of the values achieved with a commercial solid-state laser system pumping the same oscillator. However, the superior electro-optical efficiency of the diode laser still improves the overall efficiency of the Ti:sapphire laser by a factor > 2. Autocorrelation measurements show that pulse widths of less than 20 fs can be expected when using our laser. This opens the opportunity of using diode laser pumped Ti:sapphire lasers for applications like pumping of photonic crystal fibers for CARS (coherent anti-stokes Raman spectroscopy) microscopy or retinal optical coherence tomography. We will present our first results applying this new, compact Ti:sapphire source.

8235-46, Session 11

Mode hop free tunable blue laser

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We report on a mode hop free tunable blue laser based on an external cavity system. Continuous-wave blue laser is generated by direct intra-cavity frequency doubling (ICFD) of edge-emitting diode laser using MgO-doped periodically poled lithium niobate (MgO: PPLN) bulk crystal. Ultra-low reflectivity coating on the output facet of the diode laser gives less than 0.1% in the wavelength range of ±15 nm, which eliminates the original diode laser cavity allowing the extended longer laser cavity to dominate. An external dichroic mirror is used as output coupling mirror. A rotating etalon combined with a angle placed silica plate is inserted into external cavity. A narrowband pass filter is inserted between etalon and output coupling mirror to control the laser longitudinal modes outside of the free spectral rang of the etalon. By using combination the etalon, silica plate and filter will only allow one lasing longitudinal mode and operating wavelength tuning for fundamental light. The single longitudinal mode second-harmonic generation (SHG) blue laser was generated using quasi-phase matching (QPM) based MgO: PPLN by fine control of the crystal working temperature. We investigated the length changes as a function of angle of the external cavity and see how will they match with the optical properties of an etalon combined with an angel placed silica glass plate. An experimental tuning range in excess of 100 GHz has been obtained without causing a frequency error or mode hop. 30 mw blue light was obtained at wavelength of 465 nm with beam quality better then M2 =1.3.

8235-47, Session 11

High-power compact green laser source based on wavelength-stabilized pump laser diodes

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Using proprietary BrightLock® monolithic chip wavelength stabilization technology and a unique cavity design, our next generation of high brightness, compact green laser modules was realized. We present recent results including stability over temperature and time, pulsed rise times of less than 2 nano-seconds, and powers up to 8W coupled into a 50um fiber. The Ultra-G is able to maintain power levels of 6W over a baseplate temperature range of 20-30C. Over time, at all power levels from 50mW to 6W, the Ultra-G exhibits <2% RMS noise. And, over all power levels and all pulse trains, the Ultra-G shows rise times of <2 milli-seconds with an overshoot of <5%.

We also present stability after putting the modules through a battery of environmental testing - including shock and vibration, extreme temperature cycling and humidity testing. After five 24-hour temperature cycles from -40 to +70C, the Ultra-G exhibited <5% change in output power. After going through shock and vibration testing according to DIN ISO 10109-6, the Ultra-G still showed <5% overall change in output power. Finally, after humidity cycling from 0-95%, <5% change was maintained.

8235-54, Poster Session

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

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A complete electrical and optical characterization for the high power diode laser module operating at 808 nm was performed. The laser diode operating at room temperature 25°C gave a higher slope efficiency with low consumption electrical power and low threshold current lasing of 1.3 A. Maximum slope efficiency of 42% with a final electrical to optical conversion efficiency of 28% at 807.96 nm central wavelength with line width of 3.59 nm at FWHM was investigated. The emitted laser wavelength was measured and is affected by the temperature increasing; the diode peak wavelength was shifted by 0.35nm/°C.

Moreover, the appropriate wavelength for pumping Nd3+ doped materials (around 808nm) was obtained at the temperature range of (20-25°C). 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 36°C) 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 25°C was measured. With diode pumping power of 6.6W, the output power was 3.273W with an output coupler reflectivity of 90%. The Fundamental mode (TEM00) was examined, and the measured DEPSS divergence angle was 11±0.5 milliradian.

8235-55, Poster Session

Comparison between two active media Nd: YAG and Nd: YVO4 rods inside a cavity for producing a high power 808nm diode end-pumping laser system

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Diode end-pumped solid-state lasers have the potential to yield high quality laser beams with high efficiency and reliability. This paper presents a comparison between high-efficiency Nd: YVO4 and Nd: YAG laser rods in the 20W diode end-pumped laser systems. Comparison done by using a special finite element analysis software program (professional LasCad version. 3.6.1) for characterizing the all effective parameters inside the cavity like; optimized rod length, optimized rod diameter, beam waist spot size, optimized resonator length. Theoretical modeling of the absorbed power density for end pumped rods is studied. Stability and analyzed temperature distributions, temperature effects on the solid state crystal (thermal fracture) and thermal lensing effects in 3-D numerical model are investigated. It is important to simulate the temperature gradient on the front face and inside the pumped Nd: YAG and Nd: YVO4 crystal to avoid thermally induced fracture and evaluates the maximum pumped power. This paper shows that Nd: YVO4 laser system has higher optical efficiency of 40% than that of Nd: YAG laser system with optical efficiency of 25%, and the optimized output powers for Nd: YVO4 and Nd: YAG of 8.63 W and 5.4 W, respectively for same parametric study like; rod length of 6 mm, rod diameter of 2 mm, beam waist of 150 m and resonator length of 56.16 mm.

8235-56, Poster Session

Amplified spontaneous emission in disk lasers

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Amplified spontaneous emission (ASE) and parasitic oscillations (PO) in solid-state lasers with resonator exhibit rather different physical properties from that in amplifiers, due to coupling and competition between ASE/PO and laser oscillations (LO). We investigate ASE/PO in disk lasers with unstable resonators in theoretical. The computations include all possible reflections of the ASE waves at both surfaces and side of the disk. The results show that power loss due to ASE/PO is almost determined by the product of disk diameter D and average gain coefficient g_s, where g_s is saturated by total intensity of ASE/PO and LO and is named as ``self-maintain gain" of ASE/PO. The laser oscillations can be established as g_s is higher than threshold gain g_t of the resonator. We further show that the time evolution of laser output may exhibit behavior of relaxation oscillations, in which ASE/PO reduce the output power according to damping, and consume the energy before each of sub-pulses. When intensity of the relaxation oscillations is comparable to the intensity of ASE/PO, the effect of ASE/PO will be suppressed by LO effectively so that the optical efficiency loss due to ASE/PO is negligible. We conclude that the criterion to ignore ASE/PO in disk laser is $g_tD<3.0$ as an ASE absorber is clad on the disk side, and $g_tD<0.75$ as the disk side is roughened. The latter agrees with the experiment of the Boeing's disk laser.

8235-57, Poster Session

Influence of Ce3+ -ions in Pr,Ce:YAlO3 crystal on spectroscopic and laser characteristics

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The trivalent Praseodymium ion (Pr3+) is very interesting candidate for visible solid-state lasers because its energy level diagram offers several laser transitions practically throughout the whole visible spectral range up to the near infrared. In addition, for wavelength generation in the UV-region, Pr-lasers need only a single nonlinear step in comparison to other solid state lasers.

Efficient Pr-lasers have been demonstrated in various fluoride and oxidized laser hosts. In comparison to Pr-fluorides, Pr-oxides excel in higher hardness, thermal conductivity, and mechanical and chemical stability. Furthermore, Pr-oxides exhibits positive value of the temperature coefficient dn/dT enabling to design a microchip laser systems.

In this contribution, the preliminary results concerning the spectroscopic characteristics and laser capabilities of Pr,Ce:YAlO3 (Pr,Ce:YAP) under GaN-diode pumping at room temperature are demonstrated, for the first time to our best knowledge. The results obtained are subsequently compared with Pr:YAP crystal and the influence of Ce3+ in Pr,Ce:YAP laser material is assessed. Co-doping of the active medium by Ce-ions is proposed for crystal property improvement in terms of color center formation caused by UV radiation which could be useful, e.g., for frequency-doubling operation from the fundamental wavelengths. The Pr,Ce:YAP crystal behavior under the UV-radiation exposition is our further consecutive experimental goal.

8235-58, Poster Session

Theoretical and experimental results for using phosphate glass solar laser in the focus of powerful solar concentrator

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The authors present theoretical and experimental results on the operation of high power solar pumped laser using Nd3 doped materials, either crystalline (YAG) and glass (Phosphate glass).

The project consist of analytically and numerically solved a system of kinetic equations for the three and four-level scheme of the laser when solar pumped ideally at constant level and at constant surrounding temperature. Definite that laser output oscillation with respect to internal parametric variations in the active medium. The oscillation parameters for YAG and Phosphate glass with Nd3 are evaluated, and it is shown that the oscillations with a depth of modulations of 5 - 0, 1% may remain far above the excitation threshold, even while providing thermostatic effect.

Experimentally, lasing emission was obtained for YAG and Phosphate glass with Nd3 between 300 - 850 W/cm3 of density solar power. This relationship with accuracy up to 15% will be coordinated to correspond with the analytical and numerical dependences. The differences between modeling and experimental results are accounted for inevitable optical distortions of the framework of large concentrating system.

The ultimate applications of such experiment are wide for developing technologies in the field of natural and effective sources of solar lasers and solar energy on the planet earth and in the outer space.

8235-59, Poster Session

10-km dynamic laser oscillation with a coupled cavity assisted by four wave mixing

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In this report, we present results of dynamic laser oscillation over a 10 km distance using a coupled-cavity structure assisted by four wave mixing (FWM). The system consists of a master cavity and a slave cavity that are coupled together through FWM in a nonlinear medium. The master and slave laser beams each form two arms of the four wave mixing structure. The master laser consists of a cavity formed by two highly reflective mirrors, in which there is a gain medium and the FWM nonlinear medium. For the slave laser cavity, one of the end mirrors is the grating formed inside the FWM medium, and the other mirror is the remote moving target. In this case, this target was a retro-reflector located on a moving airplane. The laser tracking was realized with a rotating gimbal mirror system that locked on the target. Successful field tests at distances over 10 km have been achieved, and longer distances can potentially be realized. The laser oscillations were free running with a pulse width from 2-5 milliseconds. Based on the time separations between the pulses from the master and slave cavities, the target distance can be precisely calculated.

8235-60, Poster Session

Passive Q-switching of a diode-pumped (Tm,Yb):KLu(WO4)2 laser near 2-µm with a Cr2+:ZnS saturable absorber

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The eye-safe spectral range around 2 µm covered by Tm3+ and Ho3+ lasers is important for medical applications, mainly due to the strong optical absorption by water, and remote sensing (LIDAR) of CO2 and water in the atmosphere, as well as for pumping Optical Parametric Oscillators (OPO's) for conversion into the mid-IR. The Tm-ion, emitting on the 3F4 → 3H6 transition, is attractive because its absorption band around 800 nm matches the emission of AlGaAs laser diodes. Passive Q-switching (PQS) of such diode-pumped solid state lasers (DPSSL) by a saturable absorber (SA) is a common technique to generate short and high peak power pulses, mainly due to the simplicity and low cost of the cavity design.

For the present work, co-doped monoclinic (Tm,Yb):KLu(WO4)2 crystals were grown by the Top-Seeded Solution Growth Slow Cooling (TSSG-SC) method. PQS was realized in a hemispherical L-shaped cavity under diode pumping at 805 nm using polycrystalline Cr2+:ZnS as a saturable absorber. The dependence on the doping levels of Tm and Yb and the low-signal absorption of the saturable absorber has been studied. Optimum performance has been achieved for a beam size diameter of 350 µm in the position of the saturable absorber. The highest average output power achieved was 272 mW at a repetition rate of 2.04 kHz corresponding to a pulse energy of 133 µJ. The laser spectrum was centered at 1920 nm. The pulse widths were in the 130-200 ns range. The M2 parameter, measured by the knife-edge method, was 1.2.

8235-61, Poster Session

Continuous wave Yb:KGW laser with polarization-independent pump absorption

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The crystals of Yb:KGW are known to be an attractive gain medium for diode-pumped continuous wave and ultrafast solid-state lasers producing radiation with wavelength around 1 µm. Since pump absorption spectra of Yb:KGW are highly anisotropic, its efficient operation especially at high output power levels requires careful consideration of pumping configuration. Usually, an Nm axis is used for excitation because it has several times higher absorption coefficient than the other two principal optical axes Np and Ng. Unfortunately, the pump beam from the commonly used fiber-coupled laser diode modules is unpolarized. This causes inhomogeneous pump absorption along the length of the crystal, considerable thermal lensing, and dependence of pump absorption on its current state of polarization all of which are detrimental to the efficiency, beam quality and stability of a laser.

In this work a new method for significant reduction of these effects in Yb:KGW crystals is proposed and successfully tested. In our case the Np and Ng axes are selected for excitation at 980 nm, since they have very similar absorption coefficients. Therefore the pump absorption becomes polarization-independent. This pumping method results in several advantages: 1) the pump is absorbed more uniformly along the crystal length, reducing the focal length of the induced thermal lens by a factor of two; 2) lower pump absorption on the Np and Ng axes reduces the thermal load on the crystal's entrance face by 60%, leading to a lower risk of damage; 3) the pump absorption, and hence output power, is insensitive to the coiling, stress and orientation of the diode module's fiber, making performance of the laser less sensitive to mechanical disturbances. The proposed pumping technique was experimentally tested by building a 1W level continuous wave Yb:KGW laser. The obtained successful results provide a route for development of multi-Watt Yb:KGW lasers with improved performance. Such power-scaling efforts are currently underway.

8235-62, Poster Session

High-energy picosecond regenerative thin disk amplifier at 1 kHz

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We present recent progress in development of a compact regenerative laser amplifier based on the Yb:YAG thin-disk technology delivering up to 100 mJ picosecond pulses with a repetition rate of 1 kHz, designed for seeding a multi-J, kW-class multipass amplifier for industrial and scientific applications.

The generic concept involves chirped pulse amplification (CPA) technique and therefore it contains stretcher and compressor utilizing transmission gratings. Fiber oscillator produces a seed signal at 1030 nm which after stretching is amplified in a fiber preamplifier to a desired energy level of about 10 µJ sufficient for amplification up to 100 mJ. Active medium is being pumped at 939 nm by commercially available high power (kW) pulsed laser diodes with 50 % duty cycle and is electrically synchronized with an RMS jitter of less than 250ps with the seed oscillator. Amplified signal is coupled out of the cavity by use of the β-barium borate (BBO) Pockels Cell.

Detailed calculations, engineering design and performance of the laser system will be presented.

8235-63, Poster Session

Tuning possibility of dysprosium-doped lead thiogallate laser

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One of the promising active ions giving the possibility of laser radiation generation in mid-IR 4-5 um region is trivalent dysprosium in lead thiogallate crystal. Based of our previous Dy3+:PbGa2S4 laser studies, this work demonstrates the possibility of different individual wavelengths generation and also some tuning possibilities. The laser was working at the room temperature and was pumped by the Er:YLF laser generating 1.74 um radiation. For this study two Dy3+:PbGa2S4 crystal samples were investigated. Both were nearly 15 mm long and were synthesized using Bridgman technique from the melt and its nominal Dy concentration was ~0.7 at.%. In the first case the crystal without antireflection coatings was used in the 50 mm long laser resonator formed by the in-coupling flat dichroic mirror with low reflectivity at pumping wavelength (T = 87%@1.73 μm) and high reflectivity (R~100%) within the 4-5 um spectral range, and by an out-coupling curved (r = 500 mm) mirror with reflectivity of 95% in the range of 4-5 μm. Generation at three wavelengths of 4040, 4352 and 4378 nm was obtained simultaneously. Under 190 mJ incident pumping energy, the output energy was 1.2 mJ. In the second case the active sample was antireflection coated at 4-6 um. In order to obtain continuous output wavelength tuning, a MgF2 Lyot filter was inserted inside the 100 mm long resonator. Under 126 mJ incident pumping energy, the output energy was 2.5 mJ and the tuning range from 4280 nm to 4360 nm was observed.

8235-64, Poster Session

Compact pulsed high-energy Er:glass laser

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Bulk Erbium-doped laser are preferred coherent sources for long-distance telemetry and ranging. In some applications such as coherent Doppler radars, laser output with a relatively long pulse width, good beam profile and pulse shape are required. High energy Q-switched Er:glass lasers were demonstrated by use of electro-optic (E/O) Q-switching or frustrated total internal reflection (FTIR) Q-switching. However, the output pulse duration in these lasers were fixed to a relatively small value and extremely hard to tune.

We report here on developing a novel and compact Q-switched Er3+/Yb3+ co-doped phosphate glass laser at an eye-safer wavelength of 1.5 μm. A rotating mirror was used as a Q-switch. Co-linear pump scheme was used to maintain a good output beam profile. Near-perfect Gaussian temporal shape was obtained in our experiment. By changing rotation speed, pulse duration was tunable and up to 340 ns was achieved. In our preliminary experiment, at pump peak power of only 30 W, output pulse energies obtained in un-Q-switched and Q-switched operation modes were above 10 mJ and above 1 mJ respectively. Near diffraction limit beam profile was obtained. Larger output pulse energies can be achieved in our future work.

8235-65, Poster Session

Influence of undoped YAG cup on diode pumped composite YAG/Er:Yb:glass laser

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Two samples of Er-Yb doped phosphate glass were tested as a gain medium of longitudinally diode pumped laser. One sample was a simple Er:Yb:glass rod (length 2.8 mm), second sample was composite rod consisting of 2.8 mm long Er:Yb:glass and 6 mm long YAG crystal. Diameter of both samples was 6 mm. Dopant concentration for Er:Yb:glass was 0.75×10^{-20} cm^{-3} Er and 1.7×10^{-21} cm^{-3} Yb. The goal of the experiment was to investigate an effect of the undoped YAG cup on the Er:Yb:glass laser operation. The active medium, fixed in cupreous heatsink, was placed inside the 150 mm long resonator consisted of a flat pumping mirror (HR @ 1.52-1.65 μm, HT @ 0.97 μm) and curved output coupler (r=150 mm, R=97 % @ 1.52-1.61 μm). For Er:Yb:glass pumping a fiber coupled laser diode, operating in pulsed regime, was used. The pumping pulse width, energy, and wavelength were 1 ms, 6 mJ, and 976 nm, respectively. The decrease of Er:Yb:glass laser output pulse energy with increasing pumping repetition rate was observed for both samples. In case of simple Er:Yb:glass the energy dropped from 1.4 mJ to 0.6 mJ after pumping duty cycle increase from 0.5 % to 6 %. In case of composite YAG/Er:Yb:glass active medium the relative output energy decrease was only 20 % for pumping duty cycle increase from 0.5 % to 10 %. This result showed that the slope of the output energy decrease with increasing duty cycle was approximately four times slower for composite active media in comparison with simple Er:Yb:glass.

8235-66, Poster Session

Spectroscopic characterization of Ti3+:AgGaS2 and Fe2+:MgAl2O4 crystals for mid-IR laser applications

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Development of new mid-IR (2-20um) tunable laser sources is in great demand for many scientific, sensing and biomedical applications. Mid-IR lasers based on Cr2+ and Fe2+ ions in tetrahedral crystal hosts (ZnS, ZnSe, CdS, CdSe) came of age and enable a broad tunability over 1.9-3.3 um and 3.5-6 um, respectively. However, the development of new effective gain media promising for lasing over 3-4 um and with wavelength longer than 6 um is still under progress. In this paper we report spectroscopic characterization of Titanium doped AgGaS2 and Iron doped MgAl2O4 crystals with coordination number four. Polarized absorption and luminescence spectra of titanium and chromium doped AgGaS2 crystals were measured at room and low temperature. It was shown that Ti ions in the AgGaS2 crystal were in both 1+ and 3+ valence states substituting silver and gallium sites, correspondingly. Ti3+ ions in AgGaS2 and Fe2+ in MgAl2O4 crystals feature a broad absorption band with a maximum near 2um. These ions have no excited state absorptions from the first excited states and potentially could be used as effective saturable absorbers for passive Q-switching of 2.1 um holmium laser cavities. Broad emission covering the 3-6 um spectral range was observed under 1.9 um excitation into Ti3+ absorption band. The luminescence signal between 2.5 and 5.5 um was also observed in the Fe:MgAl2O4 crystal under 1.9 um excitation of 5E-5T2 transition of Fe2+ ions.

8235-67, Poster Session

Mid-IR volumetric Bragg grating based on LiF color center crystals

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Volumetric Bragg gratings (VBG) are one of the key elements to develop of compact narrow line laser systems. Currently, a majority of VBGs use photorefractive glasses with a transmission band between 0.3 and 2.7 um. Recent progress in room temperature mid-IR lasers operating over 2-6 um stimulates development of new photorefractive materials for these lasers. We have proposed and realized LiF color center crystals (LiF:CC) for these applications. LiF has a wide transmission band and can potentially operate at wavelengths longer than 6 um. Gamma-irradiated LiF:CC crystals feature strong absorption bands in visible and near-IR spectral range, where selective color center photo-bleaching allows for the modification of the LiF refractive index. The absence of active absorption in LiF:CCs at wavelengths longer than 1.3 um results in a VBG that is stable under mid-IR irradiation. Our calculations predict that dn>10^-4 in LiF crystals over 1-6 um spectral range, which results in ~60% diffraction efficiency in ~1 cm VBG. To verify this calculation, we fabricated periodic structures in LiF:CC crystals with 24 and 12 um spacings by CCs photo-bleaching using femtosecond Ti:sapphire laser pulses. Periodic structures exhibit diffraction in multiple orders in the Raman-Nath regime at 0.532, 0.632, and 1.56 um. The first order diffraction efficiencies were stronger for visible radiation due to a bigger refractive index variations and additional amplitude modulation, however, diffraction at 1.56 um is a clear manifestation of a phase grating in LiF and serves as a proof of feasibility of these LiF:CC crystals for mid-IR VBG applications.

8235-68, Poster Session

Yb:YAG/Cr:YAG composite crystal with external and microchip resonator

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A compact diode pumped Q-switched lasers, operating at wavelength 1031 nm, were based on the Yb:YAG/Cr:YAG composite crystal. This composite crystal (diameter 3 mm) consisted of diffusion bounded 3 mm long Yb:YAG (10 at.% Yb/Y) and 1.8 mm long Cr:YAG crystal (initial transmission 85 %@ 1031 nm). External resonator allowing to tune generated Q-switched pulse parameters or microchip configuration offering shortest pulses and highest peak power were tested for this device. For longitudinal pumping of Yb:YAG gain medium fibre coupled (core diameter 200 µm, NA=0.22) laser diode, operating at wavelength 968 nm, was used. In the first case, Yb:YAG/Cr:YAG composite crystal was AR-coated and placed inside the 150 mm long semi-hemispherical resonator consisted of a flat pumping mirror (HR @ 1.01-1.09 µm, HT @ 0.97 µm) and by curved output coupler (r=150 mm) with reflectivity 70 % @ 1031 nm. Generated pulses with peak power 23 kW were 17 ns long (FWHM). The highest generated pulse energy was 0.38 mJ. In the second case, the resonator mirrors were deposited directly on the crystal faces. The output coupler reflectivity was 85 % @ 1031 nm. In this compact microchip configuration 140 ps long (FWHM) pulses with energy 0.13 mJ and peak power 0.92 MW were generated at wavelength 1031 nm.

8235-69, Poster Session

A highly efficient DPSS mode-locked Nd:YLF single-mode laser

F. F. Wu, MetroLaser, Inc. (United States)

We have achieved an output power of more than 15 watts, at a single transversal mode, with a pump power of 60 watts, and a direct optical to optical conversion efficiency of 25%. The output wavelength is 1053 nm and the mode locked frequency is 150 MHz; the pulse width is less than 120 ps. The peak power reaches megawatts per pulse. The wavelength can be converted into 527nm and 351 nm with a nonlinear conversion.

8235-70, Poster Session

DPSS laser beam quality optimization through pump current tuning

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The goal of this study is to demonstrate how DPSS laser beam quality parameters can be optimized through pump current tuning. In this study we used a JDSU 532nm G-series continuous wave (cw) laser where laser diode pump current was varied from.3 to.8 A to ascertain the lowest RMS noise region. At the lowest pump current the RMS Noise was 2.08%, and as the pump current increased the noise hit a minimum value of.07% at which the pump current was.6A. In addition, the best M2 value of 1.0 was obtained at this lowest RMS Noise current point while the laser the manufacturer reported a M2 value of 1.30 for this laser. This study therefore demonstrates that current tuning a DPSS laser pump can simultaneously optimize both RMS noise and M2 values. Future studies will strive to broaden the scope of the beam quality parameters impacted by current tuning.

8235-71, Poster Session

Observation of laser formation inside a laser cavity containing a phase conjugate mirror

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Adaptive optics (AO) systems are used to compensate atmospheric perturbations on a propagating laser beam. However, AO needs a beacon to obtain the phase information. When the target is non-cooperative, the target-in-the-loop (TIL) geometry represents perhaps the most challenging case for adaptive optics applications. Thus, observation of the laser forming process in TIL is very important to understand the progression of the laser spot on the target.

This report presents the results of the laser formation process by observing the laser formation inside a laser cavity containing a phase conjugate mirror. The laser cavity is formed with a high reflectivity mirror on one end and an optical phase conjugated mirror as the second mirror. The laser is not in a free running oscillation but rather is initialized by a single frequency 10 ns Q-switched laser pulse. This is very similar to an injection seeding or regenerative amplifier scheme to start the laser oscillation. With a cavity length of around 11 meters and an initial laser pulse of 10 ns, we have been able to isolate laser field images related to each round-trip pulse. Furthermore, by replacing the first mirror with a rough-surface target to simulate an uncooperative target and adding phase distortion elements to simulate atmospheric effects, we can observe the image status under such conditions.

8235-48, Session 12

Passive alignment and soldering technique for optical components

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The detection of greenhouse gases is a relevant issue nowadays. For local measurements airborne LIDAR (Light Detection and Raging) systems are available. Global detection requires space borne systems. Due to extreme conditions during the launch and maintenance new packaging technologies for optical components must be developed. Soldering is a suitable method for mounting optical systems for space application due to following features: low outgassing, high long-term stability and high thermal conductivity. Components within the laser can be divided in two parts. Components that have to be aligned actively and such where passive alignment is sufficient enough. Non-linear crystals belong to the second part. The requested tolerances for the angle deviation are ±100 µrad and for the position tolerance ±100 µm. In this paper a passive alignment technique by means of mechanical stops is described. Only the angle tolerances were investigated, because they are more critical. The measurements were carried out with an autocollimator. SiO_2 components were used for test series. Several substrate materials (copper, aluminum and invar) were analyzed. Furthermore a solder investigation was carried out. Different types of solder were tested. Due to good solderability on air and low induced stress in optical components, Sn based solders were indicated as the most suitable solders. In addition several concepts of reflow soldering configuration were realized. In the first iteration a system with only the alignment of the yaw angle was implemented. The deviation for all materials after the thermal and mechanical cycling was within the tolerances.

8235-49, Session 12

High-power continuous wave Nd:YAG single crystal fiber laser emitting at 946 nm

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Recent laser developments using the 4F3/2-4I9/2 transition of Nd:YAG at 946 nm have been mostly driven by the demand of high power blue laser sources. Frequency doubled 946 nm lasers have numerous potential applications such as biological and medical diagnostics, trace gas detection, Raman spectroscopy. Using a Nd:YAG single crystal fiber in which the pump signal is guided and the laser beam is in free propagation, we obtained a high power 946 nm laser. The 0.2% doped, 1 mm diameter and 5 cm long crystal was pumped by a fiber coupled laser diode providing an incident pump power of 86 W. The maximal temperature difference between the cooling mount and the center of the crystal was measured to be only of 30°C by using a thermal camera. Indeed, the small diameter of the crystal and the low doping concentration contribute in keeping a low temperature increase. A simple biconcave laser cavity was used to obtain a maximum output power of 34 W. The slope efficiency was as high as 53% and there was no rollover observed in the efficiency curve. It shows that the output power was only limited by the available pump power. The beam quality M^2 value was lower than 5. In addition, we obtained an output power of 20 W at 938 nm using a Fabry-Perot etalon in the cavity. Compare to previous results, the output power obtained in this work are the highest for such a low M^2 beam quality factor.

8235-50, Session 12

Yb3+:LuAG single crystal grown by micro-PD: spectroscopy and laser experiments

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A LuAG single crystal fiber, doped with Yb^{3+}, has been grown by micro-PD technique with iridium crucible at about 2350 K working temperature. During growth the pulling rate was 0.3 mm/h. The fiber shows a constant diameter of 3.02 (+/-0.04) mm and its length is around 130 mm. A Gaussian laser beam was used to investigate the optical quality of the fiber showing a negligible distortion. The absorption and emission of the sample have been studied in the temperature range 10-300 K. The experimental data together with the lifetime value of the upper laser level have been utilized to calculate the cross-sections. By these data it has been developed a theoretical model for the quasi-three levels laser which provides the laser performances. In the laser experiment the Yb:LuAG sample was placed in a X cavity and pumped longitudinally obtaining an efficient CW laser emission with different output couplers. The Yb:LuAG laser yielded a maximum output power of 23 mW with a slope efficiency of 32% and a threshold around 35 mW, at lasing wavelength of 1030 nm. No significant depolarization effects were observed, indicating a crystal growth with negligible stress. The output beam profile was investigated, yielding M2 ~ 1.0 in both directions, further confirming the good optical quality of the sample. This feature makes LuAG, grown by micro-PD, an appealing material for high power laser applications opening the way to obtain low cost laser grade old and new materials.

8235-51, Session 12

Rare-earth doped photo-thermo-refractive glass for monolithic solid state lasers

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Compact, alignment free, and thermally and mechanically robust narrow-linewidth lasers with good beam quality are desired for many applications. Even though diode-pumped DFB/DBR fiber lasers have been widely deployed for narrow linewidth applications, they fall short in situations requiring temperature insensitivity and mechanical stability in extreme environments such as airborne and space applications.

Volume Bragg gratings (VBGs) in photo-thermo-refractive (PTR) glass has been demonstrated with diffraction efficiencies >99% and FWHM linewidth 5 nm spectral width and >20% slope efficiency. The use of a reflecting VBG narrowed Nd doped PTR glass laser emission down to ~23 pm FWHM linewidth centered at ~1065.3 nm.

We show that the doped-PTR glasses retain their photosensitivity and demonstrate recording of VBGs with diffraction efficiencies of >99%. Monolithic laser geometries with holographically recorded distributed feedback elements in doped-PTR glasses are discussed.

8235-52, Session 12

Generating multiple wavelengths, simultaneously, in a Ti:sapphire ring laser with a ramp-hold-fire seeding technique

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The ability to simultaneously produce pulsed laser output over multiple discrete wavelengths can mitigate many of the timing and jitter issues associated with the use of multiple laser systems. In addition, Fourier-transform limited laser output on every pulse is required for many applications such as with pump-probe detection, non-linear frequency mixing, differential absorption lidar (DIAL), and resonance ionization. As a matter of practice, such lasers need to be capable of operating within uncontrolled or noisy environments. We report on a novel Ti:sapphire ring laser that has been developed to produce Fourier-transform limited 20 ns laser pulses at multiple discrete wavelengths, simultaneously, utilizing a Ramp-Hold-Fire (RHF) seeding technique. Resonance of the seed light is achieved by using a KD*P crystal to modify the phase of the light circulating within the slave oscillator cavity where the fast response of the KD*P results in a seeding technique that is immune to noise throughout the acoustic regime.

8235-53, Session 12

Voltage tunable polymer laser device

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Since organic laser materials offer a broad optical gain spectra they are predestined for the realization of tunable laser sources. Here we report on a compact organic laser device that allows for voltage controlled continuous wavelength tuning in the visible range of the spectrum without the usage of an external motion control. The compact optical element consists of an elastomeric distributed feedback (DFB) laser and an electro active elastomer actuator also known as artificial muscle. A second order DFB laser is realized by covering a grating line structured elastomer film with a thin layer of dye doped polymer. To enable direct wavelength tuning the elastomer laser is placed in the center of the prepared actuator. The chosen configuration geometry and electrode distribution of the elastomeric actuator gives rise to homogeneous compression in the center of the actuator. The voltage induced deformation of the artificial muscle is transferred to the elastomeric laser and results in a decrease of grating period. This leads to an emission wavelength shift of the elastomer laser. The increase of actuation voltage to 3.25 kV decreased the emission wavelength of the laser device from 604 nm to 557 nm, a change of 47 nm or 7.8%.

Conference 8236: Laser Resonators, Microresonators, and Beam Control XIV

Sunday-Wednesday 22-25 January 2012

Part of Proceedings of SPIE Vol. 8236 Laser Resonators, Microresonators, and Beam Control XIV

8236-01, Session 1

Fine control of ultrashort pulse trains with a Fabry-Perot intracavity resonator

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Fabry-Perot resonators have been used extensively as a wavelength tuning element inside a laser for continuous operation. This well-known optical component is less explored in mode-locked laser designs, due to the complication of multiple pulse train coupling. The operation of a mode-locked laser including an intracavity Fabry-Perot etalon is investigated. The simultaneous impact of the Fabry-Perot on the the pulse train carrier frequency, carrier to envelope offset and repetition rate are demonstrated. The Fabry-Perot pulse shaping is presented in time and frequency, and monitored through coherent population trapping with Rb87. The case under study is a 6.8 GHz pulse train generated through insertion of a fused silica plate in a 155 MHz Ti:sapphire laser cavity.

8236-02, Session 1

Experimental verification of path length sensitivity to coherent beam combining by spatial filtering

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The sensitivity to path length changes is theoretically analyzed and experimentally explored in coherent beam combining architectures based on Fourier plane spatial filtering. The supermodes of a two-laser spatially filtered cavity exhibit two distinctly different types of behavior depending on the path length error. When the error is small, the two modes present different cavity loss values and can be differentiated by gain. However, cavities containing path length errors greater than a critical value produce modes with identical losses and different resonant frequencies. Changing the spatial filter size has an impact on mode losses, mode discrimination and the phase errors associated with the two regions. There is an apparent tradeoff between mode loss and phase error tolerance. A diode-bar side-pumped plano-concave Nd:YAG laser cavity is built to experimentally verify the theory. The experiment utilizes a polarization multiplexing technique to ensure a path length balance between the two lasing channels. The filtering is provided by a three-micron thick tungsten wire in the Fourier plane of an afocal system. Experiments show two distinct regions as predicted by theory: in the small path length error region, the cavity can lase in one single mode; however, when the path length difference goes beyond a critical value, the two modes have the same loss and switch randomly between modal states. Mode selection can easily be accomplished by moving the wire in the Fourier plane to suppress the unwanted mode. Detailed loss versus phase error curves will be presented and compared to the theoretical analysis.

8236-03, Session 1

Beam control of nonplanar ring resonators based on the analysis of optical-axis perturbation

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Abstract: Nonplanar ring resonators are widely used for high precision ring laser gyroscopes including Zero-Lock Laser Gyroscopes. To the best of our knowledge, the generalized ray matrix, an augmented 5×5 ray matrix for a faraday rotator transmission and its detailed deducing process has been proposed in this paper for the first time. All the faraday rotator's possible perturbation sources including the wedge angle of the rotator and two kinds of angular misalignments have been considered simultaneously. A mathematic model for the analysis of optical-axis perturbation of nonplanar ring resonator by utilizing generalized ray matrixes of mirror reflection and faraday rotator transmission is established for the first time in this paper. All the mirror's possible perturbation sources including two kinds of angular misalignments and three kinds of displacements have been considered simultaneously in the generalized augmented 5×5 ray matrix. The image-rotation caused by the nonplanar cavity has been considered too. The rules of the optical-axis perturbation induced by all the possible perturbation sources are analyzed in detail and some novel findings on beam control have been carried out. The wedge angle and two kinds of angular misalignments of the faraday rotator have been found to have singular affections on the optical-axis perturbation. All those results have been confirmed by related beam control experiments and the experimental results of beam control have been described with diagrammatic representation. These interesting findings are important to the beam control, cavity design, and cavity alignment of high precision nonplanar ring laser gyroscopes.

8236-04, Session 1

1121-nm resonator properties and impact on the design of a 1178-nm sodium guidestar laser

L. J. Henry, J. Grosek, G. T. Moore, T. Shay, Air Force Research Lab. (United States)

Generation of 589 nm is key for the creation of an artificial star for sodium guidestar laser purposes. One way of reaching 589 nm is through frequency doubling of 1178 nm. Narrow linewidth 1178 nm can be obtained through a Yb-doped amplifier/ 1121 nm Raman resonator co-seeded with 1069 and 1178 nm. It was found that the circulating power in the 1121 nm resonator as well as Stimulated Brillouin Scattering (SBS) are key aspects that must be considered in laser design. Generally, as the 1069 nm pump increases or, the 1178 nm seed decreases or, the resonator length decreases, the circulating power within the 1121 nm cavity will increase. Operation with a heavier 1178 nm seed is desirable since it leads to lower circulating power in the 1121 nm cavity and enables usage of a shorter fiber length. Even though the SBS threshold will be increased because of the shorter Raman fiber, SBS suppression will be key because of more rapid growth of the 1178 nm in this regime. Although still under investigation, it is speculated that a shorter Raman fiber will also result in less linewidth broadening since four wave mixing will be phase matched. In addition, the reflection of the 1121 nm output grating at 1178 nm is critical since any back reflection can grow significantly, resulting in decreased efficiency. Finally, the bottom line is that very high 1121 nm cavity power results in efficient amplification of the 1178 nm, a short Raman fiber, a high SBS threshold, possibly reduced four wave mixing, and high output power levels at 1178 nm. To conclude, a laser system having a 50 W output power with a minimum 75% efficiency can be easily achieved from multiple designs.

8236-05, Session 1

Comprehensive analysis of thermal lensing effects on the a coaxial resonator on a high power RF excited CO2 laser

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CO2 lasers continue to be the most widely used industrial laser on the market despite of the great advances on alternative laser sources. This mature technology still has room for improvement and innovation aimed to higher quality and lower cost products. In this paper we will describe a detailed analytical, numerical and experimental approach to the thermal lensing effects of a hybrid stable-unstable coaxial resonator used on a high power RF excited CO2 laser. The influence of a variety of parameters such as the gas composition, pressure and lateral variation of Joule heat release of the discharge at employed frequency are taken into account to derive a distributed thermal lensing expression and to numerically calculate the focal length as a function of position within the inter-electrode gap.

In the next stage of the process the effect of widening of the beam inside the resonator is investigated by means of complex ray methodology. The findings are incorporated into the optimization process of the optical resonator in the stable direction and the impact on the beam quality and power stability is verified by experimental results.

8236-06, Session 1

Unstable resonator with high magnification and low output coupling

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The application of standard unstable resonators does not allow for an independent adjustment of the resonator magnification and the output coupling. Either you get a high magnification together with a high output coupling, or vice versa. Certain laser types, like e.g. thin disc lasers or chemical oxygen iodine lasers, exhibit a quite low optimum output coupling. But the use of a low resonator magnification is equal to a bad beam quality. In order to apply unstable resonators with a high magnification also to low gain lasers an additional mirror surface retroreflects a part of the outcoupled radiation back into the cavity. The output coupling is reduced efficiently, whereas the resonator magnification stays high and provides a very good beam quality. Numerical and experimental investigations are shown. The experiments are performed with a chemical oxygen iodine laser operating at a wavelength of 1.315 µm and demonstrate the feasibility of this resonator design.

8236-08, Session 2

Effect of ring width on ring generated Bessel beam

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Bessel beams are very interesting for many applications like optical tweezers, microlithography and optical coherence tomography (OCT) where the beam diffraction is required to be limited. Ideal Bessel beams require infinite energy and can propagate infinitely. However, practical Bessel beams are generated with finite energy and have finite maximum propagation distance (Zm) with low diffraction. One way to generate Bessel beams with good quality is to use an illuminated ring in the focal plan of a lens. The main problem in this technique is its very low efficiency as the generated Bessel beam has only the power passed through the ring. To increase this power it is required to increase the ring width which results in beam quality degradation. In this work we study the effect of the ring width on Zm. A theoretical model based on the Fourier optics is used to model the Bessel beam generated by a ring illuminated by a Gaussian beam. The obtained results are confirmed using a volume optics setup with a 632 nm HeNe visible laser source. The obtained Bessel beam profile is captured using a CMOS camera. The power measured within a detector of a specific area is then plotted as a function of the propagation distance and compared to theoretical investigations. The effect of the ring width on the distance Zm is then determined. The obtained results allow the engineering of the generated practical Bessel beams to maximize the Power x Zm product.

8236-09, Session 2

Efficient beam splitting with diffractive kinoforms and microlens arrays

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Diffractive optical elements (DOEs) are of rising importance for many industrial laser applications, especially for laser beam shaping or laser beam splitting. Typically, such applications require high damage threshold of the diffractive optical elements as well as their high diffraction efficiency. Usually, DOEs with multilevel (step-like) phase profiles are made microlithographically and suffer from “quantisation” error and scattering on profile discontinuities. The step-like structure lowers DOE damage threshold compared to intrinsic material values themselves.

LIMO’s technology is suitable for production of free programmable continuous surface profiles in optical glasses and crystals. It can be applied for manufacturing of diffractive kinoforms as well as micro-lens arrays. Both optical elements are suitable for the high efficiency laser beam splitting. However, the design approaches to obtain a desirable solution for the corresponding continuous phase profiles are different.

The results of the wave-optical simulations made by LIMO’s own program and by VirtualLab software, as well as experimental studies for the kinoform beam splitter 1 to 11 with efficiency of about 97% for the wavelengths of 532 nm and 1064 nm will be presented. Continuous phase profiles for the kinoforms were designed by the procedure based on the theory of beam splitting by a phase grating. Comparative theoretical and experimental studies were also done for splitting by a double-side micro-lens array.

An advantage of the micro-lens array is the absence of the side maxima. However, its interlens “dead” spaces reduce the efficiency. Their influence on the intensity distribution can be compensated with the special design.

8236-10, Session 3

Gaussian-to-top-hat beam shaping: an overview of parameters, methods, and applications

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Direct laser patterning of various materials is today widely used in several micro-system production lines like inkjet printing, solar cell technology, flat-panel display production, semiconductors and medicine. Typically single-mode solid state lasers and their higher harmonics (e. g. 266, 355 and 532 nm) are used especially for machining of holes and grooves. The striking advantages of flat top intensity distributions compared to Gaussian beam profiles with respect to the efficiency and quality of these processes were already demonstrated. This presentation will give an overview of parameters, methods and applications of Gaussian-to-top-hat beam shaping. The top hat field size can range from about 50 µm to several km in the far field of the optics. Beam shaping for wavelengths from 266 nm to 10.6 µm were realized with field geometries of squares, rectangles, small lines and circles. With LIMO’s compact Gaussian-to-top-hat converter homogeneity better than 5% contrast was reached. Using Powell-lenses is only one of the various methods for homogenizing single mode lasers. Special focus is put on the integration of Gaussian-to-top-hat beam shapers in fast scanning systems employing Galvo mirrors and a specially developed f-Theta lens to avoid destruction of the top hat profile within the scan field. Results with a 50x50µm^2 top hat field (homogeneity down to <10%) in a scan area of 156x156mm^2 will be presented. The minimal distortions of the top hat observed within the scan area make LIMO’s compact Gaussian-to-top-hat converter excellently suited for industrial scanning applications, e.g. for the processing of solar panels.

8236-11, Session 3

Parametric optimization of refractive beam shaping systems considering diffraction and interference effects

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Beam shaping systems can be used in order to transform the intensity profile of laser beams into a customizable profile. Lenses together with refractive and diffractive beam shaping elements can be used for the transformation of the beam. Typically diffraction and interference are neglected during the optimization of refractive beam shaping elements since the simulation is often based on a geometrical optics approximation. Such an approximation is not feasible in many situations, e.g., if the shaping works at the resolution limit of the system. In the talk we present a parametric optimization algorithm for refractive beam shaping systems using the field tracing concept for the analysis of the optical system and the evaluation of merit functions. Field tracing propagates fields instead of rays through a systems. It enables using different propagation methods from geometrical optics to rigorous depending on the required physical accuracy. Especially diffraction, interference and aberrations can be included in the system analysis. In addition merit functions can be used for the evaluation of the system quality that need access to field information, e.g., intensity, phase, polarization and energy density. The optimization will be demonstrated on the example of the Gauss to top Hat converting system.

8236-12, Session 3

Wave front reconstruction using computer-generated holograms

C. Schulze, D. Flamm, M. Duparré, Friedrich-Schiller-Univ. Jena (Germany); O. A. Schmidt, Max Planck Institute for the Science of Light (Germany)

We propose a new method to determine the wave front of a laser beam, based on modal decomposition using computer-generated holograms (CGHs). Thereby the beam under test illuminates the CGH with a specific, inscribed transmission function that enables the measurement of modal amplitudes and phases by evaluating the first diffraction order of the hologram. Since we use an angular multiplexing technique, our method is innately capable of real-time measurements. An additional recording of the Stokes parameters (and therewith of the polarization state), as done by placing a quarter-wave plate and a polarizer in front of the hologram, yields the complete information necessary to reconstruct the optical field. This provides the possibility to calculate the Poynting vector which gives the wave front of the beam as the result of the minimization of an integral relation according to ISO-15357-1. To quantify single aberrations, the reconstructed wave front is decomposed into Zernike polynomials of different order.

In this way the modal decomposition with CGHs opens up the opportunity to derive a large variety of quantities, such as the Poynting vector and the wave front, that are much more meaningful to describe a laser beam than, e.g., the widely used M2-parameter.

Our method is applied to beams emerging from different kinds of multimode optical fibers, such as step-index, photonic crystal and multicore fibers, in which the coherent superposition of modes leads to distorted wave fronts.

8236-13, Session 3

Variable beam shaping with using the same field mapping refractive beam shaper

A. V. Laskin, V. Laskin, AdlOptica Optical Systems GmbH (Germany)

Modern laser scientific techniques and industrial technologies require not only simple homogenizing of a beam but also more freedom in manipulation of intensity profile and generating such profiles like super-Gaussian, inverse-Gaussian, skewed flattop and others. In many cases the task of variable beam shaping can be solved by refractive beam shaping optics of field mapping type which operational principle presumes saving of beam consistency, providing collimated output beam of low divergence, high transmittance and flatness of output beam profile, extended depth of field; another important feature is negligible residual wave aberration. Typically the fields mapping refractive beam shapers, like piShaper, are designed to generate flattop intensity profile for a beam of pre-determined size and input intensity profile. Varying of the input beam diameter lets it possible to realize either super-Gaussian (smaller input) or inverse-Gaussian (bigger input) intensity profiles of output beam that are important in pumping of solid-state lasers, hardening, cladding and other techniques. By lateral shift of a beam with respect to a piShaper the output flattop profile gets a skew in direction of that shift, the skew angle corresponds to the shift value. The skewed profile is important, for example, in some acousto-optical techniques where compensation of acoustic wave attenuation is required. All variety of profiles can be provided by the same beam shaper unit.

This paper will describe some design basics of refractive beam shapers of the field mapping type and techniques to vary the output intensity profile, experimental results will be presented as well.

8236-14, Session 3

Propagating aberrated light

A. Forbes, C. Mafusire, CSIR National Laser Ctr. (South Africa)

We outline a theory for the calculation of the laser beam quality factor of an aberrated laser beam. We provide closed form equations which show that the beam quality factor of an aberrated Gaussian beam depends on all primary aberrations except tilt, defocus and x-astigmatism. The model is verified experimentally by implementing aberrations as digital holograms in the laboratory. We extend this concept to defining the mean focal length of an aberrated lens, and show how this definition may be of use to people in controlling thermal aberrations in laser resonators. Finally, we look at aberration correction and control using a spatial light modulator.

8236-15, Session 4

Continuous single pulse resolved measurement of beam diameters at 200 kHz using optical transmission filters

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We present a novel laser beam measurement setup which allows the determination of the beam diameter for each single pulse of a pulsed laser beam at repetition rates of up to 200 kHz. This is useful for online process-parameter control e.g. in micromachining or for laser source characterization.

Basically, the developed instrument combines spatial transmission filters specially designed for instantaneous optical determination of the second order moments of the lateral intensity distribution of the light beam and photodiodes coupled to customized electronics. The acquisition is computer-based, enabling real-time operation for online monitoring or control. It also allows data storage for a later analysis and visualization of the measurement results.

The single-pulse resolved beam diameter can be measured and recorded without any interruption for an unlimited number of pulses. It is only limited by the capacity of the data storage means. In our setup a standard PC and hard-disk provided 2 hours uninterrupted operation and recording of varying beam diameters at 200 kHz. This is about three orders of magnitude faster than other systems. To calibrate our device we performed experiments in cw and pulsed regimes and the obtained results were compared to those obtained with a commercial camera based system. Only minor deviations of the beam diameter values between the two instruments were observed, proving the reliability of our approach. Further experiments as well as the investigations regarding accuracy will be presented during the talk.

8236-16, Session 4

Discerning comb and Fourier mean frequency from an fs laser based on the principle of non-interaction of waves

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

We will discuss the temporal evolution of modes in an idealized confocal mode-locked cavity containing a homogeneously broadened gain medium that can generate envelope-phase stabilized fs pulses containing a broad band frequency comb [1-Prasad et.al., Proc. SPIE 8121, paper 47(2011)]. Direct measurement of the strength of the oscillating E-vector shows a clean single frequency of oscillation of the E-vector [2-Krausz & Ivanov, Rev.Mod.Phys.81, No.1 (2009)]. In separate experiments, the cavity-mode frequency-comb from such a laser can be dispersed, individually manipulated (amplitudes and phases) and recombined to re-create new desired pulse shapes [3-Diddams, JOSA-B, 27, p.B51(2010)]. Superposition principle, embedded in the time-frequency Fourier theorem (TF-FT), apparently validates the simultaneous existence of the TF-FT synthesized mean frequency and the frequency comb; only different experimental apparatus determines different results. However, closer investigation of the physical processes involved in the various experiments reveal some contradictions [4-Roychoudhuri, "Various Ambiguities in Generating and Reconstructing Laser Pulse Parameters", Ch.7 in Laser Pulse Phenomena and Applications; Ed. F. J. Duarte; InTech (2010)]. The interaction process behind the determination of the resultant E-vector oscillation through acceleration of free electrons [2] can be modeled as the Fourier synthesis of all the physically present comb frequencies by the free-electrons as their time-resolved response to all the instantaneous E-fields. However, the Fourier decomposition process of any time finite pulse, requires the potential analyzer to have a memory to "read and store" the entire pulse envelope function before it can carry out the Fourier transform of the envelope. Spectrometers built out of periodically ruled lines on glass plates, or a pair of parallel beam splitters as in a Fabry-Perot, neither possess such "read and store" memory, nor do they have built-in computers to decompose the envelope function into its Fourier components. However, when multiple optical frequencies are physically present, these instruments naturally help re-direct their energies based upon in-phase superposition conditions. These spectrometers are linear replicators of the incident beam into a long train of periodically delayed beams. Interaction of these replicated beams with a suitable material medium determines the registered energy separation (fringes) corresponding to in-phase superposition of the replicated beams of different frequencies. Thus, the existence of the set of comb frequency cannot be explained as a result of Fourier transform of the envelope function of the long train of mode-locked pulses [4, also

5- Roychoudhuri, "Why we need to continue the 'What is a Photon?' conference: to re-vitalize classical and quantum optics." SPIE Conf. Proc. 7421-28 (2009)]. They are physically generated cavity modes and propagate collinearly without interacting with each other, or without becoming a resultant E-vector oscillation at the mean frequency. We describe this behavior of light wave as the principle of Non-Interaction of Waves, or the NIW-principle [6-Roychoudhuri, JNP 4, 043512 (2010)]. If cavity modes would have self-interfered to generate a single (central) mean frequency, it would have suppressed the intra-cavity gain of all the other mode frequencies except the central one. The physical presence of a set of comb frequency validates the NIW-principle and contradicts self-interference between different light waves.

8236-17, Session 4

Real-time monitoring of thermal lensing of a multikilowatt fiber laser optical system

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A new laser beam waist analyzer system has been developed that permits the real time focal spot measurement of a high power fiber laser in excess of ten of kilowatts with the ability to monitor thermal lensing of a laser and its entire optical system. In addition to tracking the thermal lensing of the optical system, the analyzer can provide the laser's spatial profile, circularity, centroid, astigmatism and M-squared values inclusive of the optics used in the process application, including the focus lens and cover glass for debris protection. The beam analyzer system is very compact, measures in real time and has no moving parts by incorporating an all passive optical design, thereby accommodating the measurement of the focused beam waist: spot diameter, M-squared, Rayleigh length, beam waist position and many other beam parameters to power levels in excess of 20 kW in real time and in less than one second from laser off to laser on. The core of the analyzer is a Fabry-Perot resonator coupled with a focusing lens which provides a means to both attenuate and produce a multiplicity of focused laser spots, each representing a spatial slice of the focused beam waist of interest, onto a single CMOS camera. The measured beam waist position is tracked and recorded in real time to determine the level of thermal lensing in the system.

8236-18, Session 4

Comparison of two modal decomposition techniques

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Optical multimode fibers are used for many high power applications. The appearance of several higher order modes influences fundamental beam quantities, such as beam quality, beam pointing stability, intensity distribution and state of polarization.

For an extensive analysis and control of those quantities it is necessary to modally decompose the beam.

We present the comparison of two coherent modal decomposition techniques. The first technique is based on the correlation filter (computer generating hologram) with a specifically designed transmission function. All modal amplitudes and phases can be measured by evaluating the diffraction pattern of the illuminated filter. For the second method, we use a phase retrieval algorithm. This yields the amplitudes and phases modally resolved by minimization of an error function that compares measured and reconstructed intensity distributions of the laser beam in near and far field. Thereby, the modal coefficients serve as independent variables.

We compare the two methods regarding measurement accuracy, deviations between measured and reconstructed intensity distributions and limits for application. It is shown that the correlation filter method is allows a faster measurement, whereas the phase retrieval algorithm yield more accurate results.

To circumvent the methodical disadvantages and to enable a higher performance of modal decomposition we combined the two techniques. This can be done by taking the results of the correlation filter as initial values for the phase retrieval algorithm.

The comparison of the two methods is exemplarily presented for a step-index fiber.

8236-19, Session 5

Active mirrors for intra-cavity compensation of the aspherical thermal lens in thin-disk lasers

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The development of the thin-disk laser with its highly efficient cooling scheme has led to a considerable reduction of thermal lensing problems when compared to the classical rod-type solid-state lasers and has consequently pushed the limits of achievable output power with good beam quality to the multi-kW regime. However, scaling the fundamental mode output power to the kW-regime still remains a difficult task. The strong temperature gradient at the transition from the pumped to the unpumped region of the laser crystal causes a dominant aspherical component of the thermal lens. This step-like change of optical path length introduces diffraction losses increasing with pumping power, which severely degrade the efficiency or even suppress laser operation at high brilliance. Especially for fundamental mode operation, these aspherical components have to be actively compensated for, if the output power shall be further increased.

In this contribution, we will present active laser mirrors for intracavity compensation of the aspherical components of the thermal lens present in high-power thin-disk laser resonators. The step-like shape of these aberrations implies the possibility of compensation by an intracavity mirror with a step-shaped surface. The feasibility of this compensation method has been recently demonstrated for static compensation. For active or adaptive compensation, an active mirror concept has been developed, which features a pneumatically actuated deformable surface. The use of fused silica substrates with dielectric coatings qualifies these active mirrors for the high powers present in laser cavities. In this contribution, the design concept along with experimental results will be presented.

8236-20, Session 5

New deformable mirror technology and associated control strategies for ultrahigh intensity laser beam corrections and optimizations

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When ultra high intensity lasers facilities were in their early development, the only concern was getting laser pulses with the right energy and pulse duration. As facilities are orienting toward the end users, they are now required to deliver a laser beam with additional qualities like a focal spot with constant quality. That is why Adaptive Optics is now a standard feature for the current ultra high intensity lasers facilities to correct for the aberrations of the beam exiting the laser chain. However, the very last optical components, like the off axis parabola to focus the beam induce aberrations that cannot be directly corrected as they are located after the wavefront sensing.

We present a new technology of deformable mirror and a new correction strategy to get optimal focal spot in the experiment chamber as well as measurement of the actual beam quality in the chamber while the beam is used for experiments. These deformable mirrors were designed taking into account needs of ultra intense laser applications. They provide exceptional stability, optical quality and innovative features like scalability and maintenance of the reflective surface. The method of correction proposed uses usual adaptive optics loop to correct for all the aberration from the laser chain, as well as additional steps to get an optimal focal spot in the experiment chamber on a non amplified beam, and to correct and measure the actual beam quality on the amplified beam while it is used for experiments.

8236-81, Session 5

New Hartmann wavefront sensor for high power CO_2 lasers

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In this paper we discuss the application of two types of new Hartmann wavefront sensors to measure the aberrations of high power CO_2 laser beams. First sensor was made on bolometer camera produced by INO (Canada) and the unique feature of it is its convenience for the applications. In fact it has most of the feature of a standard video cameras! So, it could be easily incorporated in any kind of standard software. The main problem of this sensor - it is very sensitive for incoming laser radiation, its intensity.

Second sensor was made based on thing film technology. It is perfect for measuring the large aperture and high power beams. While it is used for small beams it faces serious problems. We discuss the advantages and shortcomings of these wavefront sensors.

8236-21, Session 6

Unidirectional-emission, single-mode, whispering-gallery-mode microlasers

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Unidirectional-emission microcavity lasers are potential light sources for photonic integrated circuits and optical interconnection. Connecting an output waveguide to microresonator is a simple method to realize directional emission microlasers. Equilateral triangular and square InGaAsP/InP microlasers connected with an output waveguide were fabricated by planar technology processes, and so square microlsers with two and four ports connected with output waveguides were fabricated recently. In this paper, we report the fabrication and characteristics of hexagonal resonator microlaser connected with a bus waveguide and circular microlasers with one and two output waveguides.

Room temperature continuous-wave electrically injected operation is realized for a hexagon laser with the edge length of 16 μm and the output waveguide width of 2 μm. Single mode operation is achieved with a side mode suppression ratio of 33 dB and the output power of 48 W at 297 K. The mode Q factor of 6.53×103 is measured for the lasing mode at 1547 nm at the threshold current, which is in the same magnitude as the Q factor obtained by FDTD simulation. The numerical simulations also indicate that the hexagonal resonator with an output waveguide is suitable to realize single transverse mode operation.

Furthermore, InAlGaAs/InP cylinder microlasers with radius of 15 μm, connected two 2-μm-wide output waveguides, are fabricated by conventional photolithography and inductively coupled-plasma etching techniques. Room temperature continuous-wave electrically injected single-mode-operation is realized at the lasing wavelength of 1577 nm and the side mode suppression of 32 dB. And mode Q factor of 18000 is estimated as the ratio of the peak wavelength to the FWHM around the threshold.

8236-22, Session 6

Miniaturized optical microwave source based on simultaneous single-mode laser oscillations in Er:ZBLALiP whispering-gallery-mode resonator

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Micro spherical resonators have attracted significant attention in recent years due to their interesting optical properties and the range of applications for which they can be used. Most of the publications dedicated to micro spherical laser are devoted to lasing effects in different materials where the spectral properties of the emission depends on (i) the choice of dopant (e.g. Er^{3+}, Yb^{3+}, Tm^{3+}) and (ii) the host matrix (e.g. silica, fluoride, phosphate or telluride glass) in which the dopant is embedded. This work is more dedicated to a potential application of the Whispering Gallery Mode (WGM) micro resonators to obtain a dual wavelength laser source and consequently on the observation of a compact optical microwave source based on the beatnote of the two WGM laser oscillations. We use as active medium Er^{3+} doped fluoride ZBLALiP glass. This glass is well adapted to the development of micro spherical laser operating in the infrared region, in particular with emission wavelengths falling in the C-band. The use of a single erbium-doped glass microsphere (with a diameter around 100 μm) and two half fiber tapers allows a dual single-mode laser emission around 1550 nm to be obtained independently. By changing the relative position of the tapers with respect to the sphere we can obtain a spectral interval between the two emissions reduced to few gigahertz. We have observed the generation of a narrow linewidth (22 kHz) microwave signal at 10.86 GHz using this kind of dual-wavelength single mode WGM free running laser.

8236-23, Session 6

Progress in miniature sub-kilohertz microresonator based self-injection locked semiconductor laser systems

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We report on recent advances in miniature low phase noise whispering gallery mode (WGM) based passive injection locked laser systems. This injection locked WGM design architecture has been successfully deployed using single and multimode Fabry-Perot (FP) lasers as well as single mode distributed feedback (DFB) lasers over a wide range of laser wavelengths, 680nm - 1550nm, and resonator materials to produce miniature ultra-narrow linewidth lasers (linewidth ~ 300 Hz). In these systems differing resonator materials and geometries have been used to produces both desirable effects, such as high speed frequency modulation (> 2MHz modulation bandwidth) in an electro-optic resonator based laser systems, as well as parasitic effects associated with nonlinear processes which increase the relative noise levels and stability of the resulting injection locked laser system. All of these characteristics are shown to depend not only on WGM resonator material choice but also the choice of operational wavelength and laser design architecture. We observe that for all resonator material as the wavelength deceases there is a corresponding increase in the optical feedback from the WGM (coherent Raleigh scattering) into the laser which increases the relative stability of the injection lock, but this is compounded by a mutual increase in the density of modes within the resonator which serves to increase mode competition in the system. These dynamic processes are shown to be further influenced by the choice of resonator material, geometry and laser architecture.

8236-24, Session 6

Whispering-gallery-mode resonators for compact optical clocks

N. Yu, L. M. Baumgartel, Y. Chembo, I. S. Grudinin, D. V. Strekalov, R. J. Thompson, Jet Propulsion Lab. (United States)

Crystalline whispering gallery mode (WGM) resonators are small and structurally monolithic, yet capable of ultra-high quality factors and dramatically enhanced optical nonlinearities. These properties can be exploited in developing compact optical clocks. Several studies have explored using WGM resonators as frequency reference cavities, and there also exists great research interest in using WGMs for frequency comb generation. In this paper, we will describe our efforts in pursuing laser stabilization using WGM reference cavities with both passive and active temperature stabilization schemes. We will also present our latest analysis and experimental results in frequency comb generation in WGM resonators.

8236-25, Session 6

Exploring the frequency stability limits of whispering gallery mode resonators for metrological applications

Y. K. Chembo, FEMTO-ST (France); L. M. Baumgartel, I. S. Grudinin, D. V. Strekalov, R. J. Thompson, N. Yu, Jet Propulsion Lab. (United States)

Whispering gallery mode resonators are attracting increasing interest as promising frequency reference cavities. Unlike commonly used Fabry-Pérot cavities, however, they are filled with a bulk medium whose properties have a significant impact on the stability of its resonance frequencies. In this context, thermal and other refraction index fluctuations of the medium induce additional frequency instability that has to be reduced to a minimum. On the other hand, a small monolithic resonator provides opportunity for better stability against vibration and acceleration. This feature is essential when the cavity operates in a non-laboratory environment. In this paper, we will report a case study for magnesium fluoride resonator. We will discuss the fundamental thermal limits of frequency stability and reduction of its sensitivity to vibration and acceleration.

8236-26, Session 7

Whispering-gallery-modes for nonlinear light generation from a low number of molecules

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We report on the design and fabrication of a nonlinear spherical resonator to experimentally measure second harmonic generation (SHG) from molecules deposited on its surface. This generation requires phase matching in the whispering gallery modes, which we achieved by implementing a new procedure to periodically pattern with nanometric precision a molecular surface mono-layer. Temporal walk-off between the fundamental and SH pulses reduced the interacting length down to a very short distance. With radii of approximately 180 μm, pulse overlap can be lost well before a single cavity round-trip is completed [1]. To circumvent this problem the pump pulses were stretched using 140 m of an optical fiber loop to ensure permanent overlap. Using such type of walk-off compensation allowed us to reduce the surface molecule concentration by four orders of magnitude. Approximately between 50 to 100 molecules were needed to measure a change in the SH light. This result confirmed the relevant role played by such high Q micro-spheres. By comparison, when molecules are deposited on a flat transparent substrate, typically one would need 1 billion molecules to obtain a measurable SHG signal. The possible application of nonlinear spherical micro-resonators in the detection of small molecules will be discussed.

[1] J. L. Dominguez-Juarez, G. Kozyreff, and J. Martorell, Nat. Commun. 2, 254 (2011).

8236-27, Session 7

Monolithic optical parametric oscillators

I. Breunig, Albert-Ludwigs-Univ. Freiburg (Germany)

Stability and footprint of optical parametric oscillators (OPOs) strongly depend on the cavity used. Monolithic OPOs tend to be most stable and compact since they do not require external mirrors that have to be aligned. The most straightforward way to get rid of the mirrors is to coat the end faces of the nonlinear crystal. Whispering gallery resonators (WGRs) are a more advynced solution since they provide ultra-high reflectivity over a wide spectral range without any coating. Furthermore, they can be fabricated out of nonlinear-optical materials like lithium niobate. Thus, they are ideally suited to serve as a monolithic OPO cavity.

We present the experiental realization of optical parametric oscillators based on whispering gallery resonators. The devices demonstrated recently show oscillation thresholds of several μW, and their output wavelength can be tuned between 1.78 and 2.5 μm by varying the crystal temperature. We explore different schemes, how to phase match the nonlinear interaction in a WGR. In particular, we show improvements in the fabrication of quasi-phase-matching structures. They enable great flexibility for the tuning and the choice of the pump laser.

8236-28, Session 7

Photonic microwave receivers based on high-Q optical resonance

M. Hossein-Zadeh, Ctr. for High Technology Materials (United States)

The quest for low power and high frequency electro-optical modulator has been one of the important endeavors in microwave photonics. The advent of microdisk electro-optic modulator created a new domain in optical modulator and photonic microwave receiver design by exploiting the unique properties of optical resonance in high quality (high-Q) whispering-Gallery optical cavities. High-Q crystalline WG cavities were the first devices used as compact and low power resonant electro-optical modulators and gradually semiconductor and polymer based microring modulators emerged from this core technology. Due to its small size, high sensitivity and limited bandwidth, originally microdisk modulator was developed with the objective of replacing the conventional microwave wireless receiver front-end with a sensitive photonic front-end. Later it was shown that the electro-optic microdisk modulator could also function as a microwave frequency mixer in optical domain. Starting from fundamentals of resonant electro-optic modulation in high-Q WG cavities, in this talk we review the development of high sensitivity microdisk modulators and the recent progress toward more efficient modulation at higher frequencies. Next, photonic microwave receiver configurations that employ high-Q optical resonance for modulation, filtering and mixing will be discussed. We will show that high-Q optical resonance is one of the promising routes toward the general idea of an all-optical microwave receiver free of high frequency electronic transistors, mixers and filters. Finally we briefly cover related topics such as single-sideband modulation, all-dielectric photonic receiver, and semiconductor microring modulators followed by challenges and future trends in resonant optical modulator and photonic microwave receiver technology.

8236-30, Session 8

High-Q resonators and ultralow-loss delay lines

K. J. Vahala, H. Lee, T. Chen, J. Li, California Institute of Technology (United States)

TBAWe review a new method for fabrication of silicon-chip-based resonators having Q factors as high as 750 million. These devices do not require silica reflow and therefore expand opportunities for ultra-high-Q performance on-a-chip. In addition to resonator applications, we also describe how this same process provides a way to fabricate delay lines on silicon with unprecedented optical loss. 7 meter long waveguides are presented having loss values of 0.05 dB/m.

8236-31, Session 8

Coupling approaches and new geometries in whispering-gallery-mode resonators

G. Nunzi Conti, S. Berneschi, M. Brenci, F. Cosi, D. Farnesi, S. Pelli, G. C. Righini, S. Soria, Istituto di Fisica Applicata Nello Carrara (Italy)

In order to fully exploit the unique properties of micro-optical resonators with whispering gallery modes (WGMs), both for fundamental investigations as well as for practical applications, a critical point is an efficient, controllable, and robust coupling of the light to the cavity WGMs. We present the results of our studies on phase-matched evanescent field couplers with particular reference to the coupling to high-index crystalline resonators like lithium niobate disks. We focus on couplers based on different types of waveguide configurations and include demonstration of optical coupling to high-Q lithium niobate resonators from integrated planar waveguides as well as from angle polished waveguides. These systems are all in guided optics architectures. We also briefly present our recent achievements in the development of microbubble resonators fabricated from silica capillaries. We show that, as high-Q hollow 3-D cavities with intrinsic microfluidics, these resonators represent a promising biochemical sensing platform.

8236-32, Session 8

Novel resonance-based CMOS-compatible reconfigurable nanophotonic structures

A. H. Atabaki, Q. Li, P. Alipour, A. A. Eftekhar, Z. Xia, A. Adibi, Georgia Institute of Technology (United States)

The development of ultra-compact integrated nanophotonic structures for communications, sensing, and signal processing has been of great interest lately. The use of compact microresonators (e.g., microrings, racetracks, and microdisks) with high quality factors has resulted in order of magnitude reduction in the size of functional integrated photonic structures that used to be formed using waveguides. Such resonators can be effectively tuned using free carrier injection and/or using the thermo-optic effect. This feature can be used to form reconfigurable photonic structures. Among existing substrates, silicon (Si) is the most promising one for infrared wavelengths due to the existence of excellent CMOS-based fabrication facilities. The same fabrication infrastructure can also be used to manufacture integrated nanophotonic structures in silicon nitride (SiN) for operation in visible and near-infrared wavelengths. With recent advances in the design and fabrication tools for photonic nanostructures, Si-based integrated photonic platforms are a strong candidate for the realization of ultra-compact functional photonic microchips for a wide range of applications including signal processing, communications, and sensing.

In this talk, we will first demonstrate the recent achievements in the design and demonstration of high Q resonators in CMOS-compatible platform. We will then focus on the ultimate miniaturization of high Q resonators for dense integration of photonic functionalities. Using the fast and low-power tuning mechanism for high Q resonators, we will discuss the realization of reconfigurable photonic chips for signal processing applications.

8236-33, Session 8

Integrated terahertz microcavities, filters, and waveguides

F. Rana, P. A. George, C. Manolatou, Cornell Univ. (United States)

Although several types of passive terahertz waveguides and resonators have been experimentally demonstrated,they have typically been fabricated using bulk micromachining techniques and are not suitable for on-chip dense integration. In this talk we will discuss our work in realizing fully integrated terahertz microcavities, filters, and waveguides using the Silicon platform. We will discuss air-core metallic microcavities, photonic bandgap filters and cavities, and dielectric and metallic waveguides. We will also present results on microcavities aperture-coupled to waveguides. These components are realized using deep reactive ion etching of two separate Silicon wafers that are then bonded together. Device testing and characterization is performed using ultrafast terahertz time-domain spectrometer. The measured quality factors of metallic cavities are found to be significantly smaller than theoretical predictions and depend sensitively on the fabrication process. In particular, surface roughness of the deposited metal plays an important role in determining the cavity and the waveguide losses given the small skin depth at Terahertz frequencies. We discuss designs for hybrid metal-dielectric cavities for achieving integrated terahertz cavities with quality factors in the 1000-3000 range. We also discuss applications of integrated terahertz components in sources, such as integrated terahertz klystrons and travelling wave amplifiers, and in bilogical and chemical sensors, and in terahertz integrated circuits.

8236-34, Session 9

Localization of light and photonic microresonators in an optical fiber with nanoscale radius variation

M. Sumetsky, OFS (United States)

No abstract available

8236-35, Session 9

Neutron whispering-gallery and its application to fundamental and surface physics

V. V. Nesvizhevsky, Institut Laue-Langevin (France)

The ‘whispering gallery’ effect has been known since ancient times for sound waves in air, later in water and more recently for a broad range of electromagnetic waves: radio, optics, Roentgen and so on. It is intensively used and explored due to its numerous crucial applications. This phenomenon consists of wave localization near a curved reflecting surface and is expected for waves of various natures, for instance, for atoms and neutrons. For matter waves, it includes a new feature: a massive particle is settled in quantum states, with parameters depending on its mass. Here, we present the quantum whispering-gallery effect for cold neutrons. This phenomenon provides an example of an exactly solvable problem analogous to the ‘quantum bouncer’; it is complementary to the recently discovered gravitational quantum states of neutrons. These two phenomena provide a direct demonstration of the weak equivalence principle for a massive particle in a quantum state. Deeply bound whispering-gallery states are long-living states weakly sensitive to surface potential; highly excited states are short-living states very sensitive to the wall potential shape. Therefore, they are a promising tool for studying fundamental neutron-matter interactions, quantum neutron optics and surface physics effects.

V.V. N., A.Yu. Voronin, R. Cubitt, K.V. Protasov (2010). “Neutron whispering gallery.” Nature Physics 6: 114.

V.V. N., R. Cubitt, K.V. Protasov, A.Yu. Voronin (2010). “The whispering gallery effect in neutron scattering.” New Journal of Physics 12: 113050.

8236-36, Session 9

Guided resonances for light-assisted self assembly and structural-absorption engineering

M. L. Povinelli, C. Mejia Prada, C. Lin, E. Jaquay, L. J. Martinez Rodriguez, The Univ. of Southern California (United States); A. Dutt, Indian Institute of Technology Kharagpur (India)

We study the application of guided resonance modes in photonic crystals to two distinct applications: light-assisted self assembly and structural absorption engineering.

In the first case, we propose to use a photonic crystal as a template to assemble nanoparticles in regular crystalline patterns. The structured light fields above the photonic crystal form an array of optical traps to direct pattern formation. We predict that the wavelength or polarization of the input can be tuned to reconfigure the assembled patterns. We further present experimental progress towards this goal.

In the second case, we exploit guided resonances of silicon nanowire arrays to increase the predicted absorption of a thin film, boosting photovoltaic efficiency. Further, we show that localized resonances of aperiodic structures can fulfill a similar function. We show that under certain conditions, aperiodic structures absorb more than 100% as much light as their periodic counterparts. We compare compare and contrast absorption behavior in silicon and direct bandgap materials such as GaAs.

8236-37, Session 9

Time-reversed lasing and coherent control of absorption in resonators

A. D. Stone, H. Cao, Y. Chong, Yale Univ. (United States); L. Ge, Princeton Univ. (United States); H. Noh, Yale Univ. (United States); W. Wan, Shanghai Jiaotong Univ. (China)

We describe a class of optical devices that can function as narrow-band perfect absorbers and/or interferometers, based on the time-reversed process of lasing. These devices, termed, “coherent perfect absorbers” (CPAs), are lossy resonators that perfectly absorb the time-reverse of the lasing mode of the resonator with gain. Single-channel CPAs correspond to variants of the critically-coupled resonator. We have proposed and demonstrated a two-channel CPA in silicon, which functions as an absorptive interferometer, in which the absorption can be tuned from > 99% to < 35% by varying the phases of the input fields. Generalizations to random and nanoscale CPAs will be discussed.

8236-38, Session 10

Dynamic multi-mode analysis of passive Q-switched lasers

C. Pflaum, Z. Rahimi, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany)

Passive Q-switched lasers are constructed using saturable absorbers (SA). One characteristic of these lasers is that they are built with small dimensions. This makes the passive Q-switch interesting for applications, such as medical equipment. There are difficulties in designing lasers with a given pulse repetition rate or pulse energy using saturable absorbers. Numerical simulation of Q-switches facilitates the design and production of such lasers and helps to reduce development time and cost.

This paper presents a new simulation method which calculates beam quality, maximal output power, pulse-width and pulse energy. This numerical method is developed based on a set of rate equations for high and low order Gauss-modes and space dependent rate equations for population inversion and SA inversion. This approach can be applied to the simulation of lasers with fundamental mode or lower beam quality.

This paper also presents and discusses the simulation results of thermal lensing effects and an accurate analysis of the pump light using the ray tracing method.

8236-39, Session 10

Improvements in monoblock performance using external reflector

A. D. Hays, J. E. Nettleton, N. Barr, N. Hough, L. Goldberg, U.S. Army Night Vision & Electronic Sensors Directorate (United States)

During the past few years the Monoblock laser has become the laser-of-choice for Army laser range-finders. It is eye-safe 1570 nm emission, high pulse energy, simple construction, and high efficiency, when pumped by a laser-diode stack, provide advantages that are not available with other laser types. Although the relatively divergence of the Monoblock output beam is relatively large, it can be reduced to 2.5 X reduction from the unmodified laser. Performance using this technique over temperature as well as fraction of feedback and etalon spacing will be presented. Laser diode array and VECSEL pumping were both investigated with similar results.

8236-40, Session 10

Characterization of the longitudinal Gouy phase branches in cascaded optical systems

S. K. Nirmala, S. P. Tewari, Univ. of Hyderabad (India)

The Gouy phase is an important phase, however rather poorly understood. It has been shown recently that it can be used to control the frequency of a ring laser and can help in achieving a control over mode-locking problem of ring laser gyro. It is demonstrated now that with the help of the Gouy phase one discovers further characterization of a laser in terms of what may be called longitudinal Gouy phase branches. On such a Gouy phase branch one can tune the laser in a manner described elsewhere. It is noted that the longitudinal Gouy-phase-branches play significant role in cascaded optical systems as well as have potential characterization feature in several ring configurations that get naturally selected in a random lasing medium. The concept is further clarified with Collins chart diagrams of several cascaded optics lasers. These systems help in elucidating the Gouy phase, its origin, and the related concept of a point source of light and/or its point image.

8236-41, Session 11

Nonlinear modes of plasmonic microcavities: theoretical analysis and device applications

N. C. Panoiu, C. G. Biris, Univ. College London (United Kingdom)

High fabrication costs of complex photonic nano-devices make it imperative to have access to high-performance computational tools, which can greatly accelerate the device design process by reducing the design-fabrication-testing cycle. In this connection, in this talk we first briefly review a numerical method based on the multiple scattering algorithm, which we used to describe the optical properties of plasmonic nanostructures. Then, by using specific examples, we illustrate how this method can be employed to characterize the optical modes of microcavities made of plasmonic nanowires. Our algorithm incorporates the effects of both the surface and bulk nonlinear polarizations generated at the second harmonic, providing thus a complete description of the nonlinear properties of plasmonic structures. In particular, we investigate the physical properties of plasmonic modes generated at the second harmonic and show that such plasmonic microcavities have three distinct types of modes, namely, plasmonic cavity modes, multipole plasmon modes generated via the hybridization of modes of single nanowires, and whispering gallery modes. Moreover, our time domain analysis of plasmonic cavity modes shows that these modes exhibit large lifetime in the nonlinear regime, allowing thus for applications to nano-scale lasing cavities and plasmonic sensors. More specifically, we show that due to the sensitivity of the nonlinear plasmonic cavity modes to the changes of the parameters of the background medium, they are ideal candidates for nano-scale sensing devices, e. g., plasmonic sensors. This novel approach to sensing reveals that detection limits of 10-5 RIU can readily be achieved by using wavelength-sized plasmonic devices.

8236-42, Session 11

Developing horizontal slot disk resonators for optical biosensing and more

J. H. Shin, S. Lee, S. C. Eom, KAIST (Korea, Republic of)

Slot structures can achieve sub-wavelength scale photon confinement using dielectric materials only. This enables fabrication of resonators that combine high degree of energy concentration with high Q-factors, thereby providing an ideal platform for sensitive, label-free biosensing. Recently, we have shown how one can create a pedestal-type disk resonator with ultra-thin, ultra-smooth horizontal slots using selective etching. In this presentation, I will present recent results that show how such a horizontal structure may be further optimized for biosensing and more. By using multiple slots, and by carefully adjusting the number of slots, their widths, and their vertical location, it is possible to achieve higher surface sensitivity, but not bulk sensitivity. Indeed, for bulk-sensing applications, slot-resonators in general do not provide as great of an advantage. Furthermore, by adding Si nanocrystals, it is possible to obtain luminescence under non-resonant, vertical pumping such that optical modes may be observed without an externally coupled signal input. Introducing such Si nanocrystal layer into a horizontal slot structure is demonstrated, integration of further photonic components for increased functionalities will be discussed.

8236-43, Session 11

Silicon microring sensors

Z. Zhou, H. Yi, Peking Univ. (China)

Due to its closed-loop structure, the silicon microring resonator can have a very high quality factor value and its output intensity is very sensitive to different wavelengths. These characters, plus the potential in CMOS compatible fabrication process, are making the silicon microring resonator a key building block of photonic integrated circuits for the applications of filtering, switching, modulation, and wavelength conversion. In parallel, the silicon microring resonator has also been proposed as a compact and highly sensitive optical sensor. In recent years, microring sensing related research and development has been growing consistently and rapidly for the purposes of environment monitoring, health diagnosis, and drug development. This article will firstly review the recent development in silicon microring sensors, which are mainly concentrated in two areas: to improve the sensitivity and to enhance selectivity. In order to have better understanding of this class of sensors, the basic structure of the microring sensors, its working principle, and its unique properties will be described. Then, our own works, in particular, the methods to improve dynamic range, sensitivity, and stability of the silicon microring sensors, will be presented. By studying the fundamental optical properties of the coupled microring resonators, novel silicon microring sensors with better and more reliable sensing performance are constructed. Finally, through studying the interactions between chemistry and optics, acceleration and optics, the specific applications in glucose sensing and seismic sensing are discussed.

8236-44, Session 11

Silicon nitride microresonators for optical manipulation of microparticles and biosensing

A. W. Poon, H. Cai, T. Lei, Hong Kong Univ. of Science and Technology (Hong Kong, China)

Silicon photonics using microresonators are finding interesting applications in biosensing. In this paper, we will report our latest progress in this arena using silicon nitride (SiN)-based microdisk and microring resonators for on-chip optical manipulation of microparticles and refractive index sensing. SiN is of particular interest because of its transparency to visible and near-infrared light, relatively high refractive index contrast to water (~2.1:1.33) and compatibility with complementary metal-oxide-semiconductor (CMOS) process.

We will review our recent work using SiN waveguide-coupled microring (Cai et al. Optics Letters 35, 2855-2857, 2010.) and microdisk (Cai et al. CLEO 2011.) for dropping and trapping 1-micron-sized polystyrene particles using resonance-enhanced surface fields. In the case of microdisk resonator-based optical manipulation, we have observed microparticles guided along multiple tracks that are consistent with the whispering-gallery modes field distributions. Self-assembling of multiple microparticles on a microdisk has also been observed.

We will also review our recent work using SiN microdisk-based coupled-resonator optical waveguides (CROWs) as refractive index sensors in the spatial domain (Lei et al. CLEO 2011.). The sensing principle depends on measuring the out-of-plane scattering of the surface wave of the CROW mode-field distribution at a single wavelength within the CROW periodic passband. Our studies reveal that the CROW mode-field distribution at a single wavelength varies sensitively as a function of the refractive index change. Spatial Fourier analysis suggests that such a CROW sensor with sufficiently large number of coherently coupled resonators demonstrates superior functionality compared to conventional high-Q microresonator-based sensors. Proof-of-concept experiments will be discussed.

8236-45, Session 11

Giant sensitivity of coupled optofluidic active ring sensors

L. Xu, Fudan Univ. (China)

Whispering gallery (WG) mode resonators are good candidates for high sensitive bio and chemical sensors. The ratio of the WG mode effective refractive index change (Delta neff) and real environment refractive index change (Delta n), S=Delta neff /Delta n, determines the device sensitivity. In a tightly confined WG mode, S<<1. Many attempts have been made to produce larger proportion of evanescent field, and improved sensitivities to several hundreds nm/RIU. In addition, Coupled ring resonator (CRR) can enhance further the device sensitivity by so called Vernier effect. A CRR has two rings that have a little different sizes. A CRR has a sensitivity that is M=FSR/DeltaFSR times higher than a single ring resonator. Here FSR and Delta FSR are average free spectral range of the two rings and their difference respectively. If the two rings in a CRR have just a little different sizes, M can be very large.

In this paper, we report on ultrahigh sensitivity of a coupled optofluidic ring laser. The new sensor consists of one ring laser (master resonator) and one optofluidic tube (slave resonator). The optofluidic tube also serves as sensing element. Majority portion of the WG mode distributes in the tube, therefore S~1. Combining large M and S, very high sensitivity is expected. Experimentally, a sensitivity of 5930 nm/RIU was achieved, which is two orders of magnitude higher than conventional ring resonator sensors, and one order of magnitude higher than evanescent field engineered ring resonator sensors.

8236-46, Session 11

Optical microcavities: taking detection to the limit

F. Vollmer, Max Planck Institute for the Science of Light (Germany)

Photonic resonators have generated much excitement in the field of label-free biosensing where they promise ultimate single molecule detection capability - a dream of scientists and biotechnologist.

Great progress has been made in achieving this goal and I will review current approaches for sensitivity enhancements which include the use of hybrid photonic plasmonic modes, optical bistability in photonic crystal cavities, as well as disordered photonic crystal lasers.

8236-47, Session 12

On-chip whispering-gallery-mode lasers for sensing applications

L. He, S. K. Ozdemir, J. Zhu, W. Kim, L. Yang, Washington Univ. in St. Louis (United States)

Ultra-high-quality Whispering-Gallery-Mode(WGM) microresonators have shown great promise for ultra-sensitive and label-free chemical and biological sensing. By probing the surroundings using evanescent waves leaking out of a WGM resonator, ultra-sensitive detection of chemicals or molecules can be achieved by monitoring either frequency shift or linewidth variation of a resonant mode. In general, the linewidth of a resonant mode determines the smallest resolvable changes in the WGM spectrum, which, in turn, affects the detection limit. Despite the progress shown in the past few years on pushing the detection limit of resonators based sensors, there are some fundamental limits set by the resonators themselves, such as linewidth broadening due to material absorption introduced photon loss. We report a real-time detection method with single nanoparticle resolution that could surpasses the detection limit of existing micro/nano photonic resonant devices. This is achieved by using an on-chip WGM microcavity laser, whose linewidth is much narrower than its passive counterpart due to optical gain in the optical trajectory of the resonant lasing mode. In a WGM microlaser, the lasing line undergoes frequency splitting upon the binding of single nanoparticles. We demonstrate detection of polystyrene and gold nanoparticles as small as 15 nm and 10 nm in radius, respectively, and Influenza A virions by monitoring the changes in self-heterodyning beat note of the split lasing modes. The built-in self-heterodyne interferometric method achieved in the monolithic microlaser provides a self-referencing scheme with extraordinary sensitivity, and paves the way for detection and spectroscopy of nano-scale objects using micro/nano lasers.

8236-48, Session 12

Integrated whispering-gallery mode resonators for fundamental physics and sensing applications

R. Henze, Humboldt-Univ. zu Berlin (Germany); J. M. Ward, Humboldt-Univ. zu Berlin (Germany) and Cork Institute of Technology (Ireland); M. Gregor, Humboldt-Univ. zu Berlin (Germany); C. Pyrlik, A. Thies, A. Wicht, Ferdinand-Braun-Institut (Germany); A. Peters, Ferdinand-Braun-Institut (Germany) and Humboldt-Univ. zu Berlin (Germany); O. Benson, Humboldt-Univ. zu Berlin (Germany)

Whispering-gallery mode resonators have been studied for many years. Different systems, such as microsphere, microtoroidal, bottle or bubble resonators have been successfully demonstrated. A key issue for more complex experiments in quantum electrodynamics or for robust sensing devices is an efficient and reliable coupling technique.

In this contribution we discuss two approaches. One is tapered fiber coupling and the other is on chip integration. With the first system we introduced an all fiber coupled sensing concept and demonstrate gas sensing by measuring the thermal conductivity of the resonator's environment. With a sensitivity to thermal shifts of 3.8 GHz/K the system was capable to discriminate different mixtures of He and Ar, and at the same time provided a long-term stability with a frequency drift of less than 80 kHz/s.

The second system consists of a SiO_2 toroidal resonator integrated on a chip where coupling is achieved via integrated waveguide couplers. This configuration is particularly useful for frequency comb generation or for linear optical quantum computing (LOQC). We discuss the properties of the integrated device and show experiments where we couple single photons from nitrogen vacancy centers into the chip. A key goal here is the observation of two-photon interference at an integrated beam splitter. Further implementations of LOQC gates are introduced.

8236-49, Session 12

High-sensitivity and wide-directivity ultrasound detection using high-Q polymer micro-ring resonators

T. Ling, S. Chen, L. J. Guo, Univ. of Michigan (United States)

Microresonators can be used as ultrasonic detectors because their resonances can respond sensitively to the change in the effective refractive index of the guided optical mode. When acoustic pressure modulates the stress and strain in the waveguide, the change in strain results in geometric deformation which affects the effective refraction index of the guided mode. Due to its unique design and fabrication, ultrahigh Q factor polymer microring resonators with Q = 3.5×105 has recently been achieved, which provides high sensitivity with a noise equivalent detectable pressure (NEDP) value of 29 Pa, two orders of magnitude greater than any of other existing optoacoustic detectors. With a much broader bandwidth (>90 MHz at -3 dB), the microring resonators have a receiving sensitivity equivalent to or even higher than most commercially available PZT transducers. The high-Q polymer microring devices are fabricated by a scalable imprinting process with a prefabricated mold. By combining a resist reflow and a low bias continuous etching and passivation process in mold fabrication, imprinted polymer microrings with drastically improved sidewall smoothness were obtained. The surface roughness induced scattering loss was suppressed to a level that is smaller than the intrinsic absorption loss of the polymer material used for making the microring resonators. The device's wide acceptance angle with high sensitivity considerably benefits ultrasound-related imaging, e.g. photoacoustic microscopy application in imaging depth and axial resolution. An experimental demonstration will be presented with superior performance than results obtained using commercial piezo-transducers.

8236-50, Session 12

Fiber-optic resonator sensors based on comb synthesizers

G. Gagliardi, CNR, Istituto Nazionale di Ottica (Italy)

Over the past several years, fiber-optic resonators have been used as mechanical probes by virtue of their intrinsic sensitivity to length changes1 as well as chemical sensors2 based on direct or evanescent-wave absorption spectroscopy. In a recent work, we devised a diode-laser system for strain interrogation of a high-finesse fiber Bragg-grating cavity, achieving a 10-13 resolution in the infrasonic and acoustic frequency ranges, thanks to the exceptional stability of an optical frequency comb (OFC)3. A Pound-Drever-Hall (PDH) frequency locking technique is implemented for low-noise and wide dynamic range readout of the sensor keeping the interrogating laser always linked to the OFC reference. In this way, the low-frequency strain noisefloor is free from laser noise and possibly limited by thermodynamic phase fluctuations or other thermal effects in the fiber.

[1] J.H. Chow et al., Opt. Lett. 30, 1923, 2005

[2] H. Waechter et al, Sensors 10, 1716 (2010)

[3] G. Gagliardi et al., Science 330 (6007), 1081 (2010)

8236-51, Session 13

Hybrid optoplasmonic elements for ultrasensitive detection and information processing on the nanoscale

S. V. Boriskina, W. Ahn, Y. Hong, B. M. Reinhard, Boston Univ. (United States)

We will discuss the concept and applications of hybrid optoplasmonic elements, which combine sub-wavelength confinement of electromagnetic fields near plasmonic nanostructures with long photon dwelling times in high-Q photonic microcavities and thus enable active control over cascaded photon-emitter interactions over both short (nanometer-size) and long (up to hundreds of microns) length scales. We will show that embedding resonant photonic elements into nanoplasmonic circuits provides cascaded hot-spot intensity enhancement, strong wavelength selectivity and multiplexing capabilities, long distance energy transfer with subsequent sub-wavelength light re-focusing, adaptive switching of spatial light distributions on the nanoscale, and strong resonant manipulation of radiative rates of embedded emitters [1,2]. As photon re-cycling in photonic microcavities greatly enhances the sensitivity of light to small changes in their refractive index, dynamically re-configurable plasmonic structures can also be realized. Finally, we will highlight the opportunities of hybrid optoplasmonic structures as biosensing platforms that combine high sensitivity of plasmonic elements with high spectral resolution of high-Q microcavities and thus can feature improved detection limits as compared to individual photonic and plasmonic sensors [3].

1. S.V. Boriskina and B.M. Reinhard, Proc. Natl. Acad. Sci. 108 (8), 3147-3151 (2011).

2. S.V. Boriskina and B.M. Reinhard, to appear in Opt. Express, Focus Issue Collective Phenomena in Photonic, Plasmonic and Hybrid Structures (S.V. Boriskina et al Eds.) (2011).

3. M.A. Santiago-Cordoba, S.V. Boriskina, F. Vollmer, and M.C. Demirel, Appl. Phys. Lett. 15 Aug (2011).

8236-52, Session 13

Plasmon lasers and circuits

R. Ma, Univ. of California, Berkeley (United States); X. Zhang, Univ. of California, Berkeley (United States) and Lawrence Berkeley National Lab. (United States)

Plasmon lasers not only allow for the fundamental investigations towards the understanding and manipulation of strong light-matter interactions at the nanometre scale, but also enable the ultra-dense integration of photonic circuits with unprecedented operation bandwidth, processing speed and degree of functionality. I'll discuss recent progress of the plasmon lasers and circuits. The ultra-compact integrated circuits enabled by plasmon lasers simultaneously addressed several critical challenges of integrating a nano-scale laser into photonic circuits.

8236-53, Session 13

Fabrication of hybrid optoplasmonic microresonators for high-efficiency photonic-plasmonic mode coupling

W. Ahn, S. V. Boriskina, Y. Hong, B. M. Reinhard, Boston Univ. (United States)

Hybrid optoplasmonic structures that combine high-quality optical microcavity resonators and plasmonic nanostructures achieve much narrower linewidths of photonic modes than those of plasmonic resonances, which can improve sensing capabilities of a plasmonic sensor beyond its limits. In addition, photonic microresonators offer great opportunities for cascaded hot-spot intensity enhancement, long distance energy transfer, and adaptive switching of spatial light distributions. Meanwhile, plasmonic components in hybrid optoplasmonic microresonators generate high local E-field outside of the microresonators resulting in redistribution of light between plasmonic and photonic components and high efficiency mode coupling. Although theoretical researches have been spurred by the aforementioned advantages of hybrid optoplasmonic structures, robust fabrication strategies for practical realization of hybrid resonant optoplasmonic structures are still missing. Here we introduce a novel nanofabrication approach that enables a precise and controllable vertical and horizontal positioning of plasmonic elements relative to embedded microspheres by self-assembling microspheres on lithographically patterned, dry-etched surfaces. This approach ensures that the whispering gallery mode evanescent field and plasmonic mode interact synergistically at equatorial plane of the microspheres, which has been one of the greatest challenges of existing fabrication methods. We will also show high design flexibility of our template-assisted self-assembly approach for further performance optimization, and characterize its photonic-plasmonic mode coupling behavior through experimental spectroscopy, which will be supported by computational studies performed in our group [1].

[1] S.V.Boriskina & B.M.Reinhard, Proc. Natl. Acad. Sci. USA 108(8), 3147-3151 (2011).

8236-54, Session 13

Porous-wall hollow-glass microsphere as an optical microresonator for chemical vapor detection

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Optical microresonators have been proven effective for developing sensitive chemical and biological sensors by monitoring the changes in refractive index or mass near the resonator surface. The rotationally symmetric structures support high quality (Q) whispering gallery modes (WGMs) that interact with the local environment through the evanescent field. The long photon lifetime of the high-Q resonator (thus the long light-material interaction path) is the key reason that a microresonator can achieve very high sensitivity in detection.

In this paper, we present our recent research on using porous wall hollow glass microsphere (PW-HGM) as an optical microresonator for chemical vapor detection. The diameter of the PW-HGM ranges from 10μm to 100μm. The wall thickness is about 2μm and the pore size is about 20nm. The Q-factors and free spectrum ranges (FSR) of PW-HGMs with different diameters were measured by coupling light into the PW-HGM using a single mode fiber taper. Various types of chemical vapors were used to characterize the PW-HGM resonator. The resonant wavelength shift was measured as a function of vapor concentration. Comparisons between a PW-HGM and a solid glass microsphere indicated that a PW-HGM can effectively adsorb vapor molecules into its nano-sized pores, providing a direct and long light-material interaction path for significant sensitivity enhancement for chemical vapor detection.

8236-55, Session 13

ICLAS-based detection of low vapor pressure compounds using external cavity QCL and Fabry-Perot interferometer

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No spectral sensing method exists with sufficient sensitivity to detect vapors of low vapor pressure compounds, such as explosives. The opportunity is for ultra-trace molecular vapor recognition by Intracavity Laser Absorption Spectroscopy (ICLAS) at Mid-IR (MIR, 3-5 μm) and Long-Wave IR (LWIR, 8-12 μm) wavelengths. Objectives are to detect characteristic absorption signatures of ultra-trace vapors in the multi-mode emission spectra of external cavity IR quantum cascade lasers (QCL). We have conceived a compact field deployable system for IR spectral sensing of vapors that will be simple, low-power, man portable, and composed entirely of off-the-shelf components. An advantage is the exploitation of spectral signatures in an underutilized wavelength region, which is enabled by the unprecedented sensitivity. Benefits include the invention of a new spectral detection and analytic methodology for ultra-trace vapors. This methodology will be complementary to current methods in other wavelength ranges and, being faster and more sensitive than current technology, displace such technology in the MIR and LWIR ranges. Applications include military and commercial screening for threat compounds and contraband having very low vapor pressures. The key enabling technology for this LWIR ICLAS system is the multi-mode QCL with external cavity that allows infusion of target vapors as well as the Fabry-Perot spectrometer to measure multi-mode emission spectra at high resolution and in real time. This paper presents results of numerical solutions of laser rate equations of an 8.1 μm QCL that support feasibility of kilometer effective active-cavity path lengths and sensitivity to concentrations of 10 ppb.

8236-56, Session 14

Whispering gallery mode resonators as tools for non-linear optics and optomechanics

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The use of whispering gallery mode (WGM) resonators across a range of activities has become very popular during the last decade. These resonators can have many forms, such as toroidal, spherical, disk-like and bubble, and can be used as photonics devices such as miniature lasers, for sensing particularly with bio-applications, for demonstrating optomechanical effects, and in a profusion of other areas. In this presentation we will focus on the use of solid, microspherical resonators made from silica, with some reference made to other devices used within our laboratory. In a typical experiment, light is coupled into the WGM resonator using a tapered optical fibre with a waist diameter smaller than the wavelength of light propagating through it. The WGM resonator is generally attached to a thin stem for ease of manipulation during experimental investigations and we have taken advantage of this technique to produce a micropendulum device with a very low spring constant enabling us to use it for measuring optical forces and for demonstrating thermo-optical effects. The mechanical resonance frequencies of the pendulum evanescently-coupled to the tapered fiber have been determined and evidence of the optical force between the resonator and the fiber has been shown. In addition, we determine the power required in order to observe the optical force and illustrate how experiments conducted in vacuum remove some of the environmental factors that could lead to an apparent enhancement of the optical force effects.

8236-57, Session 14

Brillouin optomechanics

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

Brillouin scattering is now available in a triply-resonant microcavity to support mechanical and optical-Stokes modes that are excited from a single optical input. I will report on the experimental study of mechanical whispering gallery modes that are vibrating from 50MHz and up to 11 GHz rates.

8236-58, Session 14

Surface acoustic wave frequency comb

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We report on realization of an efficient triply-resonant coupling between two long lived optical modes and a high frequency surface acoustic wave (SAW) mode of the same monolithic crystalline whispering gallery mode resonator. The coupling results in an opto-mechanical oscillation and generation of a monochromatic SAW. A strong nonlinear interaction of this mechanical mode with other equidistant SAW modes leads to mechanical hyper-parametric oscillation and generation of a SAW pulse train and associated frequency comb in the resonator. We visualized the comb observing the modulation of the light escaping the resonator.

8236-59, Session 14

Micro-opto-mechanical damping and amplification in a waveguide-DBR microcavity

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Recent demonstrations of cavity opto-mechanical systems have utilized microtoroids, metallic cantilevers, and so-called zipper cavities. Many of these opto-mechanical systems require extensive alignment of off-chip optical components for probing and measurement, which limits their eventual integrability and manufacturability. In this work, we experimentally describe a new silicon-based opto-mechanical architecture incorporating a waveguide-DBR microcavity coupled to an in-plane microbridge resonator. This design enables large-scale integration on-chip with the ability to individually tune the optical and mechanical designs. We demonstrate both mechanical damping and amplification, depending on the sign of the detuning from the optical cavity resonance. We theoretically describe the cavity opto-mechanical interactions with a new model that takes into account both photothermal and radiation pressure in a distributed reflector microcavity. In addition, our data show a clear onset of coherent mechanical oscillations above a threshold optical power, accompanied by a collapse of the resonance linewidth. We describe this ``phonon lasing” with a newly-developed opto-mechanical oscillator theory that is analogous to classical laser theory with a well-defined threshold power, population inversion, acoustic gain, saturation power, and slope efficiency. These rate equations for opto-mechanical amplification show excellent agreement with our measured parameters across a number of different devices. The ability to either dampen or coherently amplify the motion of mechanical resonators is of interest for a variety of chip-scale high-resolution sensing approaches. We describe paths by which we believe our waveguide-DBR microcavity structures can achieve this goal.

8236-60, Session 14

Effects of spatial confinement of electromagnetic field on optical forces due to whispering-gallery modes

J. T. Rubin, L. I. Deych, Queen’s College (United States)

Considering the interaction between whispering gallery modes of a spherical resonator and a sub-wavelength polarizable particle, we demonstrate that spatial confinement of the electromagnetic field dramatically changes the character of optical forces exerted. In particular, we find that the part of the optical force proportional to the real part of the particle’s polarizability is no longer a conservative force, expressible as a gradient of the potential energy. This result is in contradiction with standard approach to optomechanical interaction between dipoles and cavity modes, which is based on Hamiltonian formalism. Moreover, we show that again in apparent contradiction with conventional wisdom, this part of the force acquires a component in the direction of the momentum flux of the whispering gallery mode. It is usually presumed that the force in this direction results from photon scattering, and is, therefore, proportional to the imaginary part of the polarizability. These results are obtained using rigorous Maxwell stress tensor calculations, which, in the case of spherical resonator, can be carried out analytically. We show that these phenomena result from modification of the field of the mode due to the dipole, which cannot be reduced simply to the renormalization of the resonance frequency. We apply these results to a nanoparticle optically engaged in orbital motion around the resonator. This effect was previously observed for a particle suspended in a solution. We show that it can be also realized in a rarefied atmosphere, where it can be used for experimental verification of the predicted properties of the force.

8236-61, Session 14

Evanescent light fields coupling effects and optical propelling of microspheres in water immersed fiber couplers

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A proposal that optical forces exerted on microspheres in evanescent light wave couplers can have strong resonant peaks is a relatively novel idea that can have profound consequences for sorting spherical cavities with extraordinary high size uniformity. Such precisely size-matched microspheres can be used for building photonic devices with strongly coupled whispering gallery modes (WGMs). It should be noted that realization of the size sorting requires a liquid environment where the spheres can be optically propelled. However, the reduced refractive index contrast in liquid significantly impairs the Q-factors of WGMs. In this work we developed evanescent wave couplers to microspheres with refractive indices n ranging from 1.47 to 2.1 and diameters d from 3 to 22 µm in liquid environment. Both tapered and side polished fibers were used. We demonstrated that in water environment Q-factors above 1,000 can be achieved for compact barium titanate glass (BTG) spheres with diameters d~4 µm and n~2 [1], which should be sufficient for observation of the resonances in the optical forces. Our preliminary experiments did show the presence of optical propelling effects in water immersed fiber couplers. In particular, we observed trapping of 15 µm polystyrene spheres by the evanescent field of the tapered fiber for the time interval of 1 second, and moving along the fiber for a distance of, approximately, 50 µm during this time. Currently, our efforts are directed towards observation of size selective optical forces.

[1] O.Svitelskiy et al., Opt. Lett. 36, in print (2011)

8236-74, Poster Session

Generalized model for beam-path variation in ring resonator and its applications in backscattering coupling effect

M. Chen, J. Yuan, X. Long, Z. Kang, Y. Li, National Univ. of Defense Technology (China)

A generalized model for beam-path variation analyzed with vector method is established. Beam-path variation means a change of beam-path geometry in ring resonator including not only optical-axis perturbation but also beam-path length and position of every point on beam path. The model can be applied to analyze beam-path variation in various ring resonators induced by all the possible perturbation sources. The generalized model is useful for the cavity design, cavity improvement, alignment of planar ring resonators, controlling the shape of laser beams and research on backscattering coupling effect. Backscattering coupling effect in square ring resonator as a decisive parameter of threshold of laser gyro has been chosen as an example to show its application. Backscattering coupling coefficient r is obtained as a function of mirror's axial displacements. Delta1, Delta2, Delta3 and Delta4 are axial displacements of spherical mirrors P1, P2 and planar mirrors P3, P4 in square ring resonator respectively. Some novel results of backscattering coupling effect have been acquired. The results indicate that r can not be reduced to zero because of the initial machining errors of terminal surfaces of plane mirrors. However, r can be reduced to zero almost when stabilizing frequency of laser gyro by modifying the machining errors of terminal surfaces of plane mirrors. These findings have been proved by experiment. A method for reducing R to minimal value by choosing appropriate values of Delta1, Delta2, Delta3 and Delta4 has been proposed. All those novel findings are important for high precision laser gyro.

8236-75, Poster Session

Performance of the smoothing of small target spots in frequency-tripled high-power laser

X. Jiang, Y. Li, Y. Zheng, Guangdong Univ. of Technology (China)

Uniform on-target irradiation is one of the key requirements in the researches of inertial confinement fusion(ICF), high-energy-density physics and plasma physics. Various beam smoothing methods have been proposed. Target spots of different sizes are demanded in different situations, for example, spots larger than 100 times of the far-field diffraction limitation (DL) of the focusing lens are needed in direct-drive researches, while the spots are generally 30-70 times of the DL in indirect-drive experiments. Most of the studies on beam smoothing are now focused on the large spots used for direct drive where severe constraints on target irradiation uniformity is demanded. However, in the indirect-drive approach, the beam should also be smooth enough to pass through the holes of the hohlraum target and generate x rays efficiently.

In this paper, it is studied the performance of the smoothing of small target spots with a lens array (LA) and the technique of two-dimensional smoothing by spectral dispersion (2-D SSD) in frequency-tripled high-power laser driver. LA can reduce the near-field nonuniformity of the beam and control the envelope of the target intensity distribution. 2-D SSD has obvious effects in eliminating high-contrast intensity modulation, even in the cases the spots are very small. Simulative results show that SSD works somewhat differently for spots of different sizes. For very small spots, SSD mainly smoothes the nonuniformity of low-to-middle spatial frequency, while for large spots, SSD sweeps the fine speckle structure to reduce nonuniformity of middle-to-high frequency. With the two methods, spots of clear envelopes can be obtained and intensity modulation of very short spatial wavelength can be smoothed out efficiently, and therefore performance of indirect-drive experiments is expected to be evidently improved.

8236-76, Poster Session

FDTD analysis of light storage in coupled micro-ring resonators

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Photonic coherent effects such as coupled-resonator-induced absorption (CRIA) and transparency (CRIT) have been investigated in coupled fussed-silica micro-resonators. Those effects are in direct analogy with the electromagnetically-induced absorption (EIA) and transparency (EIT) in driven three-level atomic systems. Coherently coupled micro-resonators are therefore promising for applications such as optical delay lines, buffers and gyroscopes utilizing observable properties of the systems such as slow light, storage and fast light. In this report, we demonstrate ways in which light can be stored in coupled micro-ring resonators using finite-difference time domain (FDTD) simulation. We consider a system consisting of a chain of identically coupled fussed-silica micro-ring resonators that couples one ring (the first) of the chain to a tapered fiber or excitation waveguide. The coupled light excites one of the resonant modes of the rings. We observe numerically that there is a "bottoms up" property in that light is "fully" stored first in the "bottom" resonator, being the furthest one from "gate" or the fiber coupling, after which light storage commences in other rings. In contrast with the intuitive extrapolation, light is not stored fully one by one from the bottom resonator up the first one, which is closest to the fiber coupling. There is a competition among the other rings to establish resonant modes in those rings. Light will be stored in those rings in which the resonant mode is fully established earliest. Other rings where resonant modes are never established then act as waveguides that connect the chain of ring resonators.

8236-77, Poster Session

About some possibilities of influencing the energetic relief of metals in order to favor micro-joining processes

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The energetic relief depends on the nature of the considered element which has its own internal energy, cohesion, structure and other characteristic parameters.

Former experiences has shown that we could appreciate how and when a metal part was cut, with the aid of an electron counter system - in a determined period of time.

To join or aggregate metal parts - or particles like powder - we must reduce or eliminate the influence and effect of the energetic relief between the considered parts or particles.

Different types of fields or energy may be applied in order to do that.

Authors experienced some kind of energies and studied the resulting plasma with the magnetohidrodynamic theory.

They found that the variation of plasma density and the intensity of the magnetic field appears in a time interval which is under - or comparable - with the wave lenght at this was the start point to develope further research.

The experiences were made with the aid of an original device.

Of course, after measuring and studying the main obtained data, authors have designed installation and devices, for industrial use.

One of the - economical - conclusion, was that is possible to influence the energetic relief in order to diminish costs of all type of aggregation processes, like sintering, welding a.s.o.

In the same time, the processing time, may be reduced.

ACKNOWLEDGEMENTS

Research conducted under project POSDRU 7706 Increasing the role of doctoral studies and doctoral competitiveness in a united Europe co-financed by European Social Fund through Sectoral Operational Programme Human Resources Development 2007 - 2013.

8236-78, Poster Session

Model for a partially coherent pump beam for an alkali laser

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

A pump beam is modeled as a superposition of mutually incoherent gaussian sub-beams. The gaussian sub-beams have finite frequency widths. The initial spatial width of each gaussian sub-beam corresponds to the spatial coherence width of the pump beam. The level population densitiy distribution of the alkali vapor atoms is determined from the total frequency dependent intensity of the pump beam. Light is absorbed from each sub-beam as it passes through the gas. The intensity and frequency distributions are calculated for examples for which the pump beam is brought to a line focus in the gas. The small-signal gain distribution is also calculated.

8236-62, Session 15

Nonlinearities in silicon photonics: something to exploit or to counteract?

A. Melloni, F. Morichetti, C. Ferrari, A. Canciamilla, Politecnico di Milano (Italy); M. Sorel, Univ. of Glasgow (United Kingdom)

In the 1550-nm wavelength range, in silicon (SOI) waveguides a plethora of non-linear phenomena can arise if the optical power is sufficiently intense, especially if microresonators are used.

The two main nonlinearities that affect the propagation are the two-photon absorption and free-carrier absorption and the Kerr effect.

The main impairments are the TPA-induced thermal effects producing a not rigid red-shift of the spectral response, but a resonance spread disrupting the frequency and time behaviour of the device. We demonstrate that an active thermal control of the individual resonators is a viable strategy to adaptively compensate for the intensity-dependent distortions, responsible for dramatic cross-talk increase in WDM filters.

Wave mixing inside optical resonators experiences a large enhancement of the nonlinear interaction efficiency. Here we show that by exploiting the concept of travelling-wave resonant four-wave mixing (FWM), both the efficiency and the bandwidth of the structure can be enhanced. Compared with bare waveguides, FWM exhibits higher robustness against chromatic dispersion and propagation loss, while preserving transparency to modulation formats. Travelling-wave resonant FWM has been demonstrated and was exploited to realize a 630-μm-long wavelength converter operating over a wavelength range wider than 60 nm and with 28-dB gain with respect to a bare waveguide of the same physical length. Full compatibility of the travelling-wave resonant FWM with optical signal processing applications has been demonstrated through signal retiming and reshaping at 10 Gbit/s.

8236-63, Session 15

Linear and nonlinear effects of electron paramagnetic resonance in high-Q cryogenic sapphire microwave resonators

M. E. Tobar, The Univ. of Western Australia (Australia)

Cryogenic sapphire resonators operating in Whispering Gallery Modes (WGM) have very high Q-factors at microwave frequencies of >10^9 due to the extremely low loss-tangent of sapphire. Such a property makes them useful for a host of applications, including a history of the construction of the most stable microwave oscillators for pulsing atomic clocks[1], fundamental physics tests[2] and VLBI[3]. This was only possible due to the inclusion of residual paramagnetic impurities, which annul the frequency-temperature dependence of sapphire. Consequently, these annulment points can occur anywhere between 10 K to tens of mK[4]. Based on this principle Pound stabilized oscillators have been built with fractional frequency stability of parts in 10^16 by temperature controlling to this annulment temperature[5]. More recently residual Fe^3+ impurities of ppb concentration within the lattice have been shown to create a three level system[6]. By matching a WGM to the third (31.3 GHz) and first level (12.04 GHz) and pumping at 31.3 GHz, a stable 12.04 GHz maser signal of parts in 10^14 has been created without any stabilization circuitry[7]. Also we have observed the fundamental thermal noise limit near 4 K by operating such masers in a bimodal configuration[8]. By annealing in air in one resonator, we have converted Fe^2+ ions to Fe^3+ ions from a ppb to 150 ppb. At this concentration we observe non-linear effects such as a degenerate four-wave mixing due to a third-order χ^(3) magnetic non-linearity as well as frequency comb generation9.

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8236-65, Session 15

The beam quality of self-phase modulated Gaussian beams

S. Mokhov, B. Zeldovich, L. B. Glebov, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

The divergence of an optical beam is often characterized by the parameter M2. For one transverse axis, this beam quality parameter is proportional to the product of the minimal observed beam size divided by the wavelength and multiplied by the divergence angle. Furthermore, M2 is normalized such that its minimum value equals unity, which is achievable only by a Gaussian beam having the smallest divergence and, as result, the best beam quality. An arbitrary phase distortion of a Gaussian beam increases M2. Self-phase modulation is a common distortion in which the phase difference varies across the beam aperture and is proportional to the beam intensity profile. For self-phase modulation, the deterioration of the beam quality parameter will depend on only one parameter, the phase at the center of the beam. We have found this dependence analytically. A general phase distortion profile can be represented by higher-order radial phase modes. We have also found the analytical dependence of M2 on amplitudes of these higher-order radial phase modes. In addition, we derived expressions for beam quality deterioration of super-Gaussian beams due to phase distortions. If waists of Gaussian and super-Gaussian beams are defined by residual power criterion, which means both beams outside the same radius have the same amount of residual power, then a super-Gaussian beam will better tolerate phase distortions. It is important that our results cannot be efficiently reproduced by the traditional approach, based on the polynomial representation of aberrations, due to poor convergence of power series for Gaussian profiles.

8236-66, Session 15

Ab initio theory of nonlinear effects in individual and coupled microdisk resonators

L. I. Deych, Queens College (United States)

Theoretical description of nonlinear properties of optical whispering gallery mode resonators presents specific challenges for theoreticians. In order to preserve a convenient description of nonlinear effects in terms of interacting modes of the linear system, one needs to reconsider the concept of modes in view of the open nature of the resonators. The situation is further complicated by the fact that the modes are usually excited by an outside field, and its correct incorporation into the modal picture is also not straightforward. In this talk we present a mathematically rigorous way to address these challenges and discuss possible consequences of their improper treatment.

More specifically, using microdisk resonators as an example, we introduce modes of a single resonator as a system of biorthogonal functions, which satisfy outgoing boundary conditions at infinity while retaining their constant (non-diverging) flux. Coupling of these modes to the outside radiation is described using Green's function approach, which allows us to derive a system of coupled equations for modal amplitudes for both, the single and coupled resonator configurations. We also discuss the physical nature of so called "evanescent" coupling and its relation to the radiative leakage (either directly or via roughness induced scattering) of the modes as oppose to its non-radiative absorption.

The derived equations are used to analyze self-trapping phenomena and Josephson oscillations in the system of two coupled disk resonators. The analysis reveals existence of the transition between these two regimes and the phenomenon of anomalous relaxation in presence of imbalance between individual radiative rates of the disks.

8236-80, Session 15

Characterization of picosecond pulse trains from a microresonator optical frequency comb

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

Microresonator optical frequency combs present a unique platform for numerous applications which are enabled by large comb line spacings, heterogeneous optical integration, and efficient low power operation. Using disk-like fused-quartz microresonators, we generated an optical frequency comb with 36 GHz mode spacing at 1560 nm. By addressing the amplitude and phase of individual comb lines we observed near transform-limited 2.5 ps waveforms. Frequency-domain measurements of the comb's line spacing fluctuations and progress toward controlling the comb's mode spacing and offset frequency will also be reported.

8236-64, Session 16

Hybrid microspheres for nonlinear Kerr switching devices

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In this paper, we demonstrate the first evidence all optical switching of WGM resonances excited in silica microspheres based on third order Kerr non-linearity in a thin cladding polymer layer. For this work, we have chosen as a Kerr-material a polyfluorene derivative, PF(o)n, functionalised at the C9 position of the fluorine ring with two pendant octyl chains for attaining adequate solubility in common organic solvents and mesogenic behaviour. The nonlinear coefficients of this material are obtained with Z-scan technique. The measured n2 and □□coefficient are n2 = 0.2□10-11 cm2/W and □□□□7□10-7 cm/W.

NIR pumping at 780 nm in pulsed laser regime is used for non-linear switching of the WGM resonances that shift as much as 2 GHz for 50 mW of average pump power. This shift is one order of magnitude higher than in the CW optical pumping case, showing a clear discrimination of □(3) related detuning at room temperature. The absence of temporal drift and the magnitude of this shift confirm the Kerr nature of the switching, ruling out thermooptical effects. We have estimated roughly the n2 value of the PF(o)n coating, neglecting the thermal effects and taking into account the stretched pulses after fiber propagation, the repetition rate and the maximum frequency shift, □=500 fs, □= 82 MHz and 2.1 GHz, respectively. The obtained value is about 0.3□10-11 cm2/W, which is in good agreement with the experimental value obtained from the z-scan experiment n2 = 0.2□ 0-11 cm2/W1.

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8236-67, Session 16

Spherical resonators coated by glass and glass-ceramic films

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Glass ceramic activated by rare earth ions are nanocomposite systems that exhibit specific morphologic, structural and spectroscopic properties allowing to develop interesting new physical concepts, for instance the mechanism related to the transparency, as well as novel photonic devices based on the enhancement of the luminescence. At the state of art the fabrication techniques based on bottom-up and top-down approaches appear to be viable although a specific effort is required to achieve the necessary reliability and reproducibility of the preparation protocols. In particular, the dependence of the final product on the specific parent glass and on the employed synthesis still remain an important task of the research in material science. Looking to application, the enhanced spectroscopic properties typical of glass ceramic in respect to those of the amorphous structures constitute an important point for the development of integrated optics devices, including coating of spherical microresonators. This lecture presents spherical microresonators coated by glass and glass-ceramic film undoped and activated by rare earth ions. Er3+ ions appear to be embedded in a crystalline or amorphous environment and the lifetime dynamic is influenced by the geometry and by the morphology of the system. The AFM images show structures that are assigned to growth of nanocrystals.

8236-68, Session 16

Coherent spectroscopy of rare-earth-ion doped whispering-gallery-mode resonators

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Rare-earth-ions are interesting systems for studying with respect to quantum information processing. This is due to their long optical and hyperfine coherence times. Using ensembles it has been shown that rare-earth-ions satisfy four of the five DiVincenzo criteria, leaving a qubit-specific measurement capability as the major remaining challenge for scalable quantum computing. The ability to detect a single rare-earth-ion would enable this to be achieved.

One approach to single site detection is cavity QED. Crystalline whispering gallery mode (WGM) resonators are a logical as the favourable coherent properties of the rare ion dopants depend on a crystaline host.

As a first step towards performing strong coupling cavity QED experiments using rare-earth-ions, we have measured properties of the ions in a Pr^{3+}:Y$_2$SiO$_5$ WGM resonator. The atom-cavity coupling has been measured using photon echos, and by modelling of optical bistability in the resonator. These measurements are shown to be in good agreement with that calculated from the theoretical mode volume of the cavity.

It is important to consider whether the process of making the resonator has altered the properties of the ions in any way. To this end we have used two pulse photon echos, stimulated photon echos and accumulated photon echos to measure the coherence time (T_2), population lifetime (T_1) and the hole lifetime of the ions in the resonator. These measurements are compared to the properties of ions in a bulk Pr^{3+}:Y$_2$SiO$_5$ crystal. Small differences are measured which we attribute to variations in temperature between the resonator and bulk crystal.

8236-69, Session 16

Composite micro-sphere optical resonators for electric field measurement

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Polymer based multi-layer spheres are investigated for high-resolution electric field sensors. The external electric field induces changes in the morphology of the spheres leading to shifts in the whispering gallery modes (WGM). Light from a distributed feedback (DFB) laser is side coupled into the microspheres using a tapered section of a single mode optical fiber to interrogate the optical modes. The base material of the triple-layer spheres is polydimethylsiloxane (PDMS). The core is 60:1volume ratio of PDMS-to-curing agent mixture that is coated by a thin layer of 60:1 PDMS that is mixed with varying amounts of barium titanate nano particles. The outermost layer is again a thin coat of 60:1 PDMS which serves as the shell waveguide. Light from the tapered laser is coupled into this outermost shell that provides high optical quality factor WGM (~ 10^6). The microspheres are poled for several hours at electric fields of ~ 1 MV/m to increase sensitivity to electric field. Preliminary results show that electric fields of the order of ~ 100 V/m can be detected using these composite micro-resonators.

8236-70, Session 17

Coupled micro-cavities with Vernier effect for lasers and sensors

J. He, Zhejiang Univ. (China)

Designs and experimental results of coupled micro-cavities for laser and sensor applications are presented, including novel V-coupled cavities for digitally wavelength switchable laser and intra-cavity laser sensing, and cascaded micro-ring resonators for waveguide sensors. The Vernier effect is used to increase the tuning range of the laser and the sensitivity of the waveguide sensors. By using a novel half-wave coupler design in V-coupled cavity laser, a side-mode suppression ratio as high as 40dB is experimentally demonstrated. Digital wavelength switching over 26 channels with 100GHz spacing is achieved using a single electrode control. Compared to distributed feedback lasers and widely tunable laser based on sampled gratings, the V-coupled cavity laser does not require multiple epitaxial growths and complex grating structures. It has advantages of compactness, fabrication simplicity, and operational simplicity for wide wavelength tuning. An intensity interrogated intracavity laser sensor based on the V-coupled cavity is also proposed and analyzed. By simply detecting the power ratio of two output ports, a refractive index sensitivity in the order of 10-8 RIU can be achieved thanks to the intracavity sensing mechanism and the Vernier effect. An intensity interrogated passive waveguide sensor based on two cascaded microring resonators with Vernier effect is also demonstrated experimentally.

8236-71, Session 17

Longitudinal mode selection in laser cavity by moiré volume Bragg grating

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The use of ultra-narrowband spectral filters in single frequency, high-power lasers is of particular interest in recent years. The most common methods for achieving such filtering are Fabry-Perot Etalons (FPE) or fiber based π phase shifted gratings. Of these methods, only the FPE has been demonstrated for use in free space. We present a free space, π phase shifted grating for longitudinal mode selection of laser cavities. This filter was fabricated in photo-thermo-refractive (PTR) glass which, due to its excellent optical homogeneity and high-power damage threshold, can be used in high power laser systems. The approach for creating such filters uses a two-step holographic recording which generates two collinear reflecting Bragg gratings with slightly shifted periods to create a moiré volume Bragg grating (MVBG). The resulting structured grating consists of a moiré pattern, i.e. a high spatial frequency refractive index modulation with a low frequency envelope where the null points of the envelope correspond to π phase shifts. We first present a detailed investigation of the fundamental operating principles of MVBGs, including design curves. We then show methods for determining the axial grating profile and demonstrate a MVBG with a 15pm bandwidth and 90+% transmission at resonance. The MVBG as a longitudinal mode selector in a laser cavity is demonstrated, with performance comparable to a conventional FPE of similar bandwidth. Due to its nature, such filter should allow bandwidths below 5 pm over a few millimeters aperture, therefore securing single frequency operation.

8236-72, Session 17

Beam tapering effect in microsphere chains: from geometrical to physical optics

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Chains of microspheres can be considered as waveguides with periodical focusing properties. An interesting property of such structures is connected with gradual reduction of the lateral dimensions of the focused beams. Such “beam tapering effect” was first observed for mesoscale spheres with $D/\lambda \sim 6$, where D is the sphere diameter and λ is the wavelength. Recently we performed a comprehensive study of this effect in the limit of geometrical optics ($D/\lambda >> 10$). This study revealed that the beam tapering effect is much stronger pronounced in mesoscale spheres compared to the predictions of geometrical optics. The origins of this effect in mesoscale case can be connected with the interference and diffraction effects in spheres as well as with a possibility of developing microjoints connecting polystyrene spheres as a result of a material reflow process. In this work we performed a comprehensive study of this effect in chains of polystyrene spheres with diameters ranging from 0.9 to 300 µm at the wavelengths of visible light. We created microjoints using slowly evaporating aqueous necks. The optical study of such chains as a function of time provided a direct prove that the microjoints connecting the spheres dramatically facilitate the beam tapering effects. The transition from geometrical to physical optics was directly observed in completely dried chains for sphere diameters below 10 µm. It is shown that mesoscale spheres also have very small total power loses that make them ideally suitable for applications requiring focusing of multimodal beams.

8236-73, Session 17

Accurate analytical estimates of eigenfrequencies and dispersion in whispering-gallery spheroidal resonators

M. Gorodetsky, Lomonosov Moscow State Univ. (Russian Federation)

In several applications of optical whispering-gallery resonators, in particular for Kerr frequency comb generation, a possibility to calculate accurately the eigenfrequencies and their geometry dependent dispersion is an important prerequisite for device optimization.

While these calculations with significant time consumption may be performed numerically, analytical approximation are still quite desirable for theoretical considerations. Spheroidal geometry can fit the form of most types of whispering gallery resonators that are in use today. We propose and check numerically new accurate approximations for the frequencies and geometrical dispersion of fundamental and transversal modes of oblate and prolate spheroids using both the eikonal approximation and Helmholtz equation analysis. We also suggest approximations for the distribution of optical fields in a spheroidal resonator.

8236-79, Session 17

Silicon photonic resonator sensors and devices

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Silicon photonic resonators, implemented using silicon-on-insulator substrates, are promising for numerous applications. The most commonly studied resonators are ring/racetrack resonators. We have fabricated these and other resonators including waveguide-grating resonators, ring resonator reflectors, contra-directional grating-coupler ring resonators, and racetrack-based multiplexer/demultiplexers.

While numerous resonators have been demonstrated for sensing purposes, it remains unclear as to which structures provide the highest sensitivity and best limit of detection; for example, disc resonators and slot-waveguide-based ring resonators have been conjectured to provide improved sensitivity. Here, we compare various resonators in terms of sensor metrics for label-free biosensing in a microfluidic environment. We have integrated resonator arrays with PDMS microfluidics for real-time detection of biomolecules in experiments such as antigen-antibody binding reaction experiments using Human Factor IX proteins. Numerous resonators are fabricated on the same chip and experimentally compared. We identify that, while evanescent-field sensors all operate on the principle that the analyte’s refractive index shifts the resonant frequency, there are important differences between implementations that lie in the relationship between the optical field overlap with the analyte and the relative contributions from the various loss mechanisms.

The chips were fabricated in the context of the CMC-UBC Silicon Nanophotonics Fabrication course and workshop. This yearlong, design-based, graduate training program is offered to students from across Canada and, over the last four years, has attracted participants from nearly every Canadian university involved in photonics research. The course takes students through a full design cycle of a photonic circuit, including theory, modeling, design, and experimentation.

Conference 8237: Fiber Lasers IX: Technology, Systems, and Applications

Monday-Thursday 23-26 January 2012

Part of Proceedings of SPIE Vol. 8237 Fiber Lasers IX: Technology, Systems, and Applications

8237-01, Session 1

Beam combination of kilowatt fiber amplifiers

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

There has been significant recent progress in achieving multi-kilowatt output power from a near-diffraction limited single fiber. Some applications, however, require much higher power, and research continues into methods for combination of many kilowatt fiber beams while maintaining aggregate beam quality. These methods include coherent combination of phased tiled arrays or whole beams, and spectral beam combination. The beam combination methods have varying implementation and performance features, sensitivities, and considerations; most notably frequency, phase, and fiber array stability; linewidth; and power/thermal tolerance of combining optics. Fundamental and practical limitations on combination efficiency and beam quality, along with potential approaches to further develop these methods, are also discussed.

8237-02, Session 1

Phase-locked multi-core photonic crystal fiber laser by end-sealing

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Coherent beam combining of fiber lasers is the important subject for power and energy scaling. Multi-core fiber, in which multiple single-mode gain cores are built in a single fiber format and evanescently coupled with each other, has been extensively investigated. However, since there are as many supermodes as cores, exciting only the in-phase supermode is the key issue for brightness scaling. The mode selection method widely used is an external Talbot resonator working in a free space. By splicing a multimode fiber, an all-fiber method was also reported.

We have proposed and investigated truly monolithic phase-locking architecture, end-sealing a multi-core photonic crystal fiber. It involves a lot of advantages. The self-imaging in the seal gives the in-phase mode selection without diffraction loss and hence highly efficient laser operation is enabled. It is very robust, and enables us to develop more compact and reliable systems. The side lobes at the far-field beam profile, which is an inherent problem in tiled-aperture coherent beam combining, can be suppressed dramatically because the air holes collapse gradually and the fill-factor enlarges adiabatically. Phase locking of a large-mode-area Yb-doped 6-core fiber laser, with as high as 77% central-lobe fraction (twice higher central-lobe fraction than that (36.6%) given by the intrinsic core arrangement), 84% slope efficiency, was successfully demonstrated. Q-switched, phase-locked operation has also been obtained delivering 100ns pulses with 280uJ energy, 20kHz repetition rate, and 62% slope efficiency. The details and future prospects will be presented at the conference.

8237-03, Session 1

Coherent and spectral beam combining of fiber lasers

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State-of-the-art diffraction-limited fiber lasers are presently capable of producing kilowatts of power. Power levels produced by single elements are gradually increasing but beam combining techniques are attractive for rapidly scaling fiber laser systems to much higher power levels. We discuss both coherent and spectral beam combining techniques for scaling fiber laser systems to high brightness and high power. Recent results demonstrating beam combination of 500-W commercial fiber laser amplifiers will be presented.

8237-04, Session 1

Multiplexed volume Bragg gratings for spectral beam combining

I. B. Divliansky, D. Drachenberg, V. Rotar, G. Venus, L. B. Glebov, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

The recent development of kW class fiber lasers makes the conception of laser systems operating at power levels from tens of kilowatts up to 100-kilowatt levels a reality. The use of volume Bragg gratings for spectral beam combining is one of the promising approaches to achieve that goal. To make such systems compact, lower the complexity and minimize the induced thermal distortions we propose and demonstrate the use of spectral beam combining by complex diffracting elements which have several volume Bragg gratings (VBGs) written inside. The multiplexed VBGs were recorded in photo-thermo refractive glass and laser beams with wavelength offset of 1 nm were successfully combined with efficiency of 98% and no significant beam quality degradation. Thermal experiments were also performed in order to investigate the detuning from Bragg condition and beam quality change at higher thermal loads resulted from absorption of high power laser radiation. The results demonstrated that the approach of using multiplexed volume Bragg gratings for spectral beam combining is excellent extension and alternative to the current state of the art combining techniques. Especially valuable is the capability to reduce the number of optical elements in the system and still be able to manage the expected thermal load when kilowatt level sources are used for beam combining.

8237-05, Session 1

Spatial chirp-precompensated high density spectral beam combining

E. C. Cheung, J. Ho, T. S. McComb, S. Palese, Northrop Grumman Aerospace Systems (United States)

A method for spectrally combining a large number of lasers with very closely packed wavelengths is introduced. By way of spatial chirp-precompensation of individual pre-combined beams we demonstrate 80% spectral utilization and theoretically show the potential to approach 100% spectral utilization without beam quality degradation. The beam quality of the individual laser channels becomes the limiting beam quality for the spectrally combined system. Several proof of principle experiments are conducted, showing the utility of our method compared to other spectral beam combination techniques in terms of the maximum allowable bandwidth of individual channels, channel packing density and combining efficiency. We also demonstrate a compactly packaged MW class peak power pulsed fiber laser system using photonic crystal fiber rods with 0.15 nm wavelength spacing and near diffraction limited beam quality. The compactly packaged spectral combiner portion of the laser system is realized by way of all-reflective optics including mirrors and diffraction gratings. Direct scalability to efficient combination of 100's of densely packed kW class average power spectral channels within the gain bandwidth of Yb:fiber lasers in a relatively compact footprint is discussed. This technique is also not limited to use at Yb wavelengths and is equally applicable to spectral combination at other rare earth fiber laser wavelengths.

8237-36, Session 2

Coherently phase locked high pulse energy fiber amplifiers

S. Palese, E. C. Cheung, F. Di Teodoro, T. S. McComb, C. C. Shih, M. Weber, M. Hemmat, Northrop Grumman Aerospace Systems (United States)

There is strong interest in the use of pulsed fiber sources for active sensing, ladar and material processing applications due to advantages in electrical efficiency, packaging benefits and wider waveform flexibility compared to bulk solid state lasers. Significant effort has been devoted to pushing the energy limits of individual pulsed fiber amplifiers, producing multi-mJ pulse energy and multi-MW peak power through novel fiber designs which increase mode areas while maintaining beam quality. Producing higher energies from a single fiber is becoming more challenging as these techniques have pulse energy limitations. A promising method for energy scaling of fiber laser sources is the coherent beam combination (CBC) technique. In this method, an array of lasers is actively phase-locked and combined into a single beam with brightness substantially greater than the individual array elements, especially interesting for applications requiring extreme spectral brightness unattainable with spectral beam combination techniques. Here we report active coherent phase locking of high peak power (up to 1.5 mJ/pulse @ 1ns FWHM) fiber-based MOPAs featuring large mode area Yb-doped fibers as power amplifiers. This talk provides an overview of the fundamental sources of non-linear chirp that complicate active phasing for pulsed architectures, phase compensation schemes to correct interpulse and intrapulse distortions and factors influence maximum channel count. The phase noise spectrum relative to an ultra-stable CW reference source and phasing fidelity measurements for mJ level pulse energies are presented. Our results point to CBC as one promising method for scaling pulse energy beyond that achievable from single fibers.

8237-37, Session 2

Coherently combined fiber CPA system delivering 3-mJ femtosecond pulses

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The use of spatially separated amplification stages for ultrashort laser pulses and the coherent combination of the individual emissions appears as a very promising concept to achieve a higher performance compared to a single amplifier system. The experimental setup consists of a femtosecond oscillator, a grating stretcher and a pre-amplifier system as the seed source for two main laser amplifiers in a Mach-Zehnder type interferometer. The splitting of the pulses for the seeding and the recombination after amplification is carried out with polarization dependent beam-splitter cubes by using the polarization combining concept. The active stabilization of the optical path lengths in the interferometer was realized with a Hänsch-Couillaud locking system. The main amplifiers consisted of diode pumped rod-type fibers with a mode-field diameter of about 75µm. Following amplification and combination, the pulses were recompressed using a grating compressor to pulse durations as short as 470fs. A combined and compressed pulse energy of up to 3mJ could be achieved resulting in a peak power close to 6GW. The combining process itself could be realized with efficiencies of up to 90%, which is comparable to previous results with this type of fiber at lower pulse energies and average powers proving the scalability of the concept. In a similar setup at higher repetition rates we could realize an average power of 88W. In summary, the obtained results show that coherent combining is a promising concept for even further performance improvements of fiber based and also non-fiber based laser systems.

8237-38, Session 2

Passive coherent beam combining of two femtosecond fiber chirped-pulse amplifiers in a Sagnac geometry

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In this contribution, we report on the passive coherent beam combining of two femtosecond fiber chirped-pulse amplifiers. For the last few years, active coherent beam combining setups have been demonstrated in CW, and very recently in nanosecond and femtosecond regime with two fiber amplifiers. High efficiencies have been obtained while retaining the temporal, spectral and spatial properties of the pulses to combine. However, the active feedback loop involved in the phase stabilization requires building complex architectures and is also very sensitive to strong environmental perturbations. The scheme presented in this paper performs passive coherent beam combining without any phase control element. This is achieved by using a Sagnac interferometer that allows two beams to travel the exact same path with opposite propagation directions. The phase-matching between both channels is automatically performed and robust to thermal and acoustic noises. The setup is experimented in linear regime with two fiber amplifiers inserted inside the interferometer. 10 W of uncompressed average output power are obtained, with a combination efficiency of 96% and a preservation of the pulse qualities with 250 fs duration. A comparison with a standard two-stage amplifying scheme at the same power level confirms the advantage of the combining scheme, showing stronger pulse distortions due to self-phase modulation in the standard arrangement. In nonlinear regime, the combination efficiency remains acceptable, with 84% at a B-integral of 12 rad. Passive coherent beam combining of amplifiers supresses the need for phase control electronics and can be extended to more than two amplifiers.

8237-39, Session 2

Active coherent combining of multiple parallel femtosecond-pulse CPA channels

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Femtosecond pulses from fiber chirped-pulse amplifier systems are limited in energy to approximately the millijoule level, with insignificant prospects of achieving substantially larger energies by simply increasing fiber core size. However, orders-of-magnitude increase in pulse energy is necessary to access emerging applications associated with high-intensity laser-plasma interactions, such as laser-plasma accelerators, laser wakefield X-ray generation, etc. Coherent combining of multiple fiber-CPA channels offers a way to reach high pulse energies, with practicality of the approach critically hinging on the ability to monolithically integrate fiber-based systems. Recent published results demonstrate coherent combination of two free-space ultrashort-pulse fiber laser channels. Here we experimentally explore active coherent combining of multiple femtosecond-pulse channels in a monolithic fiber CPA array to determine scalability of this approach to large parallel-channel arrays. Combining multiple channels requires carefully matching the spatial and temporal properties (e.g. dispersion, path length, wavefront, nonlinearity) for each channel individually. Each channel in the array includes specially designed micro-optic delay lines to achieve exact optical path matching between parallel amplifiers. Phase locking between the channels have been implemented through fiber-optic piezo-stretchers, providing up to 384π of continuous phase control. With three and four combined parallel-CPA channels we have achieved combining efficiencies between 87% and 93%. Compressed pulses are bandwidth-limited and shorter than 600fs, the same as for the single channel compressed pulses. Experiments also revealed critical importance of maintaining identical dispersion as well as nonlinear phases in all parallel amplification channels. In an ongoing work we are increasing the number of coherently combined femtosecond-pulse channels.

8237-40, Session 3

Thermally induced mode instability in high power fiber amplifiers

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We developed a beam propagation model for high power fiber amplifiers that includes a refractive index grating induced by interference of two propagating transverse modes with offset frequencies. Because the grating moves along the fiber, it has a phase shift relative to the co moving optical interference pattern. This phase shift allows power coupling between the modes caused by the index grating. Observations from several laboratories indicate there is a sharp power threshold above which light in the fundamental mode can transfer to higher order modes. Further there is sometimes an oscillatory behavior near this threshold with a frequency that approximates the inverse of the thermal diffusion time across the core, suggesting a thermal origin. If the pump level exceeds the instability threshold, the transfer of light out of the fundamental mode can be complete. Our model replicates all of these features, but detailed quantitative comparisons between model and experiment are still under way.

8237-41, Session 3

Temporal dynamics of mode instabilities in high power fiber amplifiers

H. Otto, F. Stutzki, F. Jansen, Friedrich-Schiller-Univ. Jena (Germany); T. Eidam, Friedrich-Schiller-Univ. Jena (Germany) and Helmholtz-Institute Jena (Germany); C. Jauregui, Friedrich-Schiller-Univ. Jena (Germany); J. Limpert, Friedrich-Schiller-Univ. Jena (Germany) and Helmholtz-Institute Jena (Germany); A. Tünnermann, Friedrich-Schiller-Univ. Jena (Germany) and Helmholtz-Institute Jena (Germany) and Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

In order to increase the average output power extracted from state-of-the-art high power fiber lasers and amplifiers beyond the existing limits it is necessary to investigate in detail their limiting mechanisms. These fundamental experiments are the base for future approaches to overcome the limitations. One of the most detrimental effects that has been recently published is the threshold-like onset of transversal mode instabilities. Beyond a specific level of average output power, the initially stable fundamental mode operation of the fiber amplifier is switched to a chaotic regime, where the power contents and relative phase of several transversal modes are fluctuating rapidly with time. In order to experimentally investigate this phenomenon we used a high-resolution, high-speed camera to temporally resolve the mode instabilities on a sub-millisecond time scale. We investigated the behaviour of mode instabilities in different active photonic crystal fibers with varying core diameters. To analyze the observed mode instabilities we applied Fourier analysis to the recorded data. Thereby we could obtain characteristic time constants for this effect. It can be seen that the larger the core diameter, the slower the mode instabilities are fluctuating with time. Furthermore, we used an intensity distribution based modal reconstruction method to estimate the power transfer between the involved modes. The results of our investigations support the thesis that the origin of the mode instabilities is the thermal load induced in the fiber during the amplification process.

8237-42, Session 3

On the thermal origin of mode instabilities in high power fiber lasers

C. Jauregui-Misas, T. Eidam, H. Otto, F. Jansen, F. Stutzki, J. Limpert, A. Tünnermann, Friedrich-Schiller-Univ. Jena (Germany)

The threshold-like onset of mode instabilities in high average power fiber laser systems has rapidly become one of the most limiting effects for a further power scalability of these systems. Therefore, the understanding of its physical origin is of capital importance to find ways to overcome this effect. In the past we have shown that mode interference in few-mode LMA fibers can, via inversion or temperature induced index change, indirectly generate an index grating with exactly the right period to transfer energy between the interfering modes. Further simulations and experimental evidence strongly point towards the thermal origin of this index grating. In this contribution we make some detailed simulations of the temperature profile inside of a LMA fiber in high power operation in which two modes have been excited in the fiber core. These simulations show that the pump power is not homogeneously absorbed along the fiber, but its absorption varies periodically with the beat period of the interfering modes. In turn this periodically varying absorbed power gives rise to a longitudinally oscillating temperature profile along the fiber, which is then transformed in an index grating through the temperature dependence of the index of refraction. It can be shown that the temperature can change in the fiber core by more than 10°C within only a few centimetres of fiber. Consequently, this will give rise to a strong longitudinal heat flow that might provide the required mechanism to couple energy between the interfering modes.

8237-43, Session 3

High power extraction from very large mode area fibers approaching MFDs of 100µm

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

In order to overcome the limitations imposed by nonlinear effects in ultra-short high power fiber laser systems, the mode field diameter (MFD) of effectively single-mode active fibers requires further scaling. Up-scaling the MFD makes these fibers extremely sensitive to waveguide changes. Presently, power-dependent waveguide changes are neglected in high power fiber lasers. However, in very large mode area fibers with MFDs well beyond the 50µm size even small waveguide changes can have a dramatic impact in the fiber modes. Thus, power-induced, i.e. temperature-induced, waveguide changes in active very large mode area fibers manifest themselves in two effects: mode shrinking and dynamic changes of the mode set. Mode shrinking comes as a result of a temperature-induced parabolic index profile that can no longer be neglected. This shrinking may amount to a significant percentage of the MFD in very large mode area fibers above 100µm MFD. The dynamic change of the mode set implies that, depending on the pump power, the modes of the fiber can look very differently due to resonant effects. In large-pitch photonic crystal fibers these resonant effects are mainly avoided crossings. Pumping these fibers leads to a power-dependent index change in the range of at least 2E-05, experimentally determined by taking advantage of these avoided crossings.

We study these thermal effects in ultra-short high power fiber laser systems, both experimentally and numerically, using two large pitch fibers with MFDs of 70µm and >100µm, respectively. Potential ways to reduce the sensitivity to these thermal effects will be discussed.

8237-25, Session 4

High-power disk and fiber lasers: a performance comparison

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The Performance of High Power Disk Lasers and Fiber Lasers along with their rapid development to the high power cw regime have been of great interest throughout the last decade.

Both technologies are still in the focus of several conferences, workshops, and papers and represent the “state-of-the-art” of industrial high power solid state lasers for material processing. As both laser concepts are considered to be the leading 1µm light-source, this presentation gives a fair comparison of the two different technologies from a manufacturer who pursued both.

From the geometry of the active material through the resonator design, cooling regime, and pumping method to the point of beam quality and power scaling, the different approaches associated with the advantages, challenge, and limits of each technology will be highlighted.

Based on ROFIN’s substantial industrial experience with both laser concepts, an outlook into future trends and chances, especially linked to fiber lasers, will be given.

8237-26, Session 4

High-power disk lasers: advances and applications

D. L. Havrilla, T. S. Ryba, TRUMPF Inc. (United States); M. Holzer, TRUMPF Laser- und Systemtechnik GmbH (Germany)

Though the genesis of the disk laser concept dates to the early 90’s, the disk laser continues to demonstrate the flexibility and the certain future of a breakthrough technology. On-going increases in power per disk, and improvements in beam quality and efficiency continue to validate the genius of the disk laser concept. As of today, the disk principle has not reached any fundamental limits regarding output power per disk or beam quality, and offers numerous advantages over other high power resonator concepts, especially over monolithic architectures.

Fast approaching 2,000 high power disk lasers installations, with demand upwards of 1,000 lasers per year, the disk laser has proven to be a robust and reliable industrial tool. With advancements in running cost, investment cost and footprint, manufacturers continue to implement disk laser technology with more vigor than ever.

This paper will explain recent advances in disk laser technology, including the introduction of the new 6 kW power at the work piece from 1 cavity product, and process relevant features of the laser, 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.

8237-27, Session 4

Ultrafast disk lasers and amplifiers

D. H. Sutter, J. D. Kleinbauer, D. Bauer, M. Wolf, C. Tan, R. Gebs, A. Budnicki, P. Wagenblast, TRUMPF Laser GmbH & Co. KG (Germany); S. Weiler, TRUMPF Inc. (United States)

Disk lasers with multi-kW CW output power are widely used in manufacturing, primarily for cutting and welding applications, notably in the automotive industry. The disk technology combines high power (average and/or peak power), excellent beam quality, high efficiency and high reliability with low investment and operating costs.

Additionally, fundamental mode picosecond disk lasers are well established in micro machining at high throughput and precision. Since the worlds first market introduction of industrial grade 50 W ps lasers (TruMicro 5000) at the Photonics West 2008, their second generation now provides twice the average power (100W IR, 60W green) at significantly reduced footprint.

Mode-locked thin-disk oscillators achieve by far the highest average power of all un-amplified ultrafast lasers, significantly exceeding the 100W level in laboratory set-ups. With robust long resonators their pulse energy approaches that of typical ultrafast amplifiers.

In recent times much interest in thin disk technology has come from the ultra-high peak power, petawatt laser community.

This presentation reviews the state of the art of ultrafast disk lasers and amplifiers.

8237-44, Session 4

Multi-kW single fiber laser based on an extra large mode area fiber design

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The quality of Yb-doped fused bulk silica produced by the sintering of Yb-doped fused silica granulates made tremendous progresses within the past five years. In particular the refractive index and doping level homogeneity of such materials are excellent. By the material improvement we achieved excellent background fiber attenuation values of the active core material below 20 dB/km at 1200 nm. The improvement of the Yb-doped fused bulk silica enables multi-kW fiber laser systems based on a single very large multimode laser fiber.

We have produced different extra large mode area (XLMA) fiber concepts by jacketing and filament stacking. The advantage of the stacking technique is that even very complex fiber structures can be set easily. The utilization of a single active fiber in combination with the XLMA multimode fiber concept with fiber diameters of 1000 µm and above enables simple and robust high power fiber laser setups without complex fiber couplings.

We will present the current improvements of the core material development. Yb-doped fibers with different core compositions, based on the Yb-doped bulk silica, have been characterized in detail. In particular the laser efficiency and photodarkening performance of such fibers were studied. We will report on the excellent laser performance of a multi-kW fiber laser based on a single XLMA-fiber.

8237-45, Session 4

1.2-kW single-mode fiber laser based on 100-W high-brightness pump diodes

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We have demonstrated a monolithic (fully fused), 1.2-kW, Yb-doped fiber laser with near-single-mode beam quality. This laser employs a new generation of high-brightness, fiber-coupled pump sources based on spatially multiplexed single emitters, with each pump providing 100 W at 915 nm within 0.15 NA from a standard 105/125 fiber. The fiber laser is end pumped through the high-reflector fiber Bragg grating using a 19:1 fused-fiber combiner. The laser power can be modulated at a frequency of up to 10 kHz by modulating the drive current of the pump diodes. The output wavelength is 1080 nm with a linewidth of 0.5 nm FWHM; the lack of amplified spontaneous emission and stimulated Raman scattering indicates that further power scaling is possible with increased pump power. Multiple lasers can be combined with a fused-fiber output. The system architecture has several advantages for practical applications:

1. The use of single-emitter diodes provides high reliability, high efficiency, and graceful system degradation in case of diode failure.

2. The end-pumped design minimizes loss of pump brightness and eliminates the need for complex pump/signal combiners that can cause loss and beam-quality degradation for the signal beam.

3. The system is monolithic (no free-space beams) for high reliability and environmental stability.

4. The output power can be varied by varying the diode drive current or by varying the duty cycle (pulse duration or repetition rate) in modulated operation.

5. The laser modules are field replaceable with a simple splicing procedure to the output combiner.

8237-46, Session 4

65 W of average power and 6-MW peak power generation from a mode-locked fiber oscillator

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The development of powerful ultrashort pulse laser sources opens the door for a large variety of applications. Both high-average powers and high pulse peak-powers are required to initiate nonlinear processes and to allow for a reasonable detection procedure. Energy scaling of ultrafast Yb-doped fiber oscillators has experienced rapid progress and has reached the levels that traditional solid-state lasers offer. The revolution arises from the discovery of new pulse shaping mechanisms in combination with the emergence of large-mode-area (LMA) photonic crystal fiber (PCF) technology.

We report on the generation of femtosecond pulses from an all-normal-dispersion fiber laser featuring a LMA ytterbium-doped large-pitch PCF. The 1.2m long fiber has two rings of air holes with a pitch of 44µm and a relative hole size of 0.2. Nonlinear polarization evolution assisted by passive spectral filtering in combination with the large-pitch fiber design enables a significant peak power enhancement with the generation of multi-megawatt pulses. 65W of average power at a 76.5MHz repetition rate, corresponding to 850nJ pulses are generated in a compact oscillator setup. The output pulses are extra-cavity dechirped down to 111fs with 6MW of peak power. To the best of our knowledge, these are the highest average and peak powers ever reached by a mode-locked fiber laser.

8237-47, Session 4

800-W CW near diffraction limited beam delivery through a 100-m long multi-mode fiber

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We present the efficient propagation of 800 W of near diffraction limited cw laser power through a 100 m long fiber delivery system. This is an important advance with regard to high-power material processing applications where the fiber-optic beam delivery of high-brightness beams is typically limited to a few meters. The presented all-fiber system consists of an oscillator, two amplifier stages and a passive fiber comprising a tapered region.

Behind the passive fiber a M2 value of 1.35 was measured using a Spiricion M2-200 at a total power of 800 W. A minor spectral content was observed at the Stokes-shifted wavelength (1139.5 nm) at output powers above 780 W, indicating the onset of Stimulated Raman Scattering (SRS).

The passive fiber and the tapered region were drawn at the IFSW from the same step-index preform supplied by CeramOptec GmbH, having a cladding-to-core diameter ratio of 20 and a numerical aperture (NA) of 0.056. The approximately 500 mm tapered fiber region was utilized to match the 20 µm core diameter of the MOPA system with the 30 µm core diameter of the passive transport fiber.Since the SRS-gain scales to the inverse of the effective area of the propagating mode, we could show an efficient solution to scale power handling limits.

Additional experiments are in progress to further explore the power handling limits of this delivery fiber and various other fiber designs, e.g. due to the massive increase of SRS.

8237-48, Session 5

Cascaded Raman fiber laser at 1480 nm with output power of 104 W

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The ability to generate wavelengths where rare-earth gain is not available has made cascaded Raman fiber lasers appealing for a variety of applications. Some applications of particular interest are high brightness, low quantum defect pumping of large mode area Erbium fiber lasers, pump sources for distributed gain in telecom systems, and as sources of high power radiation for frequency doubling in laser guide stars.

A high power cladding pumped Yb-doped fiber laser source at around 1.1µm wavelength serves as the initial seed source. This is followed by a cascaded Raman resonator (CRR) consisting of nested fiber Bragg grating pairs and a small effective area fiber providing the Raman gain. The CRR provides the wavelength shift to 1480nm. Recently, a Raman fiber laser was demonstrated with ~81W of power at 1480nm, but temporal instability of the input oscillator due to backward Raman lasing prevented further power scaling. Here, through system optimization we achieve a record 104 W of power at 1480nm, limited only by pump power. This is a 30% increase over the previous demonstration and, to the best of our knowledge, this is the highest power achieved at 1480nm from a Raman fiber laser.

The Raman fiber used has a low frequency cut-off at 1500nm which prevented further conversion of 1480nm light into the next stokes wavelength. This allowed for longer cavity lengths improving efficiency. The conversion efficiency from pump power to output at 1480nm was ~32%. In contrast, the best achieved efficiency previously without the filter fiber was 23%. Furthermore, the fraction of the output light at 1480nm is ~95%. This high ratio again is made possible due to the long cavity lengths possible with the new fiber.

8237-49, Session 5

High-power continuous wave erbium-doped fiber laser pumped by a 1480-nm Raman fiber laser

J. W. Nicholson, OFS Labs. (United States)

High-power erbium-doped fiber lasers are of interest for their eye-safe operating-wavelength range around 1550 nm. The highest power demonstrated to date from a fiber laser at 1.5 um, 297 W, was from an ErYb fiber laser but the slope efficiency and further power scaling were limited by parasitic lasing of the Yb ions at 1.06 um. (Jeong, et. al. JSTQE 2007).

Because of these limitations, there has been recent interest in high power Yb-free Er-doped fiber lasers. Recent results include a 67 W Er-doped fiber laser directly cladding pumped by 975 nm diodes (Kuhn et. al. PTL 2011) and an 88 W Er-doped laser cladding pumped by 1530 nm diodes (Zhang et. al. Opt Exp 2011).

Another option for scalable high-power pumping of Er-doped fibers is a cascaded Raman fiber laser. The output of the Raman fiber laser is single-moded, allowing for a core pumped system. This architecture has the benefit of keeping the fiber length short compared to cladding pumped systems which helps mitigate nonlinearities, and reduces the build-up of parasitic higher order modes in large-mode area fibers due to the high overlap between pump and signal. In this work we use a 1480 nm Raman fiber laser to pump an Er-doped fiber laser operating at 1555 nm. We achieve 54 W output power at 1555 nm for 68 W of launched pump power with a slope efficiency of 80%. To the best of our knowledge this is the highest power achieved from a core-pumped Er-doped fiber laser.

8237-50, Session 5

Further power scaling of resonantly cladding-pumped all-glass Er-doped silica based fiber laser

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We report the results of further power scaling of the highly efficient, low quantum defect, resonantly cladding-pumped, Er-doped fiber lasers and amplifiers. The laser designs under testing were the FBG-based simple power oscillator with the output spectral width of ~0.2 nm as well as the single longitudinal mode (SLM) master oscillator - power amplifier (MOPA). Wavelength-narrowed (to ~2 nm full width half maximum) InGaAsP/InP fiber coupled (100 um/0.15 NA) 1532-nm diode laser modules were used for integrated pumping along with commercial pump couplers. For optimization purposes the laser fibers used in this study were based on Er-doped silica as well as experimental silicate glass compositions. Effects of Yb co-doping of resonantly clad-pumped Er-doped fibers are also studied and discussed. Laser operation regimes with the optical-to-optical efficiency of ~75% were demonstrated. Pump-limited maximum output power of over 200 W has been achieved from fully integrated Er-doped system. This is believed to be the highest power ever reported from resonantly pumped Er-doped LMA fiber laser.

8237-51, Session 6

Efficient nonlinear frequency conversion scheme for cladding-pumped fiber lasers

R. Cieslak, W. A. Clarkson, Univ. of Southampton (United Kingdom)

High-power visible laser sources have a diverse range of applications. For the continuous-wave operating regime the most popular approach for generating visible output is via intracavity frequency doubling in a ‘bulk’ solid-state laser. However, this approach is limited by the effects of heat generation to relatively modest power levels. Fiber lasers have a geometry that is relatively immune to thermal effects and hence offer the prospect of much higher power in the visible regime. Unfortunately, the technique of intracavity second harmonic generation is not well-suited to fiber lasers due to their high resonator losses.

Here we present a simple scheme for efficient frequency doubling in cladding-pumped continuous-wave fiber lasers. Our approach employs a fiber laser resonator containing an internal resonant enhancement cavity with a nonlinear crystal for frequency doubling. The fiber laser automatically lases on axial modes which are simultaneously resonant in the enhancement cavity and main cavity. As a result, the power in the enhancement cavity is increased to many times the extractable continuous-wave power, leading to high second harmonic conversion efficiency. In contrast, to external resonant frequency doubling, our approach does not require a single-frequency source and there is no need for active cavity length stabilization. Using this scheme we have generated ~19W of stable green output at 540 nm from an Yb doped fiber laser cladding-pumped with ~90 W of diode power at ~975 nm. The prospects for further improvement in performance in terms of output power, conversion efficiency and wavelength coverage will be discussed.

8237-52, Session 6

High power picosecond fiber laser emitting 50 W at 343 nm at 80 MHz

D. Sangla, J. Saby, B. Cocquelin, F. L. Salin, EOLITE Systems (France)

Industrial applications such as laser direct imaging or material processing require the development of high power UV-laser sources. In this work, we developed an all fiber master oscillator power amplifier producing more than 200 W at 1030 nm and 50 W at 343 nm. The seed source was an amplified passively mode-locked fiber oscillator emitting 3.3 W of average power at a repetition rate of 80 MHz at 1030 nm with a pulse duration of 40 ps and a spectral width lower than 0.3 nm (FWHM). It was launched into a power amplifier based on two stages Rod-type Photonics Crystal fibers pumped with fiber-coupled laser diodes at 976 nm. We obtained 20 W for 80 W of pump power from the first stage and 205 W of IR for 400 W of pump power after the final amplifier. The beam quality was very good (M^2<1.2) and the spectral width remained preserved below 0.3 nm width showing no sign of Self Phase Modulation. The output was focused into LBO crystals for third harmonic generation. We obtained 50 W at 343 nm for 200 W of incident IR power. In conclusion, we demonstrated very highly efficient UV generation by the use of the rod-type fibers amplifiers. This technology is perfectly suitable to achieve high average and high peak power with a diffraction limited output and without any limitations of non-linear effects.

8237-53, Session 6

Frequency conversion from IR to UV of a high average power and high peak power ultrafast fiber amplifier for scientific and industrial applications

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In this contribution, we report on the realization of an ultrafast fiber amplifier and its subsequent second, third and fourth harmonic generation. The amplifier, that uses the chirped pulse amplification scheme in combination with a state-of-the-art Yb-doped photonic crystal fiber allowed for the extraction of high peak power pulses that are recompressed in a finely tuned grating based compressor. The infrared pulses generated at the repetition rate of 100 kHz have a compressed energy of 350 µJ i.e. 35 W of average power and an autocorrelation duration of 460 fs leading to a peak power in excess of 1GW. These pulses are used as seeds for a second harmonic, a third harmonic and a fourth harmonic module. While limited to 250 µJ of IR, the second harmonic generation leads to 150 µJ, 15 W and 350 fs pulses, the third harmonic generation leads to 90 µJ, 9 W and 320 fs and the fourth harmonic generation to 35 µJ, 3.5 W and 600 fs pulses. This is to our knowledge the first demonstration of frequency conversion in the UV of a GW level fiber chirped pulse amplifier. Furthermore, the whole setup fits on a 1.2m x 0.4m breadboard and is an ideal device for industrial applications (micro-machining, selective ablation...) and scientific applications (multi-color OPA for ultrabroad tenability...). Comparison with theoretical simulations is also done and future power scaling will be discussed. Future optimization of the non-linear crystals will allow for the use of the full 350 µJ.

8237-54, Session 7

Advanced components for multi-kW fiber lasers

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

Single stage Fiber lasers with output powers in excess of 1kW place unique requirements on constituent components in terms of efficiency, power handling capability and affordability. The development of multi-kW capable components such as multi fiber coupled pumps, etched air taper fiber combiners, and large core, large clad PCF gain fibers will be discussed. Multi fiber coupled pumps provide a pathway towards aggregate output powers in excess of 2kW at very low costs. Etched air taper combiners have been shown to have pump inefficiencies near 95% at zero brightness drop into PCF fiber with demonstrated power handling capabilities of over 1.5kW. PCF fibers, in a monolithic architecture, provide the best method for gaining single mode operation at high levels of pump integration. In addition, the integration of these components with defined power handling and stray light rejection will be also discussed. A key aspect in the design of these components is the management of the brightness processing of the light from the laser diode pumps to the double clad gain fiber in order to spread out the brightness requirements over several components in order to make the entire system more affordable. Finally methods for pumping pre-stage amplifiers for MOPA systems from a common pump source will also be discussed.

8237-55, Session 7

Advanced fiber combiner capable of 400-W CW operation for the realization of monolithic counter-propagating pumped high power fiber amplifiers

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The integration of commercially available all-fiber combiners for counter-propagation pumping in monolithic fiber laser systems is problematic due to susceptibility of pump combiners and damage to diodes by signal light. In this contribution, we present an all-fiber pump and signal combiner suitable for monolithic counter-propagating pumped high power fiber amplifier systems. By experimental application of a novel fiber bundle structure a low loss combiner consisting of 4 tapered multi-mode fibers with core diameters of 105 µm (NA 0.22) which were side-coupled to a double-clad fiber with a pump cladding diameter of 250 µm (NA 0.46) was realized. The signal core of the double clad fiber was specified with a core diameter of 25 µm and a NA of 0.06. In order to get a deeper theoretical understanding regarding loss mechanism of the optical design of this side-pumped combiner we present detailed ray tracing simulations. The theoretically achieved coupling efficiency of about 90 % was verified experimentally with a maximum pump power handling of 440 W (4 x 110 W) at a wavelength of 976 nm and was limited by the available pump power. Hence for each pump port a verified pump power of 110 W was obtained. This is, to the best of our knowledge, the highest reported output power and efficiency for a side pumped all-fiber combiner with multiple pump ports in the literature. To demonstrate the application we set up a monolithic counter-propagation pumped continuous-wave fiber amplifier by implementation of a developed device.

8237-56, Session 7

High-spectral-flatness mid-infrared supercontinuum fiber source and its applications for component characterizations

J. Geng, AdValue Photonics, Inc. (United States)

Mid-infrared broadband light sources are of critical importance to a variety of military and commercial applications, such as infrared countermeasure, chemical sensing, molecular spectroscopy, mid-infrared component characterization, and silicon photonics. Amplified spontaneous emission (ASE) based on Tm- and Ho-doped fiber provides an easy way to offer broadband light sources near 2-micron, but their applications are limited by their bandwidth (FWHM bandwidth 20GW/cm2 laser peak intensity. This kind of compact, highly reliable mid-infrared supercontinuum fiber source, in combination with a commercial mid-infrared optical spectrum analyzer (Yokogawa), offers a powerful tool for mid-infrared component characterization with high spectral resolution and high dynamic range in a wide spectral range. In this talk, we will focus on its application for mid-infrared component characterizations. Some experimental results will be presented, including the characterizations of 2-micron fiber components (such as fiber isolator, splitter/coupler, fiber Bragg grating, and tunable filter), gain measurement of Tm- and Ho-doped glass fibers, and the characterization of in-house chalcogenide glass fiber. Other potential applications will also be discussed.

8237-57, Session 7

Micro-optics for spatial phase, polarization, and spectral control in passive and active fibers

E. G. Johnson, Clemson Univ. (United States)

Diffractive and micro-optics have evolved a great deal over the last decade or so for a variety of applications in imaging and sensing. However, the ability to engineer the phase, polarization and spectral selectivity of an optical element has many advantages in guided wave optics. For example, higher order azimuth modes can be selectively excited, free space optics can be used for spectral feedback in lasers, and polarization can be spatially manipulated for excitation of specific polarization eigenmodes of fibers. These examples and others will be highlighted in this talk with perspectives on future applications in passive and active fiber systems.

8237-58, Session 8

Ultraviolet absorption and excitation spectroscopy of rare-earth-doped glass fibers derived from glassy and crystalline preforms

P. D. Dragic, Y. Liu, T. Galvin, J. G. Eden, Univ. of Illinois at Urbana-Champaign (United States)

Ultraviolet absorption and photoluminescence excitation (PLE) measurements are presented for rare-earth-doped optical fibers produced from both glassy and crystalline preforms. Absorption spectra are obtained via broad-spectrum UV LEDs emitting in the 250nm region. PLE measurements are obtained utilizing a tunable UV laser source. The tunable laser employed is a frequency-doubled titanium:sapphire laser-pumped optical parametric oscillator (OPO) operating down to a minimum wavelength of about 225nm. Our results indicate a roughly linear relationship between the concentration of oxygen deficiency centers (ODC) and rare-earth content, regardless of the preform type, and the slope of the line is found to vary significantly with the rare earth. Additionally, PLE measurements are used to elucidate the energy transfer mechanism from pumping in the UV to emission by the rare-earth. In all cases the fibers are Al co-doped and those produced from glassy preforms are manufactured

via standard methods. Fibers produced from crystalline preforms start with a pure silica-sleeved rare-earth doped YAG crystal rod that becomes glassy (amorphous) post-draw.

8237-59, Session 8

Experimental characterization of robust single-mode operation of 50-µm and 60-µm core chirally coupled-core optical fibers

X. Ma, A. Kaplan, A. Galvanauskas, Univ. of Michigan (United States)

Flexible optical fibers with large core sizes but exhibiting robust single-mode and polarization-preserving performance are necessary for developing integrated “all-fiber” power and energy scalable laser systems. Chirally-Coupled-Core (CCC) fibers have been previously shown to produce effectively single-transverse mode and robust polarization performance, but with core sizes up to 35µm - 38µm. Here we report further core-size scaling of this technology into >50µm core diameter range. We have designed and fabricated Ge-doped CCC fibers with 50µm and 60µm cores operating single-mode in ~1µm range of Yb-doped fibers (as well as at shorter and longer wavelengths) and 64µm core fiber producing effectively-single-mode output at wavelengths longer than 1250nm. Central-core numerical aperture of NA = 0.068 is the same for all three designs but helix periods are different, ranging from 5.5mm to 7mm. Single-mode performance was experimentally verified using spectrally- and spatially-resolved measurements (so-called S2 measurements). Measured higher-order mode throughput of below - 20dB, is consistent with the standard definition for single-mode performance. Operation of these fibers does not require any coiling for achieving single-mode operation, but in practical systems they must be coiled for packaging purposes. It has been experimentally verified that single-mode performance is maintained for fiber coiling diameters as small as 30cm, although we estimate that mode-deformation constraints limit practically usable coiling diameters to ~50cm. Due to short helix periods these fibers have interesting polarization-preserving properties, maintaining polarization-extinction of up to 20dB, even under external mechanical and temperature perturbations. Demonstrated fibers constitute an important step in increasing core sizes of monolithically-integrated all-fiber high power lasers.

8237-60, Session 8

Amplification of a large-mode area single higher order mode in a fiber amplifier

C. Headley III, J. Phillips, J. Fini, E. Gonzales, S. Ghalmi, M. Yan, J. Nicholson, P. Wisk, J. Fleming, E. Monberg, F. Dimarcello, R. S. Windeler, M. Fishteyn, OFS Labs. (United States); K. Brar, Lockheed Martin Aculight (United States); S. Ramachandran, The Boston Univ. Photonics Ctr. (United States); D. DiGiovanni, OFS Labs. (United States)

A fiber amplifier which operates in a higher order mode with effective area > 3000 µm2 is described. The input signal is launched into the higher order mode using a long period grating, and a second long period grating reconverts the signal back to the fundamental mode after amplification. Using such a module, a 1084 nm input signal was amplified by 6.5 dB up to 46 W with slope efficiency = 52%. In addition, without reconverting back to the LP01 mode >12 dB of gain was demonstrated when a 1082 nm signal was amplified up to 170 W with 57% efficiency.

8237-61, Session 8

A comparative study of tapered fiber laser configurations

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Recently, we have proposed an active tapered double-clad fiber (T-DCF) as a gain medium for fiber lasers and amplifiers. In the presented work, we have comparatively studied two different schemes of fiber lasers with T-DCF as an active medium. The work consists of a theoretical part based on a rate equation model, and an experimental part based on characterization of several Yb T-DCF samples with different geometries. We have studied the T-DCFs in two laser schemes, namely co- and counterpropagating with respect to pump propagation, that differ by the location of the output coupler (at the narrow end or at the wide end, respectively). Due to the non-uniformity of the medium geometry, these schemes have very distinct properties.

Using the developed theoretical model, we obtained the distribution of power and power density inside the fiber for both considered schemes with different longitudinal shapes of T-DCF. Experimentally, we have comparatively studied the performance of both considered lasing schemes for ytterbium T-DCFs. In particular, a spontaneous transition to the passively Q-switched regime with the narrow end output configuration has been observed; arising from distributed feedback along the active fiber, and the associated problems have been investigated in detail. Moreover, the slope efficiencies and spectral characteristics of both laser configurations have been experimentally investigated and compared. The core/cladding contrast and beam quality deterioration associated with the mode conversion were also studied experimentally for both schemes.

8237-62, Session 9

Polymer optical fibres: conventional and microstructured fibres

A. Argyros, The Univ. of Sydney (Australia)

I will initially outline the main commercially available polymer optical fibres (POF), looking at their properties and application. I will, however, focus on microstructured POF and outlined the various optical properties and potential applications that have been and can be investigated when the microstructured optical fibre work is combined with polymers. The flexibility in fabrication obtained allows familiar things like data transmission, gratings and sensing to be considered, as well as more exotic applications of optical fibres in THz propagation and metamaterial fabrication.

8237-63, Session 9

Photonic crystal fiber with large-mode area and low-bending loss for high-power compact lasers and amplifiers

M. Napierala, Vrije Univ. Brussel (Belgium) and Wroclaw Univ. of Technology (Poland); E. M. Beres-Pawlik, Wroclaw Univ. of Technology (Poland); T. Nasilowski, Military Univ. of Technology (Poland); P. Mergo, Marie Curie-Sklodowska Univ. (Poland); F. Berghmans, H. Thienpont, Vrije Univ. Brussel (Belgium)

We report on a flexible large mode area (LMA) photonic crystal fiber (PCF) dedicated for high power laser and amplifier applications. We designed a fiber cross-section that includes two regions with different air-filling factors on opposite sides of the fiber core. This design allows suppressing higher order modes (HOMs) when the fiber is bent over a 10 cm radius at a wavelength of 1064 nm. The fiber then exhibits single-mode (SM) operation within a very large core with a diameter larger than 60 µm. The loss of the fundamental mode (FM) is lower than 0.01 dB/m. We can therefore consider building compact high power fiber lasers and amplifiers with a nearly diffraction limited beam output using our LMA PCF.

In our paper we focus on two different methods of obtaining the different air-filling factors and discuss their respective advantages and drawbacks. We outline the principle of both fiber designs and we explore the guiding properties of the fibers. We also investigate the influence of important parameters such as the bending radius and the bending orientation on the fiber performance.

In addition our paper discusses preliminary experimental results using fibers that were fabricated according to our designs. These experiments validate our simulations and confirm the expected fiber performance.

8237-64, Session 9

Influence of fiber bending and strain on the modal content

C. Schulze, D. Flamm, Friedrich-Schiller-Univ. Jena (Germany); O. A. Schmidt, Max Planck Institute for the Science of Light (Germany); M. Duparré, Friedrich-Schiller-Univ. Jena (Germany)

The constantly growing optical power output of fiber lasers is connected with a diameter increase of the associated active or passive fibers to circumvent the detrimental effects of nonlinear processes. On the other hand, this increase in diameter will eventually lead to the appearance of several higher order modes (HOMs). These HOMs will certainly determine fundamental beam quantities, such as beam quality, beam pointing stability, intensity distribution and state of polarization. A widely used approach to suppress HOMs and to maintain a good beam quality is bending.

We present a detailed experimental investigation of fiber bending induced changes of the modal content, based on the Correlation Filter Method (modal decomposition with computer-generated holograms).

Using this technique the modal amplitudes and phases of the fiber can be monitored in real-time, i.e. currently with up to 30 Hz, such that bending induced changes in the modal composition can be observed instantaneously.

This fast measurement rate can be used for adjustment purposes, e.g., to evaluate quantitatively the change of beam quality with varying bending diameter.

We have applied our method to different kinds of multimode large-mode-area fibers such as step-index, photonic crystal and multicore fibers, whereas the results for a multicore fiber are exemplarily presented, including the impact of bending on the beam quality.

8237-65, Session 9

Efficient high power fiber amplifier utilizing the single mode distributed mode filtering bandgap rod fiber

M. Laurila, Technical Univ. of Denmark (Denmark); T. T. Alkeskjold, NKT Photonics A/S (Denmark); M. M. Jørgensen, S. R. Petersen, Technical Univ. of Denmark (Denmark); J. Broeng, NKT Photonics A/S (Denmark); J. Lægsgaard, Technical Univ. of Denmark (Denmark)

Fiber lasers and amplifiers are rapidly replacing conventional solid-state lasers and have experienced a significant increase in average output power levels in the recent years. In addition, Photonic Crystal Fibers (PCFs) are advantages compared to step-index Large-Mode-Area (LMA) fibers when high average powers and pulse energies require very large Mode Field Diameters (MFDs) to mitigate the nonlinearities. However, large MFDs require the core to have extremely low NA, to only support the fundamental mode, which in many cases is the limit for the manufacturing process. LMA PCFs with very large core sizes tend to suffer modal instabilities when operated in high average output power levels. Therefore, new ways to suppress or not to guide higher order modes have been developed for further power scaling very large LMA PCFs. One way to do this is to use Distributed Mode Filtering (DMF) which enables efficient higher order mode suppression and increases the modal stability.

In this paper we use an ytterbium doped single mode DMF rod fiber (60µm MFD) in a high power amplifier configuration and demonstrate high average output powers, up to several hundreds of watts, and high pulse energies with good beam quality and high threshold level of the modal instabilities. The DMF rod has high efficiency and gain, which enables simple system architecture and robust and high output power levels can be reached only using one amplification stage.

8237-66, Session 9

Mode analysis of LMA fibers using the correlation filter method

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The characterization of optical fields by means of direct modal description has become an important task in the last few years. Recently, the access of modal power spectrum of beams emerging from multi-mode fibers used for high power applications is of particular interest. Since the modal content strongly affects essential beam properties, such as, e.g., beam-propagation ratio or beam-pointing stability, the direct measurement and control results in an enhanced performance of transport fibers as well as fiber lasers.

We introduce the correlation filter method for measuring the modal power spectrum of beams emerging from multi-mode optical fibers. The method is based on an optical filter performing the integral relation of correlation. This filter is realized by a computer-generated hologram with a specifically designed transmission function based on the spatial distribution of guided modes in the investigated waveguide. The correlation filter method combined with a Stokes parameter measurement provides modally resolved information about amplitudes, phase differences and polarization states. Hence, the full information about the optical field becomes available.

Beside a detailed presentation of the measurement process, the setup and the design of the correlation filters, the major advantage of the method, the ability to perform real-time measurements, is introduced. Several movies containing real-time measurements of fast changing modal coupling processes in multi-mode fibers are presented. Thereby, we show measurement results of online-monitoring the selective excitation of the fundamental mode in an LMA fiber.

8237-67, Session 9

CGH-based real-time analysis of fiber Bragg gratings in few mode LMA fibers

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To minimize nonlinear effects, large mode area fibers are used in high-power fiber laser systems. However, LMA fibers often guide higher-order modes, which affect both beam quality and laser stability. In order to achieve stable laser output despite few mode operation, fiber Bragg grating (FBG) designs providing precise control of transversal modal content are desired.

FBGs are widely used as e.g. mirrors in fiber systems. Satisfying the Bragg condition transversal modes at certain wavelengths are reflected by these periodic refractive index modifications. Besides coupling from a forward into the same but backward propagating mode, cross-coupling from one mode to another can also be provided by FBGs (Mizunami et al., J. Lightwave Technol. 18 (2), 2000). The efficiency of this cross-coupling does depend on both the modes' spatial overlap and the spatial position of the refractive index modification. This feature of FBGs can be used to design fiber integrated (FBG-based) mode converters providing preferability of certain asymmetric mode orientations.

Utilizing a computer-controlled spatial light modulator enables real-time variation of spatial light distribution in the diffracted orders including rotation of the generated field. Thus, varying the incident light, the fiber modes can be excited selectively and instant mode switching and rotation is provided. This technique for mode excitation is combined with numerical modal content decomposition based on Shapira et al. (Phys. Rev. Lett. 94 (14), 2005). We will present transversal mode coupling at FBGs for symmetric and asymmetric fiber modes. Asymmetric FBGs that favor reflection of a designated LP11 mode orientation are demonstrated.

8237-68, Poster Session

High power all-fiber picosecond laser system for UV light generation

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UV light sources are important in many industrial applications including photolithography, material processing and wafer inspection. We will present our research on developing compact and high power picosecond Yb-fiber sources for UV light generation (down to ~ 257nm wavelength) via second and third harmonics frequency conversion processes.

8237-69, Poster Session

Numerical evaluation of pulse compressibility and chirp characterization

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An actual research challenge in laser science is compression of strongly chirped high-energy pulses obtained from ultra-long mode-locked fiber lasers which operate in the dissipative-soliton mode. All experimental attempts to compress nanosecond pulses from the mentioned lasers resulted in a low compression ratio and a significant residual chirp. Highly nonlinear or/and non-monotonic chirp profile might be the cause of that failure. To clarify this, we solved the wave propagation problem for the cases of light pulses with strong nonlinear and non-monotonic chirping in a lengthy nonlinear dispersive medium emulating a fiber compressor. We found that compressibility of pulses with highly nonlinear chirp is limited both by high-order dispersion of the optical medium (compressor) which does not match the chirp profile and by nonlinear effects which become stronger with pulse shortening. In the case of non-monotonic chirp profile the evolution of pulse during its propagation in any practical optical medium is more complicated and cannot result in strong compression. Simulations were performed by use of split-step Fourier method and a number of finite-difference methods. The developed numerical approach can be considered as inverse problem solving and, thus, allows for the chirp characterization of real laser pulses upon their propagation in an optical fiber with certain parameters.

8237-70, Poster Session

Sensitivity enhancement of in-line chemical sensing device with C-type fiber and photonic crystal fiber

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Optical fibers can significantly improve the sensitivity of a sensor by increasing the interaction length between light and the sample. Among them, photonic crystal fiber (PCF) plays an important role in sensing applications because of its noticeable potential for interaction of light with gases or liquids via evanescent field which is the overlap of the optical mode in PCFs with air holes. Also, the index-guided PCF with hollow-defect core was reported to have higher sensitivity than conventional index-guided PCF and attempts for overcoming the limitation of the low sensing sensitivity are still in progress. In our previous work, proposing an in-line chemical sensor system with a novel 'C-type' fiber and a photonic crystal fiber, we could overcame prior weaknesses such as small inlet, broken symmetry, and alignment difficulty.

We further improve the sensitivity of our in-line chemical sensing with optimization of cleaving and splicing process and introduction of packaging with glass grooves, which directly affects the sensing sensitivity and guarantees the practicality. The results show that sensitivity or light coupling efficiency and response time of device are significantly enhanced with optimized the C-type fiber length. The gas sensing experiments with the optimized are demonstrated for detecting partial pressure of acetylene. The experimentally achieved sensitivity is compared with the theoretical one that is simulated with full-vectorial finite element method (FEM).

Through the experimental and theoretical supports, it would be confirmed to have a great potential to be used not only as a gas sensor but also a liquid sensor along with PDMS micro-fluidic chips.

8237-71, Poster Session

Pulse energy scaling of ps to ns pulses in highly integrated fiber amplifiers

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Gain switched laser diodes (GSLD), Q-switched microchip lasers (ML) and modulated laser diodes (LD) are promising seed sources for micromachining laser systems in industrial applications due to their robustness, low maintenance and reliability. As the average output power of such sources is limited to some µJ at the best case, such sources cannot directly be used for industrial material processing without further amplification. Using them as seed sources for amplifier chains, the pulse energy is boosted to some ten or some hundred µJ. All-fiber amplification is the most suitable way to scale the pulse energy of such sources while maintaining the benefits of the mentioned seed systems. We demonstrate energy scaling of a GSLD, a ML and a LD, with pulse durations of 30 ps, 850 ps and 25 ns, respectively. The central wavelengths of the seed sources were between 1040 and 1064 nm. The amplifiers were based on Ytterbium doped fibers and inhouse-made fiber components such as mode-field adapters, spectral filters and pump and signal combiners. While a cascaded 3 stage amplifier was set up for amplification of the GSLD and the LD, a single stage amplifier was employed for amplifying the ML to the pulse energy range, which is relevant for industrial material processing. ASE formation and nonlinear effects like SBS and self-phase modulation were analyzed in dependence of the pump power. While the pulse energy of the GSLD was scaled from pJ to µJ, the pulse energy of the ML and the LD was scaled from nJ to hundreds of µJ.

8237-72, Poster Session

Low noise fiber laser based on gain feedback in a rare-earth doped fiber amplifier chain

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We demonstrate a low noise fiber laser (LN-FL) based on gain feedback in a high efficiency cascaded fiber amplifiers, which connect with other optical devices in a circle manner. The fiber amplifier chain (FAC) contains core pumped and double-clad pumped Erbium and Ytterbium doped fibers, and is pumped in a bi-directional mode. The laser efficiency can be experimentally and theoretically increased by optimizing the laser configuration, such as gain medium length, pumping method, cavity design and so on. Gain saturation effect and amplified spontaneous emission noise in the FAC is analyzed and suppressed within each amplifying stage. Lasing mode in the LN-FL is stabilized with fiber pigtails setting in special orbits and ensuring fiber device splicing loss low without any filters. Both continuous and pulsed pumping seeds are injected into the chain though the first amplifier stage. For continuous wave operation, mode-hopping free laser spectrum with output power of 2W and SNR of 50dB is achieved. Laser wavelength can be tuned in a wavelength span of 7nm by adjusting of a fiber pigtailed polarization controller. The narrowest bandwidth is 0.4nm for the filter-less structure and spectrum improving experiments are carried out using narrow bandwidth thin-film filters with 0.08nm bandwidth. Pulsed operation performance of the laser is experimental investigated and analyzed with different pump seed property.

8237-73, Poster Session

The role of the saturable absorber in a mode-locked fiber laser

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We investigate the role of the saturable absorber (SA) in a mode-locked fiber laser. It is shown experimentally that at a given cavity design (mainly cavity dispersion and nonlinearity) there is a group of possible solutions. The SA helps pick out a particular solution that depends mainly on its strength (modulation depth). Theoretical consideration using the Haus master equation also supports our experimental observations.

8237-74, Poster Session

Cavity loss adjustment requirement for dual wave laser generation

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A stable dual wavelength generation at room temperature requires a careful adjustment of cavity losses that can be achieved using various techniques. In spite of numerous papers on dual-wavelength generation to the best of our knowledge no investigations were reported on the relation between losses for generated wavelengths required for dual-wavelength generation. In this report we investigate a linear cavity dual-wavelength fiber laser operation with the use of two FBGs at one side of the cavity and a fiber optical loop mirror (FOLM) with a high-birefringence fiber in the loop at opposite side. Adjustment of cavity loss is achieved by the shift of the FOLM reflection spectrum caused by temperature control of the hi-bi fiber. The wavelengths of the FBGs reflection were centered on 1547 nm and 1548 nm. Axial tension is applied to the FBG with longer Bragg wavelength that allows the wavelength tuning between 1548 nm and 1550 nm. Fine adjustment of the cavity loss using FOLM makes it possible the measurement of the ratio between the cavity qualities for the generated wavelengths. We have found that the Q-factor for longer wavelength always has to be less than that for shorter wavelength. The Q-ratio grows with increasing of the separation between wavelengths from the value equal approximately 1.06 for wavelength separation equal to 0.6 nm up to the value equal to 1.6 for the wavelength separation of 3 nm. We also found that the Q-ratio increases with increasing of the pump power.

8237-75, Poster Session

New mechanical stripping methods for optical fibers

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Thermal-mechanical high-strength fiber strippers use precise blades and coating guides to center the fiber relative to the blades to limit blade contact and damage. The thermal element heats the fiber to expand the fiber coating and reduce strip force. In a new system a similar blade and guide system is used but without a heater, and in conjunction with alcohol injection into the stripping area as the stripping process proceeds. This results in high strength even without heating. The alcohol injection simultaneously cleans the fiber as the fiber is stripped. The automated process eliminates skill dependency. An excellent conical coating edge is an additional benefit.

Polyimide coated fibers are difficult to mechanically strip due to the very thin coating thickness. Typical polyimide stripping methods are the use of acid or heat stripping by an arc or flame. A new method involves precise application of a blade at a small incident angle to shave the coating. The fiber is rotated to various positions in order to shave the coating about the circumference of the fiber. This method has been successfully applied to acrylate coatings. The small incident angle of the blade relative to the fiber results in a faceted conical edge to the coating.

The angled/conical coating edge produced by both new stripping methods is well suited for recoating as the coating edge will not trap an air pocket during recoating. This makes both systems attractive for fiber lasers in which a low index recoat will be applied to reconstitute the secondary cladding, and the quality of the cladding is important to contain the pump laser power within the inner (glass) cladding.

8237-76, Poster Session

25-ps optical pulse at 850 nm with a fiber-based laser

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Fiber lasers have proven to be very useful, compact, cost-effective, versatile and robust sources for many applications including micro machining, optical microscopy, optical spectroscopy, and remote sensing. Recently a number of commercialized femotosecond fiber lasers have provided alternatives to solid state lasers which typically require frequent maintenancing and large space. Specifically, much effort has been expended towards replacing Ti:Sapphire lasers. In this paper, we present a fiber laser with a 25 ps optical pulse output at 850 nm. As the gain medum, we utilized actively mode-locked technology with semiconductor optical amplifiers (SOAs). The repetition rate is ~ 200 MHz which is the 15th harmonic frequency. Based on sampling scope measurements in persistence mode, no supermode noise was seen. We believe that stability of harmonically mode-locked pulse is mainly due to the nonlinear response of gain saturated SOA. It would be also partially caused by polarization stability of the pulse because the entire cavity consisted of polarization maintaining components and passive fiber. As the wavelength selection device, a fiber Bragg grating was employed. Time average output power can be easily scaled up to tens of milliwatts by using nominal power SOAs. It is notable to say that several hundred milliwatt pulses at 850 nm are also feasible by simply adopting tapered amplifiers with fiber as booster amplifiers.

8237-77, Poster Session

Compact picosecond laser for industrial applications

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In this contribution we present our experimental results of a compact and reliable pulsed diode-pumped solid-state laser which can be either passively or actively q-switched. Using (fiber coupled) single emitter diodes and longitudinal pumped resonator geometries we realized pulse durations from 400 ps to 1 ns with an excellent beam quality (M2 < 1.2) at a wavelength of 1064 nm. The custom made miniaturized electro-optic q-switch allows pulse repetition rates up to 125 kHz. The oscillator delivers a maximum average power of 0.8 W. The timing jitter is around 0.5 ns and of course much smaller compared to a few µs in passively q-switched operation. In contrast to gain switched laser diodes we directly obtain sufficiently high pulse energies for simple one-stage (fiber) amplification concepts. Compared to mode-locked systems expensive with pulse picking setups, the repetition rate of our laser is directly suitable for many industrial processes; an exemplary application result will be shown. This laser bridges the gap between high cost ultra-short pulsed lasers and conventional ns lasers. Thus, this source is an ideal candidate for high volume production where adequate cost of ownership is needed. Using an additional solid-state miniaturized amplifier and an optional second harmonic stage we achieved 600 ps and 60 µJ at 50 kHz and 532 nm.

8237-78, Poster Session

Holmium-doped ZBLAN fiber lasers at 1.2 µm

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Holmium (Ho)-doped ZBLAN glasses have been investigated for the purpose of achieving efficient fiber lasers at 1.2 µm. Because of the long lifetime of the upper laser level and the small phonon energy in Ho-doped ZBLAN glasses, strong fluorescence at 1.2 µm that usually cannot be observed in Ho-doped silica glass has been measured. Fluorescence and lifetime of 1 mol%, 3 mol%, and 6 mol% Ho-doped ZBLAN glasses have been measured. The effect of cerium and terbium ions on the emission of Ho-doped ZBLAN glass has also been studied. Obstacles for achieving an efficient Ho-doped ZBLAN laser are analyzed and discussed. In the experiment of a commercial Ho-doped ZBLAN fiber laser, it was found that the 3 µm four-energy-level laser can easily overwhelm the 1.2 µm laser, which is a three-energy-level system having the same upper laser level as the 3 µm laser. In order to effectively suppress the competitive 3 µm laser, advanced Ho-doped ZBLAN fiber has been designed and fabricated for 1.2 µm fiber lasers. Fiber lasers at 1.2 µm using the new Ho-doped ZBLAN fiber have been developed. Our experiments demonstrate that the new Ho-doped ZBLAN fiber is an efficient gain medium for lasers at 1.2 µm.

This work is supported by the NASA SBIR Phase II under contract/grant NNX10CB39C.

8237-79, Poster Session

High power single-mode fiber laser and a multi-mode delivery cable

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Over 500W output power Yb doped single-mode fiber laser demonstrates excellent beam quality of less than 1.1 M2 value, and new era of material process results. Once its output beam is focused, beam spot size becomes less than 20 um and then power density at target reaches more than 100MW/cm2. This power level enables process of new metal material such as copper and titanium, which has relatively high reflection in this wavelength.

Other advantage of fiber laser is flexibility of fiber delivery. Delivering optical beam directly to the process head realizes many user friendly features like high speed process and ease of maintenance, etc. However use of single-mode fiber delivery is limited by connection loss or nonlinear effects such as stimulated Raman scattering (SRS). To mitigate these conflicted characteristics, use of multi-mode fiber for delivery is one of approach. Use of a multi-mode fiber delivery enables low loss connection and reduces SRS; however beam quality will not be fully maintained. In the mean time beam quality does not always need to be good for some of process case such as welding or process of plastic material.

We present our design of 500W single-mode fiber laser and beam quality measurement of multi-mode delivery fiber. How they vary, how we can excite mode, how we can homogenize beam depends on different condition like fiber length, core size and connection style. We also present material process results in different beam performance.

8237-80, Poster Session

Passively Q-switched 2 µm Tm-doped cladding-pumped all fiber laser with graphene-based saturable absorber

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The recent demonstration of passively mode-locked or Q-switched Yb-doped/Er-doped fiber lasers based on graphene saturable absorber at 1.0~1.1 µm and 1.5~1.6 µm has proven that graphene has potential to be an effective saturable absorber for a wide broad wavelength range. The effort to realize passively mode-locked or Q-switched Tm-doped fiber lasers by graphene at 2 µm is therefore actively pursued by several research groups around world but we haven't seen any results reported yet. Here, we report a Tm-doped all fiber laser passively Q-switched by a graphene saturable absorber in a unidirectional ring cavity. The total length of the cavity was about ~25 m, which included approximately 13 m Tm-doped double-clad single mode fiber. The gain fiber was cladding-pumped by a fiber coupled multimode diode laser with a center wavelength of 790 nm and a maximum output power of 5 W. The laser was out of the 70% port of the 30/70 tap coupler while the 30% port was spliced back. When the incident pump power was 2.0 W, the average output power was 2.5 mW and the repetition rate was 56 kHz, which corresponds to single pulse energy of 45 nJ for 1.6 µs pulse width. The repetition rate of the graphene passively Q-switched Tm-doped fiber laser can be tuned by changing the pump power. The laser wavelength was 2000.5 nm and the spectral bandwidth was 2.4 nm. In addition, the work to mode-lock Tm-doped fiber laser with graphene is also on-going in our lab and results will be reported on the conference.

8237-81, Poster Session

Single-mode WDM for core pumping thulium-doped fiber at 795 nm

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Lasers based on thulium-doped fibers (TDF) extend the accessible wavelengths towards the eye-safe region of about 2 µm. Different configurations for pumping a TDF like single clad or double clad pumping with different pump wavelengths exist. Up to date no single-mode wavelength division multiplexer (WDM) was demonstrated for core pumping TDF at its absorption maximum at 795 nm. In this contribution, an in-house developed WDM capable of multiplexing two wavelengths with a spacing of 1200 nm is presented together with simulations and experiments. We employed different fibers for 795 nm and 2 µm wavelength with a mode field diameter of 5 µm and 13 µm and a numerical aperture of 0.13 and 0.11, respectively. To match the propagation constant in the coupling region of the WDM we pre-tapered the 2 µm fiber by a specific pre-taper length, which was estimated by numerical simulations based on the finite-difference beam propagation method. The achieved coupling ratio at a wavelength of 795 nm was 80% while the transmission for the signal wavelength was still 80%. To demonstrate the application of the developed WDM we integrated it in an all-fiber core pumped TDF amplifier. The amplifier setup consisted of the WDM, a TDF, a single-mode pump diode and a seed source operating at wavelengths of 800 nm and 1980 nm, respectively.

8237-82, Poster Session

Atomic layer deposition for fabrication of ytterbium doped fibers

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Optical fibers used in high power fiber lasers require a fabrication process that allows high dopant concentration while maintaining the homogeneity of the dopant distribution in the glass. Modified chemical vapor deposition (MCVD) process in combination of solution doping has become the mostly used method for fabricating rare-earth (RE) doped fibers. However, this method suffers from several disadvantages, such as difficulties to maintain a proper control on the RE-concentration or homogeneity of dopant distribution. Here we present atomic layer deposition (ALD) as a new method for fabricating high quality ytterbium doped fibers. ALD is a chemical vapor deposition-type process for thin film growth where precursors are pulsed successive onto the substrate layer by layer. We use ALD to coat uniformly the porous structure of a silica-soot with Al2O3 and Yb2O3, and their diffusion into silica is accomplished after the collapsing process. Our results show excellent penetration of dopants in a >300 µm porous silica substrate with mean concentration of 0.15 and 1.51 at% of Yb and Al respectively. The soot is collapsed under standard conditions for MCVD soot. Preliminary results of a fiber with 0.07 at% of Yb and 0.24-0.48 at% of Al show low background attenuation (<30 dB/km at 1200 nm), high efficiency and low photodarkening. Fiber degradation by photodarkening is studied for various levels of Al at a constant level of Yb. Results are in agreement with studies performed with fibers manufactured with other technologies, i.e., Al is beneficial on increasing the fiber resistance to the photodarkening effect.

8237-83, Poster Session

Switchable multiwavelength erbium-doped fiber ring laser based on nonlinear polarization rotation

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Switchable multiwavelength lasers have been widely investigated for applications to wavelength division multiplexing systems, optical time domain reflectometers, and optical sensor devices. To realize functional multiwavelength lasers, switchable multichannel filters are the most important components. Various multiwavelength filters, such as Sagnac interferometers, Mach-Zehnder interferometer, cascaded long period fiber gratings (CLPFGs) because of their various advantages, such as low transmission loss, independence of input polarization, high extinction ratio, and easy fabrication.

In this study, switchable multiwavelength erbium-doped fiber ring laser employing nonlinear polarization rotation is proposed and experimentally demonstrated. The homogenous line broadening of the erbium-doped fiber is effectively suppressed by using nonlinear polarization rotation, which consists of two polarization controller, a single-mode fiber with a length of 35 km, and an in-line polarizer. The stable output of the multiwavelength erbium-doped fiber laser is achieved. The wavelength spacing of 0.8 nm was obtained by alleviating the mode competition with nonlinear polarization rotation structure. In order to realize switching performance of the proposed multiwavelength erbium-doped fiber laser, a novel, functional multichannel filter is fabricated by combining a Sagnac interferometer with cascaded long-period fiber gratings. The lasing wavelengths can be effectively switched by changing the polarization states of both the nonlinear polarization rotation structure and the Sagnac interferometer. We achieved wavelength spacing switchable operation of the proposed multiwavelength laser, which has four lasing wavelengths with wavelength spacing of 0.8 nm at room temperature and the maximum extinction ratio of 40 dB. The number of lasing wavelengths was controllable from one to four with different wavelength spacing. The combination of the lasing wavelengths could be arbitrarily selected from four wavelengths by controlling two PCs.

8237-84, Poster Session

Generalized transfer function of a quarter-wave-shifted distributed-feedback fiber laser

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In the large family of Distributed-Feedback (DFB) lasers, the Quarter-Wave-Shifted (QWS) structure holds a special position. A pure QWS-DFB (devoid of side effects) is just composed of two active zones of the same size, differing only by the phase of their coupling constants. With its single mode oscillating exactly at the Bragg frequency, the QWS-DFB laser can be considered as a special kind of Fabry-Perot resonator, where the phase and gain properties are fully reported into the active Bragg reflectors that delimit a zero thickness "cavity". This interesting duality allows us to build an all-analytical theoretical approach that combines coupled-mode theory and extended (3x3) transfer matrix formalism including internal sources in order to establish the "Generalized Transfer Function", which expresses self-consistently the spectral and longitudinal field distribution. We apply our model to an Erbium doped fiber laser, where the active medium is looked upon as an "ideal" 3-level atomic system, well described in terms of steady-state rate equations. Nonlinear interactions with the optical fields (pump and signal) are naturally taken into account. The originality of our semi-classical model lies in the articulation between global and local characteristics of the component, including the management of the "hot spots". The ultimate goal of this study is to develop fiber lasers based on several photo-inscribed Bragg gratings, realized in cascade on the same optical fiber.

8237-85, Poster Session

Arc power calibration for fusion splicing optical fibers with variety diameters

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Optical fiber with large variety of glass diameters are widely used in research labs and production lines in different fields, such as fiber lasers, bio-medical, etc. Fusion splicing various sizes of optical fibers becomes a vital topic. A fundamental technique, known as arc power calibration, plays critical role to assure quality of splices, to automatically select correct arc power, and to enable the optimized splice parameters transferable to multiple splicers in production lines for achieving same splice results.

There are two types of traditional arc calibration methods. One is the meltback method. After heating the fiber ends, meltback distance is measured along the fiber axis. Melting of large fiber portion causes heavy electrodes deposit and inaccurate calibration. With the second method, the fibers are spliced with axis offset. The offset variation caused by surface tension is measured. For many fiber types the offset splicing is impossible without knowing the correct arc power. Therefore, this method only applies to standard fiber sizes.

A new arc calibration method is developed for a large variety of fiber sizes. This method heats fiber with multiple short arcs and measures meltback at the corner of the fiber ends. The fiber corner melting speed is found proportional to the fiber temperature. By variable arc power of the multiple arcs, a proper melting speed can be reached which represents the desired arc power for the fiber under test. This method is tested successfully for fiber diameters from 60 µm to 500 µm in a newly released splicer with controllable plasma zone.

8237-86, Poster Session

Plasma zone control for adaptable fusion splicing capability

D. M. Duke, W. Zheng, H. Sugawara, T. Mizushima, AFL Conductor Accessories (United States); K. Yoshida, Fujikura Ltd. (Japan)

Splicing of optical fibers in photonic R&D and production applications must meet the needs for a variety of applications such as fiber lasers, various fiber-based sensors, and bio-medical uses. This requires the use of fibers with sizes, shapes, material properties, structure and designs custom-tailored to meet very specific applications. In order to splice these various fiber designs and sizes, plasma zone control has been developed. By manipulating the plasma zone heating area and conditions, arc fusion splicing is made quite adaptable. The plasma zone control involves manipulating both the shape, size and heat intensity of the plasma zone, but also controlling the location of the fiber within the plasma heating zone. This is accomplished largely with mechanical design to control the electrode gap in combination with various electronic techniques for controlling the arc intensity.

A novel fiber clamping and positioning system provides the capability to meet 2 design goals. The first is to provide infinitely variable clamping size adjustability to allow effective clamping and alignment of fibers (or fiber coatings) in the range from 60µm up to 2000µm. The second goal is to provide a means of altering the position of the fiber within the plasma heating zone. This allows the fiber to be positioned at the center of the plasma arc heating zone (where the heat is the greatest), or alternatively at a position where the temperature is lower and therefore more appropriate for a lower melting point or smaller diameter fiber. The combination of these design elements results in a fusion splicing system with great versatility.

8237-87, Poster Session

Picosecond swept source laser at 1300 nm

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We present the result of a swept source laser in the 1300 nm region based on dispersive mode locking. The laser is simply composed of a semiconductor optical amplifier, a chirped fiber Bragg grating (CFBG), a 10 % output coupler and an intensity modulator. Optical pulses of 30 ps width are achievable within a 3 dB bandwidth range of 90 nm (from 1280 nm to 1370 nm) and 10 dB bandwidth of 100 nm which was restrained only by the CFBG (10ps/nm) currently used. We already demonstrated a swept source providing tens of picosecond pulses with a rapid wavelength sweeping function capable of being used for optical coherence tomography application in the 1550 nm band. Furthermore, the unique k-space sweeping feature of our programmable laser enables direct fourier transform of the data without resampling for rapid OCT images. In this paper, we use the same platform as the 1550 nm programmable laser at the 1300 nm region which is more useful for biomedical imaging. In brief, a pulse width around 30 ps was obtained and the optical signal noise ratio at center wavelength ~1325 nm was 35 dB. Modulation frequency was around obtained a 3 dB optical bandwidth of over 90 nm. We believe more than 100 nm sweep bandwidth is easily achievable by replacing the CFBGs with wider ones.

8237-88, Poster Session

Tailored fiber Bragg gratings inscribed with a phase mask and a deformed wave front by ultrashort pulses

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We report on the ultrashort pulse inscription of chirped fiber Bragg gratings (FBGs) using a phase mask with constant period and a deformed wave front. To analyze the influence of wave front deformations on the grating period of the generated FBG, a numerical model was developed. It is based on a ray optical solution of the diffraction of an arbitrary wave front at a phase mask with constant period, where the wave front is described by Zernike polynomials. Generally, a plane wave front generates an interference pattern with half the phase mask period. A wave front tilt only shifts the grating laterally and has no impact on the period, while a defocus changes the grating period and thus the Bragg wavelength, as introduced by Prohaska et al.(Electronic Lett. 29, 1993). However, higher order aberrations like coma or spherical aberration yield a chirp along the inscribed grating. In order to experimentally deform the wave front of the inscription beam, an additional cylindrical tuning lens was introduced into the setup. The tuning lens was placed directly above the phase mask. Due to decentering and tilting of the tuning lens, higher order aberrations could be generated, resulting in chirped FBGs. A chirped FBG with a FWHM bandwidth of 4 nm could be realized. The grating period of the FBG was characterized by the side diffraction technique, yielding good agreement with the computations.

8237-89, Poster Session

High power single mode optical fiber coupler with enhanced mode field diameter

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Monolithic fiber laser and amplifier systems like two-tone single frequency amplifiers, short pulse fiber oscillators and high power core-pumped amplifiers, which require low nonlinearities and high power handling, are often limited by the availability of suitable single mode components. The main drawbacks of most commercially available fused single-mode fiber couplers are the small mode field diameter (MFD) and specified power handling. In this contribution, we present an in-house developed fused single mode wavelength division multiplexer (WDM) capable of multiplexing two wavelengths (1025 nm/1065 nm) up to a power of 30 W by applying fiber with a core diameter of 10 µm and a numerical aperture of 0.08. The MFD of this fiber is approximately two times larger compared to the MFD of typically used fiber. The insertion loss and the isolation of the WDM were 17 dB. To demonstrate the application of the developed high power WDM we integrated it in an all-fiber core pumped amplifier. The amplifier consisted of a pump laser operating at a wavelength of 1025 nm and a seed diode delivering an output power of 150 mW at a wavelength of 1066 nm. With a launched pump power of up to 16 W, an amplified output power of 7 W was obtained.

8237-90, Poster Session

Thermo-optic wavelength-tunable fiber laser for the interrogation of fiber Bragg grating sensor systems

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We demonstrate experiments of fiber Bragg gratings sensor based on novel wavelength-tunable fiber laser. This laser is based on thermo-optic tuning of a Bragg reflecting polymer waveguide. By applying voltage on a micro-heater, the direct tuning of a Bragg reflecting wavelength is viable in a polymer waveguide. The developed laser source shows more than 19 nm of bandwidth of wavelength-swept range centered at 1572 nm. It is also shown that the instantaneous linewidth is 0.06 nm, signal-to-noise of the laser is almost 50 dB, and peak output power is 5 mW. Since polymer waveguide Bragg reflector of this laser could be fabricated by nano-imprinting process, it has a large potential for low-cost manufacturing and mass production.

This tunable wavelength laser was applied to a Fiber Bragg grating (FBG) strain sensor system. We can achieve a linear response of FBG peak shift for the statically applied strain change. The dynamic response was also measured successfully with an interrogating speed as fast as 15 Hz for the external strain variation around a 1 Hz repetition. For the linear response between sweeping signal and lasing wavelength, we apply an arbitrary waveform of function generator into the thermo-optic micro heater. By this way, we could achieve more accurate dynamic strain measurement.

Compared to the other conventional wavelength-tunable lasers, such as active mode-locking (AML) fiber laser and Fourier-domain mode-locking (FDML) fiber laser, this laser shows a merit of cost-effectiveness and miniaturization.

8237-91, Poster Session

Quantitative modeling of pulse amplification in multimode cladding pumped Yb/Er co-doped fiber amplifiers

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Optical pulse propagation in Er-doped fiber amplifiers (EDFA) has been qualitatively modeled by solving the nonlinear Schrodinger equation (NLSE) in a gain medium for the last 20 years or so. Subsequently, several models have been developed as extended NLSE taking into account higher nonlinear terms, and/or different methods of solving the equations NLSE. However, a fully quantitative description of the pulse propagation in cladding pumped EDFA has not yet been achieved due to fact that gain in the core has been strongly affected by the fiber shapes and structures and is not constant along the fiber as most works have assumed. The main reason for that is multimode effects in cladding pumped fiber have not been taken into account in these models. We will address all these issues in our work and show that a quantitative modeling in complicated structure fiber amplifiers can be achieved.

In our approach, NLSE is coupled with BPM to simulate pulse propagation in multimode cladding pumped fiber amplifiers. The fiber complexity, which strongly affects the pump propagation and pump absorption and therefore also affects the fiber gain can be described by BPM. The signal gain obtained from BPM is then used for modeling pulse amplification using the standard Step Split Fourier Method (SSFM). The simulation results are in quantitative agreement with our experiments.

8237-92, Poster Session

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

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

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

8237-93, Poster Session

Analytical analysis of coherent combination of amplified ultrashort laser pulses

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Coherent combining of ultrashort pulses from spatially separated amplifiers is an approach to scale the average power and peak power of laser systems. Compared to the CW and Q-switched case, additional aspects have to be considered when combining femtosecond pulses, such as dispersion management and the impact of nonlinear effects. This is especially true for fiber based amplifiers. The considered setup is a Mach-Zehnder-type interferometer employing amplifiers in each branch. Assuming a completely equal behaviour of the combined amplifiers, the combining process will be possible with perfect efficiency. However, in reality, there will be mismatches between the input and output powers of the amplifiers caused by fluctuations of the pump and seed sources, as well as by imperfect adjustments. In a linear regime, the impact of those effects will be small. However, in a non-linear regime, the mismatches result in different temporal phase terms caused by self-phase modulation. Those phase differences can have a detrimental impact on the combining process. Additionally, the lengths of the fibers might not be equal, resulting in spectral phase differences due to dispersion. The impact of these effects on the combining process has been investigated and simple analytical equations for the evaluation of this impact have been obtained. Using an introduced figure of merit, these formulas provide design guidelines for laser systems using coherent combining. The results show that, in spite of the different effects mentioned above, for a carefully adjusted and stabilized system an excellent efficiency of the combining process can still be achieved.

8237-94, Poster Session

All thulium fiber single-mode MOPA delivering 32-nJ picosecond pulses

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Picosecond fiber lasers at 2 µm have potentially many applications for nonlinear conversion in mid-infrared, in medical surgery and plastics processing. Here we report on the generation and the amplification of high peak power picosecond pulses in a single-mode all-fiber master oscillator power amplifier (MOPA). The oscillator delivers 4.5 ps transform-limited solitons at 11.2 MHz. It operates with low noise and high stability thanks to the use of a Bragg grating as a cavity mirror. The RF spectrum of the oscillator shows great stability and the signal-to-noise ratio is higher than 80 dB. The pulse energy was measured to 62 pJ corresponding to an output power of 700 µW.

To limit the non-linear distortions, the signal is amplified into a short single mode heavily-Thulium-doped fiber amplifier. The active medium is core-pumped by a fiber laser at 1560 nm. The active fiber length is 70 cm to limit the nonlinearity effects and to achieve high peak power. For 4.9 W pump power, the output energy reaches a maximum of 32 nJ corresponding to 9 kW with little SPM distortion as can be seen from spectrum. The slope efficiency is close to 13 %. This low efficiency may be due to the moderate power injected from the oscillator.

Future investigations will focus on increasing the pulse energy of the oscillator to raise the efficiency of the amplifier and operation at longer wavelength.

8237-95, Poster Session

SHARC fibers: a new paradigm for packagable ultralarge-core single-mode fibers

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We present a new class of large-mode-area optical fiber that provides: (i) a modal discrimination mechanism that does not rely on coiling the fiber; (ii) relative modal discrimination that is independent of the core area; (iii) compact coiling without impacting either the propagation loss, the mode content, or the spatial overlap of the fundamental mode with the gain profile; and (iv) record-breaking mode-area scaling beyond 10,000 µm^2.

The semi-guiding high-aspect-ratio core (SHARC) fiber departs from the circular-core symmetry common to conventional fibers by using a high-aspect-ratio rectangular core. By specifying a very small refractive-index step at the narrow core edges, the core becomes “semi-guiding,” strictly guiding only in the narrow dimension. The mode dependence of the resulting Fresnel leakage loss in the wide mm-scale dimension strongly favors the fundamental mode, promoting single-mode operation. Numerical simulations also reveal that the architecture is robust against reasonable manufacturing tolerances.

The SHARC fiber can be coiled in the thin, mechanically flexible narrow dimension to form a small package. Bending in the narrow dimension is numerically shown not to affect the propagation loss or mode content of the fiber, allowing packages as small as 14 cm in diameter.

The rectangular cross-section of SHARC fibers provides the same thermal management benefits that slab lasers exhibit relative to solid-state rod lasers. This new class of fibers, when used in a laser configuration, combines the advantageous features of conventional fiber lasers and slab lasers, extending the performance envelope beyond what is possible with either of those technologies independently.

8237-96, Poster Session

Erbium-ytterbium co-doped fiber amplifier with controlled 1060-nm Yb-ASE

G. J. Sobon, P. Kaczmarek, A. J. Antonczak, J. Sotor, A. Waz, G. Dudzik, K. Krzempek, K. M. Abramski, Wroclaw Univ. of Technology (Poland)

Erbium/Ytterbium co-doped fibers confirmed to be excellent active gain media to build medium/high power sources operating in the eye-safe 1.5 - 1.6 µm region. Co-doping with ytterbium allows to significantly increase the extractable output power of a fiber amplifier, but has one main drawback, namely the presence of amplified spontaneous emission (ASE) from the Yb3+ ions in the 1 µm band. In the presence of high pumping power, the Yb-ASE can turn into parasitic lasing, self-pulsing or giant pulses formation, which may cause unstable operation of an amplifier at the nominal 1550 nm wavelength, or can even lead to the active fiber damage. In our work we present for the first time (to our knowledge) a method of suppressing the unwanted Yb-ASE by applying a positive feedback loop for the 1 µm signal into the Er/Yb amplifier. In other words, we form a ring laser resonator for the 1 µm wavelength inside the amplifier. This feedback induces stable and controllable lasing around 1060 nm, which has a good influence on the amplifier stability and efficiency at 1550 nm. The direction of the signal circulation can be determined by applying a fiber isolator in the loop, as in conventional fiber ring lasers. Hereby, both co-directional and counter-directional 1064 nm propagation can be achieved, depending on the isolator orientation. We have shown, that the presence of a well defined and controlled 1064 nm signal can improve the amplifier stability and increase the efficiency at 1550 nm

8237-97, Poster Session

High repetition-rate narrow line-width SESAM mode-locked picosecond Yb-doped all fiber laser

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High repetition-rate narrow line-width picoseond lasers at 1.0~1.1 um are needed as seed sources for high power ultra-short pulse fiber amplification with the target average output power of hundreds of Watts. The ideal specifications for such a seed include tens of picosecond pulse width, hundreds of MHz repetition rate, tens of mili-watts output power, and narrow spectral bandwidth in sub-nanometer scale. There are several approaches to obtain such a seed source, such as gain-switched diode lasers at modulated rate of 1GHz with DFB diode feedback for spectral narrowing; mode-locked vertical-external-cavity surface-emitting semiconductor laser (VECESE) at 910 MHz and harmonic generation in mode-locked fiber lasers. Here, we report stable narrow line-width picosecond pulses generation from a passively mode-locked Yb-doped fiber laser in a short linear cavity with fundamental repetition rate up to 850 MHz. The Yb-doped fiber is pumped by a 974 nm single mode diode laser. A narrowband, 80%-reflectivity fiber Bragg grating used as an output coupler. One end of the Yb-doped fiber is fusion-spliced to the grating, the other end is perpendicularly cleaved and butted to a SESAM. When the length of the cavity is ~20 cm, stable mode-locked pulses occurred at 120 mW pump power and the pulse repetition rate was 490 MHz. Increasing the pump power to 300 mW, the output power was 17 mW. The laser wavelength was 1064.2 nm and the spectral line-width was 0.14 nm. The pulse width was measured to be ~21 ps, giving a time-bandwidth product of ~0.78. Repetition rate of 850 MHz was obtained with further shortening of cavity length. In addition, we also obtained narrow line-width (0.07 nm) graphene-based mode-locked Yb-doped fiber laser at 430 MHz in a silimar cavity configuration and details will be reported in the conference.

8237-98, Poster Session

Three-stage all-in-fiber MOPA source operating at 1550 nm with 20W output power

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High power fiber sources in MOPA (Master Oscillator - Power Amplifier) configuration become a very attractive alternative to solid state lasers in many technological and industrial applications. The mainstream of those constructions is currently dominated by diode-seeded Ytterbium-doped fiber based systems operating at 1 µm wavelength range, as they are useful in many various applications like material cutting, drilling, engraving, etc. However, there are applications where Yb-doped sources cannot be used because of required eye-safety, like free-space communications, sensing, range finding or LIDAR systems. In such areas high power 1.5 µm wavelength sources are necessary.

In our work we present a 3-stage, All-in-fiber MOPA system operating at 1550 nm with 20W of output power. The first stage (pre-amplifier) is an EDFA based on highly erbium-doped fiber pumped bidirectionally by two 650 mW 980 nm single-mode pumps. It provides about 23 dB gain in the whole C-band with a very satisfactory noise figure (NF) of 4.5 dB. The second stage (medium power amplifier) is based on Erbium/Ytterbium doped double-clad fiber with 7 µm core and 130 µm cladding diameter. It is backward-pumped by two 975 nm 10W laser diodes coupled with the double-clad fiber by a pump combiner. The third stage (high power amplifier) is based on Erbium/Ytterbium doped double-clad LMA fiber with 25 µm core and 300 µm cladding diameter. It is backward-pumped by six 915 nm laser diodes with a total power of 140W. A standard telecom 1550 nm DFB laser diode was used as a seed source.

8237-99, Poster Session

Single-longitudinal-mode dual-wavelength erbium-doped fiber laser with wide tunability for the application to CW THz signal radiation

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A terahertz (THz) frequency sources are very attractive in many fields of science and technology, such as spectroscopy and image for various biological objects. The generation and detection of THz signals using a femtosecond (fs) pulse laser and a photoconductive antenna, respectively, have been intensively investigated, which have led to the development of THz pulsed spectroscopy and THz pulsed imaging. To realize a high quality THz imaging system with high resolution, a stably tunable continuous-wave (CW) single frequency (coherent) THz source is highly required. Since tunable CW THz signals can be produced by changing output frequencies of two coherent light sources, it is important to develop CW coherent light sources with wavelength tunability.

In this paper, a widely tunable single-longitudinal-mode dual-wavelength erbium-doped fiber (EDF) laser with a single laser cavity is proposed and experimentally demonstrated for the generation of the tunable CW THz signal based on two signals beating technique. By using a ring cavity configuration and two fiber Bragg gratings (FBGs), high quality dual-wavelength outputs with a high extinction ratio of more than 45 dB are obtained. A single longitudinal mode operation can be achieved by using an unpumped EDF as a saturable absorber to eliminate higher-order longitudinal modes of dual-wavelength outputs and the output power fluctuation is measured to be less than 0.1 dB. To realize the stable operation of dual-wavelength laser outputs with nearly the same output power, nonlinear polarization rotator (NPR) effect is exploited to relieve the mode competition caused by homogeneous gain broadening in the EDF and to induce gain equalization between the two wavelengths. In addition, dual-lasing wavelengths are flexibly controlled by using a U-bending technique. The tension and compression strains depending on bending direction are simultaneously applied to two FBGs and dual-lasing wavelengths can be widely tuned in a range from 3.46 nm to 13.2 nm, which is corresponding to the CW tunable THz beat signal in a range from 0.43 to 1.66 THz.

8237-100, Poster Session

Core-shell nanoparticle erbium-doped fibers for next generation amplifiers

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New generation systems are expected to include more intelligent amplifiers able to adapt to many conditions including different gains, channel load, temperature, aging and transient events [1]. To face the challenge and meet these new requirements, having an accurate control on the Er environment within the fiber core matrix has never appeared to be so necessary and predominant as it is the case now.

Unlike conventional solution doping techniques where Erbium ions are randomly incorporated in the fiber core, our process makes use of a soft chemical synthesis to initially produce Erbium-doped nanoparticles (NPs). Erbium ions are therefore incorporated in the fiber core together with their local environment.

So far, our investigations [2] first showed that, from the material point of view, quenching levels are intimately linked to the design of the NPs through their chemical composition. Then, from the system perspective, we evidenced the higher power conversion efficiencies exhibited by NP fibers when compared to their conventional counterparts in high power amplifier configurations.

In this paper, we address our most recent work focusing on the NP optimisation towards quenching-free Erbium-doped fibers with a particular focus on core-shell alumino-silicate NPs. Completing our first amplifier results obtained in high power configurations, we also explore new NP fiber profiles that extend the range of their applications. Gain and noise characteristics of typical WDM operating points serve as key indicators on the benefits our NP doping process could provide.

[1] M. Bolshtyansky, “Evolution of Commercial EDFAs”, in Proc. OFC’11, paper OMH2

[2] D. Boivin et al., in Proc. SPIE 7914 (2011)

8237-101, Poster Session

High power Q-switched rod type fiber laser with single crystal photoelastic modulator

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A high power and high frequency Q-switched laser is demonstrated based on a rod type fiber and a Single-Crystal Photo-Elastic Modulator (SCPEM). Rod type fibers are in generally perfectly suited for high power Q switched lasers due to its intrinsic high power capability. In standard approach Q-switching is performed by an acousto-optics modulator (AOM), while in our case we a SCPEM is used. Both solutions rely on photo-elasticity, but a SCPEM modulates polarization instead of beam direction. We developed a modulator made of LiTaO3. It is electrically excited by a custom made driver in order to oscillate at the desired mechanical resonance longitudinal eigenmode. In contrast to standard electro-optic modulators the required voltage is significant lower in range of 10 volts. The most important difference to the standard photo-elastic modulator (based on an actuator-excited glass) that are usually used for low power application in measurement technique like ellipsometry is that SCPEM easily allows simultaneous excitation of two eigenmodes with different frequencies. By carefully design of the modulator a frequency ratio of exactly 1:3 can be achieved.

Applying correct adjustment of the amplitude and phase of these two modes they can be combined such that shortest rise time of the optical transmission curve can be achieved.

By using this dual mode of operation in our setup we achieve adequate optical response for high frequency and power Q-switching of rod type fiber laser. The setup generates pulses with peak power >10kW and pulse duration <30ns. The maximum average power of 47 W at approximately 200 kHz is up to now the highest ever recorded for SCPEM-Q-switching, and seems to scale with the frequency.

8237-102, Poster Session

Ultrashort pulse Yb fiber oscillator at 1064 nm by using a WDM cascade

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Ultrafast fiber lasers at a wavelength of 1064 nm are desirable seed sources e.g. for high power solid state amplifiers. Short pulses as well as high pulse energies were demonstrated with all-normal dispersion Ytterbium doped fiber oscillators. However, the operating wavelength of such systems is between 1020 nm and 1040 nm, as the gain maximum of Ytterbium doped fiber is located in this wavelength region, if it is pumped with laser diodes at 976 nm. We report on mode-locked operation of an Yb-doped all-normal dispersion fiber ring laser at a central wavelength of 1064 nm. The cavity consisted of two WDMs, 30 cm of Yb-doped fiber, a free-space isolator, two polarization controllers and a 10% output coupler. One of the WDMs was used for multiplexing the pump wavelength of 976 nm with the signal wavelength at 1064 nm and simultaneously for spectral filtering of the chirped pulses. Its transmission had a spectral full width at half maximum (FWHM) of 31 nm. The second WDM acted as output coupler between 1000 and 1040 nm and had a FWHM of 81 nm. The ring cavity had a repetition rate of 24 MHz. With this setup we achieved stable mode-locked operation at a central wavelength of 1064 nm. By using the WDM cascade, the ASE suppression was better than 40 dB. The pulses had a pulse energy of 100 pJ and a spectral FWHM of 7.7 nm, which resulted in a Fourier transform limited pulse duration of 296 fs. We were able to dechirp the pulses to a duration of 307 fs.

8237-103, Poster Session

Extreme value statistics in Raman fiber lasers

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We present the numerical study of the statistical properties of the partially coherent quasi-CW high-Q cavity Raman fiber laser (RFL). Using the NLSE-based numerical modeling, we have found that the radiation of RFL consist of two different parts which have different statistical properties. The central spectral part of the radiation comprises longitudinal modes being uncorrelated on small wavelength detunings. Whilst the far spectrally detuned longitudinal modes have to be correlated. A physical mechanism of far spectrally detuned mode correlations should be further clarified. Far spectral wings are generated at one fiber pass only. The intensity PDFs of spectral wings reveal the existence of extreme rare events. As the extreme rare events are generated at far spectral wings, they are more pronounced at the laser output being self-filtered out by laser mirrors. The main physical mechanism of extreme event emergence in Raman fiber laser is turbulent-like four-wave mixing processes between numerous longitudinal modes in generation. The similar mechanism of extreme waves appearance during the laser generation could be important in other types of fiber lasers including Ytterbium doped fiber laser and random distributed feedback fiber lasers operating via Raman or Brillouin gain.

8237-104, Poster Session

A novel sensing technique based on optical feedback interferometry to monitor fiber laser microfabrication

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We develop a compact laser ablation sensor based on the optical feedback interferometry to characterize in real-time high precision micromachining process onto metallic solids. Instantaneous monitoring of physical parameters such as the penetration depth and the removal rate is demonstrated with sub-micrometer resolution. The spatial- and time-dependent evolution of the ablation front can be simply revealed by counting the interference fringes measured at the output power of the probe laser when a fraction of light back-reflected at the bottom surface of the drilled hole is re-injected into the optical cavity. In addition, we provide both theoretical and experimental evidence that a single interferometric sensor is capable to simultaneously distinguish optical feedback coming from two surface sections, measuring the independent displacement of individual portions of the same target by arranging an appropriate combination of the optical components in the setup. Specifically, interferometer fringes relative to the ablation process are shown to be superimposed to those generated by the target translation along the optical axis, allowing real-time correction of target displacement and/or vibration during the drilling time. This novel technique is proven successful on metal plates without requiring any sample preparation and should in principle be applicable to non-metallic materials as well. Also, the ablation sensors can be easily integrated in most laser micro-machining systems due to the high-performance and inherent simplicity of our approach. This will allow a deeper and systematic investigation of laser-matter interaction physics with important implications for the development of on-line control methods of laser micromachining.

8237-105, Poster Session

Tellurite glass and fiber development for mid-IR transport and super-continuum applications

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The mid-infrared region (MIR) between 2 and 5 microns is of interest in many applications because many organic species possess fundamental absorptions in this region leading to many sensing applications. The need for very broad-band sources in the MIR is driving research into glasses with high optical non-linearity. All fiber-based systems are particularly attractive because they are monolithic, robust, reliable, and free of alignment or maintenance.

Typical fibers used in the MIR region exhibit several problems. Of major concern is that the glass displays a high degree of stability during fiber drawing in order to avoid crystallization and high losses. Because of tellurite glass relatively high Tg of > 340 C, it has potential to avoid this, and at the same time offer possibility of being mechanically stronger and more robust than glass fibers so far used in mid-IR.

We are developing low loss tellurite glass and fibers - following two main themes. One is the elimination of residual hydroxyl content by a specialized drying process. We have been successful in suppressing the strong hydroxyl peak at 3.3um with drying. A second theme is to develop glass compositions free of tungsten to extend the long wavelength edge towards and beyond 5um. As a result of these positive developments, we have produced single mode tellurite glass fibers with core loss at ~1 dB/m level, and cladding loss at less than ~ 0.2 dB/m. We are able to splice these fibers to standard silica fibers to facilitate convenient pump delivery for super-continuum generation.

8237-107, Poster Session

Lasing in thulium doped polarizing photonic crystal fibers (PCF)

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We describe lasing in thulium doped polarizing PCF. The fiber used was 4 m long, with 50/250 µm core/cladding diameters and a hole diameter-to-pitch ratio of 0.18. This fiber was end pumped with a 35 W, 793 nm diode laser, and the performance was characterized in both co-pumping and counter-pumping configurations. In both the configurations, the slope efficiency was >35 % with 13 dB without any intra-cavity polarizing components. The maximum power was ~4 W limited by the inefficient cooling of the fiber. The high cladding pump absorption of ~5 dB/m and the ~40 µm mode field diameter (1250 µm2 mode field area) make this fiber attractive for use in high energy and high peak power amplification of short and ultrashort laser pulses at 2 µm wavelength.

8237-108, Poster Session

Fiber laser micromachining of magnesium alloy tubes for biocompatible and biodegradable cardiovascular stents

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Magnesium alloys constitute an attractive solution for cardiovascular stent applications due to their intrinsic properties of biocompatibility and relatively low corrosion resistance in human-body fluids, which results in as a less intrusive treatment. Laser micromachining is the conventional process used to cut the stent mesh, which plays the key role for the accurate reproduction of the mesh design and the surface quality of the produced stent that are important factors for biocompatibility. Traditionally continuous or pulsed laser systems working in microsecond pulse regime are employed for stent manufacturing, yet the manufactured stents possess common defects such as heat affected zone and dross around the cut edges due to the melting based process. Pulsed fiber lasers on the other hand, are a relatively new solution which could balance productivity and quality aspects with shorter ns pulse durations and pulse energies in the order of mJ. This work reports the study of laser micromachining of AZ31 magnesium alloy for the manufacturing of cardiovascular stents with a novel mesh design. A pulsed active fiber laser system operating in nanosecond pulse regime was employed for the micromachining. Laser parameters were studied to realize micro cuts on tubes of 2 mm in diameter and 0.2 mm in thickness. Process window was determined initially to realize material separation with linear cuts on the tube longitudinal axis. Then the parameters were further analyzed with the aim of reducing backwall damage and dross. Process parameters were optimized for reactive and inert gas cutting solutions for quality comparison.

8237-109, Poster Session

Increasing energy in an ytterbium femtosecond fiber laser with a longer gain medium and lower doping

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An increase in energy of pulses generated in a similariton mode-locked femtosecond fiber laser is shown experimentally by increasing the length while reducing the doping of the ytterbium-doped fiber gain medium. Mode-locking is achieved by nonlinear polarization rotation evolution in a cavity using a combination of fiber and bulk optical components. The level of doping of the gain medium is varied by using lengths of differently doped ytterbium fiber. To observe only the effects of the variation in length and doping of the gain fiber while maintaining a constant nonlinear phase shift, a number of cavity parameters are adjusted after each change in the gain medium. The parameters kept constant between measurements include the repetition rate by controlling the cavity length, the total length of fiber contributing to the nonlinearity, and the pump power. Measurements are taken for several values of group velocity dispersion in the cavity by tuning the anomalous dispersion generated by diffracting gratings. The differently doped ytterbium fibers are selected to have the same core diameter and mode field diameter so that the only critical change between the physical parameters of the fibers is the doping value, which results in varying the gain per unit length and the rate at which the nonlinear phase shift is accumulated. Experimental results verify that an increase in length of gain medium with a lower doping results in an increase in the output pulse energy.

8237-110, Poster Session

Avoided-crossing based modal cut-off analysis of 19-cell double-cladding photonic crystal fibers

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Yb-doped double-cladding Photonic Crystal Fibers (PCFs) with core obtained by removing 19 air-holes from the inner cladding triangular lattice have been proposed as key components for power scaling of fiber laser systems, allowing for core diameters up to 100 µm. Anyway, single-mode operation, which is a key factor for many high power applications, is a critical design requirement for such large core fibers. It has already been demonstrated that the traditional approach based on the fundamental space-filling mode of the infinite cladding is not reliable to calculate the modal cut-off condition for this type of PCFs. On the contrary, it is necessary to consider the avoided-crossing between each guided mode and the first cladding mode of the real fiber, that is with core defect and cladding of finite dimension. In this paper the cut-off properties of 19-cell PCFs have been analyzed in further detail using a full-vector modal solver based on the finite element method. In particular, the influence of the air-hole diameter on the cut-off condition of the fundamental and the first higher-order mode has been investigated. Different values of the refractive index of the down-doped core have been also considered. The cut-off wavelengths of both fundamental and first higher-order mode, and their overlap integral on the doped core at the avoided crossing condition have been calculated, in order to find generalized results to describe the single-mode regime of 19-cell double-cladding PCFs. The Authors acknowledge the support of the EU funded FP7 ALPINE Project, n. 229231.

8237-111, Poster Session

All-in-one 1236-nm Yb/Raman fiber laser

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Cascaded Raman fiber lasers are versatile light sources that can operate at wavelengths where rare-earth doped fiber lasers are unavailable. Recently, a 1240 nm Raman fiber laser was used to extend the reach of a gigabit passive optical network (GPON) (Zhu et. al. Opt. Exp. 2010).

Typically a Raman fiber laser consists of a pump laser followed by a cascaded Raman resonator (CRR). The pump laser is often a Yb-doped fiber laser operating in the 1 to 1.1 um wavelength range. The CRR consists of a length of Raman fiber (usually a few hundred meters) and fiber Bragg gratings (FBGs) that form a nested series of cavities to provide multiple cascaded Stokes shifts. While this laser source works well, it consists of multiple fiber types and grating sets, creating complexity and increasing the cost of making such lasers.

In this paper, we present for the first time to the best of our knowledge, a cascaded Raman fiber laser where the functions of Yb-doped fiber and Raman gain are combined into a single fiber. This integration results in a substantial simplification of the CRR architecture and consequently the number of fiber types and components required.

8237-112, Poster Session

Single-output 3-wavelength multi-watt CW visible fiber laser system

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We present, to the best of our knowledge, the first 3-wavelengths (Green, Yellow, Red) CW visible all-fibre laser system providing multi-Watts output powers, using a robust and wavelength-switchable single-pass SHG architecture. We choose to combine the unique properties of Yb and Er/Yb fibre lasers with efficient non linear periodically-poled crystals for visible wavelengths generation, in a versatile and simple configuration that guarantee the robustness of the system. The whole system is based on three all-fibre infrared lasers emitting 18.5W at 1064 nm, 16 W at 1154 nm and 11.5W at 1560 nm, followed by a non linear stage generating 532 nm by SHG of 1064 nm, 577 nm by SHG of 1154 nm or 633 nm by SFG of both 1064 and 1560 nm. All the fundamental infrared fibre lasers had been specifically developed for efficient non-linear process with PP-crystals. They all provide a linearly polarized (PER >15 dB) single-mode beam (M^2<1.1), with a narrow linewidth (<0.05 nm). To keep all advantages of fibre lasers, we combined the three infrared lasers into the same output fibre, using a specific PM wavelength multiplexer. The common output of the 3-infrared-wavelengths laser system is sent into a non linear conversion stage containing 3 optimized periodically-poled crystals. The crystals are mounted on a moving thermally regulated copper mount and followed by a set of three dichroic mirrors. At the common free space output, the system provides either 4W at 532 nm, 3W at 577 nm or 3.5W at 633 nm with perfect beam quality.

8237-113, Poster Session

Mid-infrared strong spectral broadening in microstructured tapered chalcogenide AsSe fiber

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Chalcogenide glasses are remarkable not only for their strong optical nonlinear refractive index which can be up to 800 times higher than the one of silica but also for their large transparency extending far in the infrared. Theses glasses can be used for many applications such as supercontinuum generation or wavelength shifting. We report for the first time to our knowledge the generation of a supercontinuum in an AsSe chalcogenide microstructured tapered fiber. The suspended core diameter of the fiber is reduced from 5.5 µm at the fiber input to 0.8 µm in the waist of the tapered fiber. The length of the taper is 5 cm. Modeling shows that the first zero dispersion dispersion wavelength (ZDW) is shifting from approximately 3.45 µm in the non tapered region to 1.8 µm in the tapered region. To pump the fiber close to the ZDW, we use a mode-locked laser of 4 ps, with a central wavelength of 1960 nm and 43 mW average power. We adapt the size of the laser mode to the AsSe fibre mode using ultra high numerical aperture fiber. With only 20 W peak power in the chalcogenide fiber a supercontinuum is generated from 1300 to 2600 nm taking the supercontinuum wavelength edge at -30 dB from the continuum. We observe in the spectrum evidence of 3rd order Raman scattering and four wave mixing at low peak power.

8237-114, Poster Session

Broadband multi-mode group-velocity dispersion determination in photonic crystal fibers from 0.4 µm to 1.7 µm

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Group-velocity dispersion enables the efficient generation of broad supercontinuum and solitary pulse propagation. However, along with damage threshold, it also limits the power scalability for fiber laser concepts. When calculating the dispersion of microstructured fibers, structural inaccuracies and imperfections make a significant impact on the theoretical dispersion. Especially in the field of fiber lasing the dispersion in the mid-infrared and visible spectrum is essential.

This report presents a time-frequency-domain white-light interferometer for modally resolved group-velocity dispersion measurements in photonic crystal fibers via dual-channel detection in the spectral range from 0.4 µm up to 1.7 µm. By varying the delay position in the reference path the propagation time changes. Well-defined wavelengths experience a group-velocity in the fiber which leads to an equivalent time delay as in the reference path. Hence, constructive spectral interference occur for that equalization wavelength. Applying a three-term Sellmeier polynomial and derivating this function yields the overall dispersion of the fiber sample.

Using this setup allows the simultaneous dispersion characterization in the visible and near-infrared spectrum for the fundamental and higher order modes with accuracies of about 5 nm. Conventional step-index and photonic crystal fibers can be investigated. Typical applications are the validation of the drawing process for photonic crystal fibers as well as the estimation of laser fibers and fiber amplifiers.

8237-115, Poster Session

Confined-doped ytterbium fibers for beam quality improvement: design, fabrication and performance

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Increasing the output power has been one of the key targets for fiber laser research. Since the high-power laser beam is confined in the small core region and it propagates along the whole length of fiber, detrimental nonlinear effects are relatively easy to occur, which set a technical limitation for power scaling.

In order to overcome this limitation, large-mode-area (LMA) fibers are commonly used to extend the mode area, and accordingly, to mitigate the nonlinearities. However, the enlarged core diameter makes the fiber multi-mode, which significantly deteriorates the output beam quality.

Confined-doped fibers can improve the beam quality. By confining the Yb doping within a smaller radius in the center of the core of the large-mode-area fiber, the fundamental mode, which overlaps better with the Yb ions, sees more gain than the higher order modes, and dominates the output.

In this paper, modeling and numerical simulations are carried out based on three-dimensional rate equations and beam propagation method (BPM). Several design considerations, such as doping/core/clad sizes, active/passive dopant concentration distribution, refractive index profile, fiber bending, etc, are investigated. Several fiber samples with different parameters are fabricated by Direct Nanoparticle Deposition (DND) process. The confined-doped fiber samples are tested in fiber laser setups. Significant improvement in beam quality is achieved. Near-diffraction-limited beam quality (M2~1.3) is experimentally demonstrated by using a fiber sample with >40 µm core diameter.

Such fibers have shown great potential for mitigating the detrimental nonlinear effects and for power scaling of fiber lasers and amplifiers.

8237-116, Poster Session

High-power ultrashort fiber laser for solar cells micromachining

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The laser is based on an all-PM CPA operating around 1030 nm. The oscillator is an all fiber All-Normal Dispersion (ANDi) laser. This kind of laser requires spectral filtering in the cavity to ensure stable mode-lock operation. This is achieved in our case with a tilted Chirped Fiber Bragg Gratings (CFBG) for the first time to our knowledge. The oscillator remains therefore all fibered and thus compact and reliable. Self-starting operation is ensured by a MQW SESAM exhibiting high modulation depth and ultra-fast relaxation time. The oscillator delivers 6,5 ps highly chirped optical pulses at a repetition rate of 34 MHz. The optical spectrum has a FWHM of 7,5 nm. This means that less than 500 fs pulse duration could be achieved after compression.

Then the repetition rate is decreased to few hundreds of kilohertz thanks to a fiber coupled Acousto Optics Modulator. To avoid nonlinear effects during amplification, the optical pulses are temporally stretched to 370 ps with a high dispersion CFBG. Three amplification stages are used. The first stage is based on a single-mode Ytterbium-doped fiber, the second on a double-clad Ytterbium-doped fiber; and the last stage on a rod-type fiber with a core diameter of 40 µm pumped by a 976 nm 50W multimode diode. The signal is temporally compressed with a pair of transmission gratings used in the Littrow configuration.

8237-117, Poster Session

Diode lasers with programmable pulse shapes as a versatile seeding source for fiber amplifiers

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Fiber amplified diode lasers begin to establish as an ideal beam source for fast and precise material processing. Using a gain switched laser diode (GSLD) as a seeding source yields pulse width down to 40 ps and has many advantages over other technologies like mode-locking or electro-optical modulation. Pulses can be released in an arbitrary time regime which offers a wide range of pulse repetition frequencies (PRF) including adaptive PRF or burst modes. At low PRF, the ultimate extinction ratio of GSLDs helps to keep the cw background of the amplifier's output low.

In this paper we present picosecond and nanosecond seeding sources based on gain-switching technology.

The picosecond diode laser can be operated at any PRF between single shot and 80 MHz. A special electrical signal generator can create any trigger-pulse pattern on a 12.5 ns time grid.

The nanosecond diode laser is designed to provide variable pulse widths as well as sawtooth functions on a nanosecond time-scale. The combination of multiple such signals with different parameters allows for the generation of more complex pulse shapes, which can be used for the compensation of fiber amplifier's saturation effects or for special ablation modes.

As an outlook, we show the performance of an arbitrary waveform generator chip with a timing resolution of 100 ps, which can be used for laser pulse shaping at the highest degree of freedom.

8237-118, Poster Session

Theoretical mode reconstruction methods based on spatially resolved spectra

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The demand to measure and analyse the power content of modes excited in optical fibers led to a multiplicity of methods developed in recent years. Especially the spatially and spectrally resolved imaging (S2) represents an elegant and robust tool for mode reconstruction. The main advantage of this method is that no prior knowledge about the guided modes is required. However, the modal reconstruction algorithm used up to now is based on the assumption that most of the power is guided in the fundamental mode. To overcome this limitation we investigated theoretically spatially resolved spectra calculated using a simulated S2-measurement. It can be shown that if more than two different modes interfere, two analytical modal reconstruction methods exist. The accuracy in reconstructing the spatial intensity and phase distribution of the modes using these two different methods is studied as a function of the modal power contents, number of interfering modes and types of modes. It can be seen that with an increasing number of modes the analytical reconstruction methods become more robust and larger higher order mode contents can be reconstructed precisely. Furthermore, we present an iterative algorithm that significantly reduces the error when calculating the relative power contents of the modes. This algorithm is independent from the power contents of the modes and is suitable for all the explained methods.

8237-119, Poster Session

2D mode selection in laser resonators using reflecting volume Bragg gratings

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Spatial mode selection is an integral part of any laser system especially high power fiber lasers using large mode area fibers.

In this paper, we introduce a new method for 2-D transverse mode selection by utilizing the cylindrically symmetric angular selectivity of reflecting volume Bragg gratings (VBGs). The technique is demonstrated for an Yb-doped multimode (20 μm core) fiber laser with an external cavity formed with a HR mirror and a VBG output coupler (DE ~ 60%, FWHM linewidth ~110 pm at 1064 nm, FWHM angular selectivity ~15 mrad at normal incidence).

When the VBG is aligned in the collimated beam (angular selectivity of the VBG is more than order of magnitude wider compared to diffraction limited divergence of the beam), the output beam profile is unstable and shows several transverse modes as well as transitions between them. When the VBG is aligned in the convergent beam, only the part of radiation within its cone of angular selectivity is reflected while the rest is transmitted. Thus, when the focusing system is properly optimized so that only the lowest order mode receives feedback to establish lasing, while all other higher order modes incur higher losses, the output beam divergence becomes diffraction limited and very stable. We show that this method is highly robust against vibrations, temperature fluctuations, and power variations. It is important that this method provides complementary dramatic spectral narrowing of laser output without penalty in power and efficiency of the laser system.

8237-120, Poster Session

Wavefront reconstruction and modal decomposition of fiber laser beams from intensity images

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The reconstruction of the wavefront of laser beams is an important diagnosis tool that allows, among others, the fast calculation of the beam-quality parameter, the modal decomposition of the beam, and the optimization of the optics required to deliver the beam. Obtaining the intensity image of the wavefront can be done with high speed and high-resolution using commercially available cameras. However, obtaining the spatial phase is much more complicated. There are several commercially available wavefront sensors, but these tend to be expensive and lack high spatial resolution. Furthermore, a fundamental limitation of most of these systems is that they can only detect the curvature of the wavefront, and not the real spatial phase. Thus, for example a phase shift in the spatial phase (as that commonly occurring in fiber modes, for example) will not be detected. In this contribution we show a way to reconstruct the real spatial phase of a laser beam from two intensity images obtained at two different points along the propagation path of a laser beam. The method employs the Gerchberg-Saxton algorithm typically used for the calculation of holograms. Since only intensity images are required the method is inherently fast, has a high spatial resolution and is low cost. Furthermore, once that the real spatial phase has been recovered the complete wavefront can be decomposed into the different eigenmodes of the laser system by using a simple cross-correlation, making the speed and accuracy of this modal decomposition independent of the number of modes.

8237-121, Poster Session

Measurement of photodarkening losses and self-similarity of time evolution

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We report on an extensive investigation of photodarkening in Yb-doped silica fibers. To compare the photodarkening induced losses a set of similar fibers, covering a large Yb concentration range, was made. The results show that, once a careful choice of set-up parameter, the stretching parameter obtained through fitting has a very limited variation. We investigated the impact of fibre length on errors in fitting parameters. We propose to choice the proper fiber length.

This gives more meaning to the time-evolution fitting parameters and we show self-similarity for all fibre.

In addition results suggest a quadratic dependence of photodarkening losses with respect to Yb concentration. This has a strong implication in understanding photodarkening.

We also found a less that 4th power dependence of time evolution parameter.

Based on our results we can now propose a standard for measuring the photodarkening losses and a possible Figure of merit to define PD-related properties of a fiber.

This paper is a joint effort with FP7 LIFT project and more data will be presented at the conference.

8237-122, Poster Session

Broadly tunable high-power random fibre laser

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As shown recently, a long telecommunication fibre may be treated as a natural one-dimensional random system, where lasing is possible due to a combination of random distributed feedback via Rayleigh scattering by natural refractive index inhomogeneities and distributed amplification through the Raman effect. Here we present a new type of a random fibre laser with a narrow (~1 nm) spectrum tunable over a broad wavelength range (1535-1570 nm) with a uniquely flat (~0.1 dB) and high (>2 W) output power and prominent (>40 %) differential efficiency, which outperforms traditional fibre lasers of the same category, e.g. a conventional Raman laser with a linear cavity formed in the same fibre by adding point reflectors. Analytical model is proposed that explains quantitatively the higher efficiency and the flatter tuning curve of the random fiber laser compared to conventional one. The other important features of the random fibre laser like “modeless” spectrum of specific shape and corresponding intensity fluctuations are discussed qualitatively, and the techniques of controlling its output characteristics are discussed.

Outstanding characteristics defined by new underlying physics and the simplicity of the scheme implemented in standard telecom fibre make the demonstrated tunable random fibre laser a very attractive light source both for fundamental science and practical applications such as optical communication, sensing and secure transmission.

8237-123, Poster Session

3-µm optical fiber laser based on guided mode resonance filter

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In this paper, we demonstrate a continuous wave (CW) fiber laser operating in the 3 µm wavelength region using the spectral narrowing capabilities of guided mode resonance filters (GMRFs) with Er-doped ZBLAN fluoride fiber. GMRFs provide high reflection at a specific resonance wavelength, therefore they can be used as spectrally selective feedback elements in a laser oscillator. Depending on specific design parameters, the resonance wavelength, peak reflectivity and spectral linewidth of the GMRFs can be modified. The GMRFs are measured by placing them in the output path of the Er-doped fluoride fiber and utilizing the amplified spontaneous emission (ASE) of the fiber as a light source; this causes the GMRF resonance to appear as a notch on the output spectrum and a peak on the reflected spectrum. The wavelength range for which the GMRF resonances are characterized is between 2.8 µm and 3 µm. The Er-doped ZBLAN fluoride fiber is continuously pumped by a 970 nm laser diode and the laser cavity is formed between one side of the fiber end and the GMRF located on the opposing fiber end; the GMRF filters both the ASE spectrum and the residual pump light. The free lasing peak of the Er-doped fiber is roughly 2.78 µm; after implementing the GMRFs the laser is able to oscillate between 2.8 µm and 2.9 µm.

8237-124, Poster Session

Q switched PM Tm: fiber laser oscillator for mid-IR generation

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We have developed a Q-switched polarization maintaining (PM) Tm:fiber oscillator. This system is capable of generating pulses with >290 µJ polarized pulse energy and 10 W average power. At 10 kHz, this ~2 kW peak power source was used to induce nonlinear spectral broadening. After propagation through a 25 m length of SMF-28, we have observed the generation of a broadband spectrum extending from the pump wavelength of 2010 nm to 2300 nm 30 dB below the peak.

8237-125, Poster Session

High power ultra-violet quasi-CW fiber based laser system

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We present a fiber-based ultraviolet laser source that combines the advantages of a quasi-cw output and the reliability and scalability of fiber lasers. Typically, quasi-cw UV sources-sources having a repetition rate of 10 MHz or greater-are based on mode-locked infrared lasers that are frequency-converted. However, such lasers produce picosecond pulses that cannot be amplified in fiber because self-phase modulation broadens the spectrum so much that frequency conversion becomes inefficient. We introduce a quasi-cw seed source at 1064 nm with pulse lengths of approximately 0.5 nsec, whose pulses are amplified in a series of fiber amplifiers, culminating in a large mode area photonic crystal fiber. The output is frequency-converted using two LBO crystals oriented to produce the second and third harmonics. This Mobius system has previously been used to generate over 65 W of infrared and 30 W of UV power at 400 kHz. The new quasi-cw source relies on an improved amplifier chain with increased pump power, and achieves 50% conversion efficiency to the ultraviolet. Such a system can be scaled to produce 100 W of infrared, and over 50 W of quasi-cw UV light.

8237-126, Poster Session

Gain-switched laser diode seeded ytterbium doped fiber amplifier delivering 14-ps pulses at repetition rates up to 40 MHz

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Semiconductor gain-switched laser diodes with direct fiber amplification are compact, reliable and cost-effective sources of picosecond pulses with pulse energies up to several µJ and tunable repetition rates from pulse-on demand to GHz. Shorter pulses than currently available from such systems are desirable for certain applications, e.g. in material processing the efficiency and quality of metal ablation is significantly improved. Until recently, the shortest pulse duration from gain-switched laser diodes was several tens of picoseconds at MHz repetition rates.

Here, we demonstrate all-fiber direct amplification of 14 picosecond pulses from a gain-switched Diode Laser at 1064nm. The diode is driven at a repetition rate of 40MHz and delivers 15µW of fiber-coupled average output power. For the low output pulse energy of 0.4pJ we have designed a multi-stage core pumped preamplifier based on single clad Yb-doped fibers in order to keep the contribution of undesired amplified spontaneous emission as low as possible and to minimize temporal and spectral broadening. After the preamplifier we reduce the 40MHz repetition rate to 1MHz using a fiber coupled pulse-picker. The final amplification is done with a cladding pumped Yb-doped large mode area fiber and a subsequent Yb-doped rod-type fiber. With our setup we reach pulse energies of several µJ.

8237-127, Poster Session

Injection seeded Q-switched ring cavity fiber laser with transform-limited pulses in the C-band

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In this paper, we demonstrate the use of single-frequency seed injection into an erbium doped, single mode fiber laser ring cavity to achieve transform-limited, pulsed output. By tuning the seed wavelength, the output signal wavelength can also be tuned, without changing the cavity configuration. An output pulse with a smooth, single peaked temporal profile is achieved. The Q-switching is achieved by using an acousto-optic modulator (AOM) in the cavity, which allows fast and controllable switching performance. By controlling the AOM drive signal repetition rate, output pulse widths ranging from hundreds of nanoseconds to several microseconds are achieved. The transform-limited linewidth of the fiber laser pulses was verified by using a fiber-based Fabry-Perot. In order to understand the origin of pulse characteristics, we have developed a numerical model and simulated the pulse formation from the cavity. The AOM transmission and several cavity parameters that can change pulse characteristics are studied. The numerical study is a guide for the fiber laser cavity design, and the numerical results agree well with the experimental results.

8237-128, Poster Session

Mid-infrared generation in ZnGeP2 pumped by a monolithic, power scalable 2-µm source

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There is a requirement for high power, compact, efficient mid-IR (3-5 µm) laser sources for defence applications such as infrared countermeasures. The highest average power solid-state lasers targeting this wavelength region have been based on the frequency conversion of a pulsed 2.1 µm Ho:YAG laser in a Zinc Germanium Phosphide (ZGP) optical parametric oscillator (OPO). Such systems have been demonstrated with average output powers greater than 20 W. Power scaling in these systems is typically achieved by increasing the number of Ho:YAG gain modules thereby increasing the size and complexity of the laser source. Large mode-area (LMA) thulium doped fibre (TDF) offers an attractive alternative to power scaling a 2 µm source with >600 W generated from a single stage cw amplifier.

Commercially available polarisation maintaining (PM), LMA TDF with a 25 µm core and a 400 µm cladding (NUFERN) has been used in a Q-switched laser configuration to produce energies of >350 µJ. A non-PM LMA TDF with a similar core and cladding (NUFERN) has been used in an amplifier configuration to produce pulses with energies of >300 µJ. At these energies, pulse durations of 20-40 ns are required to achieve the peak power necessary for efficient frequency conversion in a ZGP OPO. So far ZGP OPO based 3 - 5 um sources pumped directly by pulsed thulium fibre lasers have used non-polarisation maintaining (PM) fibre and have demonstrated 2 W of output with a conversion efficiency of 16% from the thulium 2 um pump. We demonstrate a source, composed entirely of PM components, which operates with a significantly improved efficiency of 25%.

8237-129, Poster Session

Anti-symmetric hybrid photonic crystal fibers with enhanced filtering and bending properties

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Hybrid Photonic Crystal Fibers (PCFs) provide light confinement by both modified total internal reflection, due to the presence of an array of air-holes in the cladding, and by the photonic bandgap effect, obtained by replacing air-holes with high-index inclusions. By carefully designing the high-index features, the narrow transmission window of these fibers can be tuned at the optimum wavelength for Yb-doped fiber amplifiers, from 1030 nm to 1178 nm, with the possibility to perform ASE and SRS filtering, without worsening the pump efficiency. Double-cladding Yb-doped hybrid PCFs with one row of anti-symmetric resonators, capable of narrow-band distributed spectral filtering, has been already demonstrated.

In this paper a new design of double-cladding hybrid PCFs has been investigated with a full-vector modal solver based on the finite element method. In particular, three rows of cladding air-holes on each side of the fiber core have been replaced by high-index inclusions with different diameters. Simulation results have shown that a stronger filtering effect and a higher bending tolerance can be obtained with respect to hybrid fibers previously demonstrated. Moreover, the mechanisms beyond the unique bending properties of hybrid PCFs with anti-symmetric high-index rods have been thoroughly analyzed, showing how the fiber transmission band can be tailored by acting on the bending diameter. The Authors acknowledge the support of the EU funded FP7 ALPINE Project, n. 229231.

8237-130, Poster Session

True crystalline fibers: double-clad LMA design concept of Tm:YAG-core fiber and its mode simulation

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YAG crystalline fibers hold great promise for laser power scaling due to their ~8 times higher thermal conductivity as well as over an order of magnitude higher absorption and emission cross sections of common rare-earth (RE) dopants compared with the conventional silica glass fibers with the same RE dopant [1]. Theoretical estimates indicate that tens of kilowatts of laser output power is feasible to be achieved for cladding-pumped crystalline fiber lasers from only a meter of fiber length. Current fiber growth (or pulling) techniques have not yet been successful producing coilable, low loss, single-mode, double-clad single-crystalline or polycrystalline ceramic fibers. As an alternative, adhesive-free bond (AFB) technology may readily be used for fabricating high optical quality coilable waveguide structures from rare-earth doped YAG single crystals, though in this case the waveguide structure will have square (or rectangular) core shape.

In this work, we present a sub-100 um double-clad Tm:YAG square core AFB waveguide structure, a prototype gain medium for a large mode area (LMA) ~2-um laser with ~790-nm diode laser pumping and perform its mode simulation. The structure uses an un-doped YAG and ceramic spinel for the inner and outer claddings, respectively. The mode simulation indicates that such double-clad structure can have over 1000-um2 mode area in a 2% Tm:YAG core which will maintain a single transverse mode laser operation. The structure also has a large numerical aperture (~0.22) for the un-doped YAG inner cladding available for pumping. It is shown that LMA single-mode AFB waveguides can also be designed for higher doping Tm:YAG crystals by adjusting the refractive index of the inner cladding with laser inactive RE ion doped YAG.

References:

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8237-131, Poster Session

Robustly single-mode large-area fibers with asymmetric bend compensation

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Large mode area fiber design enables power scaling in fiber amplifiers and lasers. Several fiber types have been proposed to address the limitations of conventional approaches, but most do not overcome bend distortion. Thus, effective area is still limited to around 1000 square microns for fundamental-mode operation in a practical coiled arrangement.

This limitation can be removed using the asymmetric bend compensated (ABC) strategy [1]. We recently showed ABC designs with large calculated effective areas [2], but they had only modest suppression of higher-order modes (HOMs). Here, we show that improved designs can achieve large essentially “complete” (~50dB) suppression of HOMs along with low fundamental loss (3000 sq. micron area with highly suppressed HOMs (HOM Loss ~ 100x fundamental loss). All other strategies are limited to ~800-1400 square microns by the HOM suppression tradeoff (for perfect fabrication).

ABC fibers require very precise index profiles, and oriented of the fiber when coiled. Despite these challenges, the ABC strategy promises dramatic impact on high-power applications.

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[2] J. M. Fini, CLEO 2011.

8237-132, Poster Session

Ytterbium-doped large-mode-area photonic crystal fiber amplifier with gain shaping for use at long wavelengths

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High-power fiber amplifiers in the long wavelength regime of the Ytterbium gain spectrum are needed for frequency doubling to the yellow-orange regime, having applications within the medical industry, high-resolution spectroscopy and laser-guide-stars. Nonlinear effects and amplified spontaneous emission (ASE) are obstacles limiting peak power, decreasing slope efficiency and causing parasitic lasing. The nonlinear threshold can be lowered through large-core designs, but maintaining single-mode performance is challenging. Discrete filtering of ASE can be achieved in multi-stage amplifiers, however a delicate balance between gain and insertion loss exists.

We demonstrate a new design for efficient distributed spectral filtering (DSF) of ASE in a single-stage Ytterbium-doped double-cladding photonic crystal fiber amplifier. The outer cladding provides confinement of pump light. The inner cladding region has air holes arranged in a hexagonal structure, with seven missing air-holes defining the low numerical aperture core of ~36 um diameter. Three rows of holes along one axis, on each side of the core, are replaced with high-index inclusions, providing DSF through the photonic bandgap effect. The inclusions have different diameters on each side of the core respectively, enabling accurate selection of the amplified wavelength by size-tuning. We thereby demonstrate a large-mode-area Ytterbium-doped amplifier working in the 1180 nm region with controlled gain shaping and efficient ASE suppression.

8237-133, Poster Session

Design optimization of a photonic crystal fiber rod amplifier having distributed modal filtering

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High-end fiber amplifiers for pulsed applications require Large Mode Area (LMA) fibers having high pump absorption and near diffraction limited output. This improves limiting factors such as nonlinear effects and amplified spontaneous emission, while maintaining good beam quality. Photonic crystal fibers allow realization of short LMA fiber amplifiers having high pump absorption through a pump cladding that is decoupled from the outer fiber. However, achieving ultra low NA for Single-Mode (SM) guidance is challenging, and thus different design strategies must be applied to filter out Higher Order Modes (HOMs). The novel Distributed Modal Filtering (DMF) design presented here enables SM guidance, and previous results have shown a SM mode field diameter of 60 µm operating in a 20 nm SM bandwidth.

The DMF fiber has high index inclusions acting as resonators enabling SM guidance through modal filtering of HOMs. Large preform tolerances are compensated during the fiber draw resulting in ultra low NA fibers with very LMA. In this paper, design optimization of the SM bandwidth of the DMF fiber is presented. Analysis of band gap properties results in a fourfold increase of the SM bandwidth (80 nm) compared to previous results, achieved by utilizing zeroth order cladding modes. This covers of a large fraction of the Ytterbium absorption band, including wavelengths of 1030 nm and 1064 nm.

8237-134, Poster Session

Fiber based generation of azimuthally polarized light

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Many applications would benefit from azimuthally and radially polarized beams compared to standard polarization types. Examples are material processing, microscopy, excitation of plasmons, optical trapping and electron acceleration. A stable source with high polarization purity is required for these applications. We report on a novel approach of fiber based generation of azimuthally polarized light which employs a fiber mode filter for the azimuthally (or radially) polarized fiber modes. The mode filter consists of a Fiber Bragg Grating (FBG) written in a strongly guiding fiber with lifted modal degeneracy. Therefore, in this fiber the azimuthally and the radially polarized modes have different effective refractive indexes. The FBG maps the effective refractive index of each mode into the spectrum. Therefore, if the reflection bandwidth of the FBG is narrow enough then mode selection is possible by tuning the wavelength. In a proof-of-principle experiment we used a FBG inscribed by fs-pulses, integrated in a commercially available high NA step-index-fiber to separate the azimuthally polarized TE01 mode. A broadband single mode ASE source was spectrally filtered with two etalons thus acting as a tuneable narrow bandwidth light source. By misaligning the focussing lens it was possible to excite (at least partly) the TE01 mode in the fiber, which was then cleanly reflected by the FBG. In the presentation we will discuss possible fiber designs to generate radially and azimuthally polarized modes using a single fiber mode filter. Additionally, the possibility of building oscillators and high power configurations and the generation of pulsed radiation possessing non-standard polarization characteristics will also be discussed.

8237-135, Poster Session

Experimental characterization of Hänsch-Couillaud-based stabilization for coherent combining of ultrashort laser pulses

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The recent developments proved that the implementation of coherent beam combining for ultrashort laser pulses is not just possible but worthwhile to increase the average output power and pulse energy of ultra short pulse laser systems. The combination of ultra short pulses with a pulse energy of 66µJ, delivered by two fiber-amplifier-systems to a combined pulse energy of 120µJ, while maintaining the spectral and temporal form, was recently shown. This setup has been used to investigate the system stability under consideration of the required interferometric superposition.

We were able to show, that typical amplitude fluctuations of a common ultra short laser system, which take effect in the error-signal of the Hänsch-Couillaud detector, do not affect the stabilization mechanism in a significant way. This is an important statement if the number of channels might be increased, because every fluctuation propagates through the further system and may cause even higher errors in later combining steps.

We were also able to show that in closed loop operation our rms phase error is about $\pi/30$ rad even if two times 50W of average power were combined. These conclusions are important for designing a combining system based on fiber amplifiers, as well as any other amplifier geometries using a Hänsch-Couillaud-based stabilization. We will present the experimental setup, the resulting noise spectrum in closed and open-loop operations and what information this delivers altogether with the attended measurements of the power fluctuations in both channels.

8237-136, Poster Session

Suppression of instability in high-power passively phased fiber laser arrays

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By means of numerical dynamical simulations we show that the self-Q-switching instability of passively-phased fiber laser arrays can be significantly suppressed by using counter propagating pump fields. The nonlinear mechanism for this novel instability, which likely poses the main performance challenge to passively phased systems, will be explained. Predicted threshold power levels are in good agreement with experiment and theoretical modeling predictions. Dependence of the instability threshold on feedback level, array design parameters and other parameters such as fiber lengths will also be discussed.

8237-137, Poster Session

Optical frequency comb generation with a flat-top spectrum from a mode-locked Yb fiber laser

T. H. Yoon, G. H. Jang, Korea Univ. (Korea, Republic of)

We report an optical frequency comb generation with a flat-top spectrum from a mode-locked Yb fiber laser at 1030 nm covering the optical spectrum from 570 nm to 1400 nm. Master oscillator operating in the normal (positive) dispersion regime has polarization-maintaining intra-cavity elements only in a linear-cavity configuration consisting of a semiconductor saturable absorber mirror (SESAM) and a chirped fiber Bragg grating. Passive mode-locking and intra-cavity pulse-energy manipulation are achieved by using the SESAM operating in the high fluence regime where its reflectivity has a negative slope due to a strong two-photon. This negative slope versus fluence stabilizes the intra-cavity pulse energy since the pulses experience high loss at this regime, gain-loss balance mechanism, leading to the self-stabilization of the intra-cavity pulse-energy without any discrete spectral filter. Dissipative solitons (similaritons) with a positive chirp are emitting from the master oscillator having pulse-energy of 1 nJ, pulse-width of 2 ps, and spectral band-width of 28 nm. Repetition rate of 186 MHz is phase locked to a frequency synthesizer to obtain a short-term frequency and timing-jitter stabilization. A power amplifier is used to boot up the output power to 1.2 W and the positive frequency chirp of the pulses is compressed by using a transmission grating pair. Transform-limited pulses of 115 fs are launched into a 10-cm long photonic-crystal fiber with two zero-dispersion wavelengths to generate the flat-top octave spectrum. An optimally flat-top octave spectrum is achieved near the zero-dispersion region of the pulses at a launching optical power of 600 mW.

8237-138, Poster Session

Programmable laser at 1053 nm with 55-nm tuning range and pulse adjustability from less 100 ps to over 1 ns

B. Burgoyne, Y. Kim, A. Villeneuve, Jr., Genia Photonics Inc. (Canada)

Laser machining operates in either an ablation regime with few tens of ps pulses or a thermal regime using ns pulses. Thermal regime allows for fast, but imprecise removal of material while the ablation regime, albeit slower, yields a clean cut. There is thus an inherent advantage to go from one regime to the other.

We present a source that can seed a system to operate in both of these regimes. It is a programmable laser based on an actively mode-locked dispersion-tuned picosecond fiber laser showing adjustable pulse durations. Furthermore, the wavelength is tuneable over a 55 nm band centered at 1053 nm through dispersion tuning. In dispersion tuning, a dispersive element, in this case, a fiber Bragg grating, causes the different wavelengths to have different roundtrip times. An electrical signal driving an intra-cavity modulator then fixes the repetition rate (roundtrip time) and thus the wavelength. The pulse are adjustable electronically over two orders of magnitude, from 50 ps to 5 ns using a custom-made pulse generator. The repetition rate of the laser is also adjustable through harmonic mode-locking from 12 MHz to 60 MHz.

The pulse adjustability makes this source the perfect seed for machining purpose and the tunable wavelength makes it easily compatible with most amplifiers. The versatility of the source makes it also ideal for pump-probe experiments.

8237-139, Poster Session

High pulse energy sub-nanosecond Tm-doped fiber laser

A. Cserteg, S. Guillemet, Y. Hernandez, D. Giannone, Multitel A.S.B.L. (Belgium)

We report a core pumped thulium (Tm)-doped fiber amplifier that generates 1.4 µJ pulses at 1980 nm with a repetition rate of 3.6 MHz preserving the original 2.7 nm spectral bandwidth of the oscillator. The amplifier chain is seeded by a passively mode-locked fiber laser with 5 mW output power and the pulses are stretched before the amplification to 700 picoseconds pulse width with a highly chirped fiber Bragg grating. The amplifier is core pumped by a single mode erbium fiber laser operating at 1540 nm and multiplexed with the signal by a fused type wavelength division multiplexer. At the last stage of the amplification the slope efficiency reaches 35% which means that 5.1 W output power can be generated with 14 W pump power. Thanks to the core pumping, the 10 µm core, single mode Tm-doped fiber can be as short as 50 cm so the pulse width can be preserved and the unwanted nonlinear effects can be limited. Furthermore basically the entire pump light is absorbed by the doped fiber so no further filtering is required.

To the best of our knowledge, this is the first demonstration of sub-nanosecond pulses with energies higher than 1 µJ coming out of a thulium doped fiber amplifier.

8237-140, Poster Session

All-fiber Er-doped amplifier seeded by a gain-switched laser diode

L. Abrardi, T. Feurer, Univ. Bern (Switzerland)

Based on the amplification of a gain-switched laser diode around 1550 nm, we have designed an all-fiber laser source delivering 40 ps pulses with a pulse energy of 0.485 uJ at 1 MHz repetition rate; the laser pulses are close to bandwidth limited. Operating the system at lower repetition rates makes it an attractive candidate for material processing. Here, we explore possible frequency mixing scenarios based on nonlinear frequency mixing of two different, electronically synchronized seed diodes. Semiconductor gain-switched laser diodes are compact, stable, cost-competitive, and can provide tunable repetition rates from pulse-on-demand up to hundreds of MHz. However, their pulse energy, typically in the order of a few tens of picojoules, requires amplification by several tens of dBs for most applications. For that purpose we designed a fiber amplifier consisting of a two-stage core-pumped Er-doped fiber preamplifier and an ErYb-doped double-clad soft-glass fiber boost amplifier. The system required a careful design to effectively reduce the amplified spontaneous emission below 10% of the total output power. Spectral filtering, proper fiber dimensioning, and the multi-stage design allowed power scaling with negligible spectral and temporal distortions and a high contrast ratio. We then characterized the timing jitter between two electronically synchronized seed diodes with a fast oscilloscope and with nonlinear cross-correlation techniques. By using statistical analysis of the variations of the intensity temporal distributions we estimated that the relative jitter is less than the pulse duration (<15 ps) and can allow for efficient sum-frequency and difference-frequency mixing in suitable periodically poled crystals.

8237-141, Poster Session

Linear precompensation of FM-to-AM conversion due to spectral dispersion and frequency conversion system

J. Gleyze, Commissariat à l'Énergie Atomique (France)

The Laser MegaJoule (LMJ) in France and the National Ignition Facility (NIF) in the United States are high-power laser facilities designed to achieve inertial confinement fusion. Such energetic lasers have to be phase modulated (i.e. frequency modulated) to broaden the optical spectrum in order to suppress stimulated Brillouin scattering and to smooth the speckle pattern illuminating the target.

Ideally, pure phase modulations do not affect the temporal shape of the pulse. Nevertheless, propagation through different optical components slightly filters the optical spectrum and thus frequency modulation (FM) is partly converted into amplitude modulation (AM). This conversion adversely affects the laser performances and can prevent fusion ignition.

Intensity modulations due to linear spectral filters could be compensated with inverse transfer functions. In the first part of this talk we will present recent results of the compensation of FM-AM conversion due to chromatic dispersion in optical fibres of LMJ front end, thanks to the use of an optical fiber Bragg grating.

Concerning the main part of LMJ with the large aperture beam, amplitude modulations are principally due to non-linear phenomena in the Frequency Conversion System (FCS) and thus the suppression of this FM-to-AM conversion seems to be particularly difficult but of major interest. In the second part of this talk, we will present what we believe to be the first experimental demonstration of the linear precompensation of non-linear phase and amplitude transfer functions. We will show the effective precompensation with a linear fibre system, partly described in [1], of amplitude modulations due to frequency conversion.

References

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8237-142, Poster Session

Characterization of mid-infrared emissions from C2H2, CO, CO2, and HCN-filled hollow fiber lasers

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We have now demonstrated and characterized gas-filled hollow-core fiber lasers based on population inversion from acetylene (12C2H2) and HCN gas contained within the core of a kagome-structured hollow-core photonic crystal fiber. The gases are optically pumped via first order rotational-vibrational overtones near 1.5 µm using 1 ns-pulses from an optical parametric amplifier. Transitions from the pumped overtone modes to fundamental C-H stretching modes in both molecules create narrow-band laser emissions near 3 µm. High gain resulting from tight confinement of the pump and laser light together with the active gas permits us to operate these lasers in a single pass configuration, without the use of any external resonator structure. Studies of the generated mid-infrared pulse energy, threshold energy, and slope efficiency as functions of the launched pump pulse energy and gas pressure were performed and show an optimum condition where the maximum laser pulse energy is achieved for a given fiber length. Changes in the laser pulse shape and the laser-to-pump pulse delay with varying pump pulse energy and gas pressure have been observed. Furthermore, we have demonstrated lasing beyond 4 µm from CO and CO2 using silver coated glass capillaries, since fused silica based fibers do not transmit in this spectral region and chalcogenide fibers are not yet readily available. Gas-filled fiber lasers offer high damage thresholds with a wide variety of possible emission wavelengths from the visible to the far infrared as well as the potential to create a single coherent emission from many mutually incoherent pump sources.

8237-143, Poster Session

New approach to fabrication of a Faraday isolator for high power laser applications

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Protecting high power fiber laser systems against back reflection is subject of ongoing research. Here we report on investigations of direct bonding of Terbium Gallium Garnet (TGG) to sapphire used as high power optical isolator with increased thermo-optical handling capabilities. TGG and sapphire single crystals with considerably different coefficients of thermal expansion at room temperature (TGG: 7.5*10^-6/K, sapphire: 4.5*10^-6/K perpendicular to c-axis) were successfully bonded at moderate temperatures in vacuum. Double side polished TGG samples of 10 mm diameter and 2 mm thickness were bonded to sapphire substrates with 12 mm diameter and similar thickness.

The technology of direct bonding allows joining of transparent materials without any auxiliary materials (and related optical absorption and heating), which is very promising for high power laser applications, where laser materials need to be cooled effectively to avoid thermal lensing.

Sapphire with its high thermal conductivity of 42 W/mK at room temperature was chosen as optically transparent heat spreader. The goal is to arrange TGG and sapphire disks alternately for efficient heat transport from the beam area to the outside.

We report on sample preparation and bonding results. All samples were subjected to extensive chemical cleaning and subsequent low temperature plasma activation before bonding. Bonding was performed under compressive forces of about 1 kN per pair of samples in a high vacuum environment. Optically transparent bonds with a very low fraction of defects were obtained.

According to our experience, samples need to have high surface quality with root-mean-square (RMS) roughness smaller than 1 nm and flatness of about $\lambda/6$ (λ = 633 nm) for successful bonding. Even slight bowing or warping needs to be avoided (or at least reduced by applying moderate pressure) to bring the surfaces into intimidate contact at bonding conditions.

By simulating the effects of pressure application and thermal expansion during the heating/cooling cycle, optimized conditions for the bonding process were determined. To our knowledge, this is the first report on successful direct bonding of TGG and sapphire crystals. Functionality and mechanical stability of the isolator will be tested under real conditions using a diffraction limited fiber laser (= 1070 nm) with output power up to 400 W.

This work is supported by the European Union within the Project “LIFT” under grant agreement no. NMP2-LA-2009-228587.

8237-144, Poster Session

High-average-power actively-mode-locked Tm3+ fiber lasers

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Fiber lasers emitting in the 2 µm wavelength range doped with thulium ions can be used as highly efficient pump sources for nonlinear converters to generate mid-infrared radiation. For spectroscopic purposes, illumination and countermeasures, a broad mid-infrared emission spectrum is advantageous. This can be reached by supercontinuum generation in fibers, e.g. fluoride fibers, which up to now has, however, only been presented with either low average power, complex Raman-shifted 1.55 µm pump sources or multi-stage amplifier pump schemes.

Here we present recent results of a new actively-mode-locked single-oscillator scheme that can provide the high-repetition rate sub-ns pump pulses needed for pumping supercontinuum generators. A thulium-doped silica fiber laser is presented that provides > 11 W of average power CW-mode-locked pulses at 38 MHz repetition rate at ~ 38 ps pulse width. Upgrading the setup to allow Q-switched mode-locked operation yields mode-locked 40 MHz pulses arranged in 100 kHz bunched Q-switch envelopes and thus increases further the available peak power. In this Q-switched mode-locked regime over 5 W of average power has been achieved.

8237-06, Session 10

Fiber lasers and amplifiers for space-based science and exploration

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No abstract available

8237-07, Session 10

New applications for short pulse length and high average power Q-switched fiber lasers

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

Fiber lasers have now had real commercial success at both high and low average power levels. At the high average power multi-kilowatt level a range of cutting and welding applications have developed, at the low power levels, fiber laser markers have also established a dominant position. This has led to a real in-depth knowledge of and experience with all of the components that make up fiber laser systems. Based on this knowledge new fiber lasers up to 1 kW average power in the nanosecond regime and fiber lasers in the picosecond regime have been developed. New lasers almost inevitably enable a range of new applications and information on a range of these applications is presented. The combination of high average power and nanosecond pulses produces very interesting and sometimes unexpected material phenomena on a wide range of non-metallic and metallic substrates and examples of this will be presented. Optimising processing with these new laser capabilities also presents interesting challenges for laser controllers. Almost as inevitable is that these lasers are also challenging the incumbent laser technology in a number of different fields and some of these areas will also be discussed.

8237-08, Session 10

Progress in ultrafast fiber lasers for ultralow-jitter signal sources

J. Kim, K. Jung, C. Kim, H. Kim, T. Kim, S. Park, Y. Song, H. Yang, KAIST (Korea, Republic of)

Ultra-low timing jitter signal sources enable extremely high timing-precision scientific and industrial applications: for example, large-scale synchronization of advanced scientific facilities (such as x-ray free-electron lasers and phased-array antennas), high-speed and high-resolution analog-to-digital converters, high-precision military radars and lidars, advanced clock distribution and communication systems, and various test and measurement instrumentation.

In this paper, we introduce the most recent progress in the optimization of ultrafast fiber lasers for building such ultralow-jitter signal sources. Using a sub-20-attosecond-resolution timing jitter measurement technique, we optimized the timing jitter of optical pulse trains from mode-locked Er-fiber and Yb-fiber lasers to 70 attoseconds and 175 attoseconds, respectively, when integrated from 10 kHz to 40 MHz offset frequency. To our knowledge, these results correspond to the lowest rms timing jitter demonstrated from fiber lasers so far, the equivalent phase noise of which is comparable to that of the best microwave sources available (such as sapphire-loaded cavity oscillators). It also shows that standard nonlinear polarization rotation-based fiber lasers can achieve such low timing jitter and phase noise with much reduced cost and engineering complexity, which might enable widespread applications of fiber lasers as ultralow-jitter signal sources in the near future.

We will further introduce our research efforts toward (a) more robust and compact fiber lasers with sub-femtosecond timing jitter and (b) the optical-to-microwave conversion below the shot-noise limit of photodetection for transferring attosecond timing stability from the optical domain to the electronic domain.

8237-09, Session 10

Application of high-performance OEM fibre lasers in manufacturing

S. Norman, SPI Lasers (United Kingdom)

In the nanosecond pulsed laser domain, fiber lasers have become the dominant technology for diverse marking and scribing applications. MOPA-based pulsed laser architectures provide out-standing performance flexibility and end-use process control; moreover, their ease-of-use, reliability, energy efficiency and cost-effectiveness provide operational benefits. The design and performance advantages of ns-class lasers in representative manufacturing applications are reviewed.

Concurrently, medium and high-power fiber lasers operating in the 1um region have proven their capabilities for cutting and welding in industrial manufacturing applications. This paper also reviews the process performance capabilities of medium power (up to 500W) and kW-class OEM fiber lasers in a range of precision cutting and fusion-welding applications.

8237-10, Session 11

Innovations in high power fiber laser applications

E. Beyer, Fraunhofer IWS Dresden (Germany) and Dresden Univ. of Technology (Germany)

Diffraction-limited high power lasers represent a new generation of lasers for materials processing, characteristic traits of which are: smaller, cost-effective and processing “on the fly”. Of utmost importance is the fiber laser’s high beam quality which enables us to reduce the size of the focussing head incl. scanning mirrors. The excellent beam quality of the fiber lasers offers a lot of new applications. In the field of remote cutting and welding the beam quality is the key parameter.

By reducing the size of the focussing head including the scanning mirrors we can reach scanning frequencies up to 1.5 kHz and in special configurations up to 4 kHz. By using these frequencies we can generate very thin and deep welding seams we have experienced with electron beam welding only. The excellent beam quality of the fiber lasers offers us a lot of new applications from deep penetration welding to high speed welding.

Highly dynamic cutting systems with maximum speeds up to 300 m/min and accelerations up to 4 g reduce the cutting time for cutting complex 2D parts. However, due to inertia of such systems the effective cutting speed is reduced. This is especially valid if complex shapes or contours are cut. With the introduction of scanner based remote cutting systems in the kilowatt range, the effective cutting speed on the contour can be increased dramatically. The presentation explains remote cutting of metal foils and sheets using high brightness single mode fiber lasers.

The presentation will also show the effect of optical feedbacks during cutting and welding with the fiber laser, how those feedbacks could be reduced and how they have to be used to optimize the cutting or welding process.

8237-11, Session 11

Fiber laser beam combining and power scaling progress: AFRL Laser Division

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Numerous achievements have been made recently by researchers in the areas of fiber laser beam combining and power scaling. Industry has demonstrated > 1.5 kW power from a single fiber amplifier with < 10 GHz linewidth, and a US national laboratory has published a 4 kW result from the coherent combination of eight fiber amplifiers. This paper will focus on recent fiber laser results from the Laser Division of AFRL's Directed Energy Directorate, and future plans. Progress has been made in the power scaling of narrow-linewidth fiber amplifiers, and we are transitioning lessons learned from PCF power scaling into a monolithic design. SBS suppression has been achieved using a variety of techniques including acoustically tailored fiber, laser gain competition resulting from multi-tone seeding, and lowered Brillioun gain resulting from the presence of a thermal gradient across the gain fiber. We recently demonstrated a 32-channel coherent beam combination result using AFRL's LOCSET technique and are focused on probing the limitations of this technique including linewidth broadening, kW-induced phase nonlinearities and auto-tuning methods for large channel counts. We have recently refurbished our JTO-sponsored 16-amplifier fiber testbed to meet strict PER, spatial drift, power stability and beam quality requirements. The power scaling of components critical to fiber amplifiers continues through in-house and contracted programs. Recent AFRL/Industry progress in the power scaling of stable master oscillators, all-fiber optical isolators, pump/signal couplers and combiners, cladding mode strippers and finally the active control of phase, polarization, and pathlength will be reviewed.

8237-12, Session 11

From CW to fs: fiber lasers for high-end product manufacturing

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Since decades, lasers are a well-established tool in development and production of high-end products, like medical devices, solar cells, automotive and electronic components. Within those industrial application areas, fiber lasers are gaining a significantly increased market share amongst the different laser concepts. Typical applications of fiber lasers comprise cutting, welding, surface structuring and marking processes.

Manufacturing of medical devices from tube material (i.e. stents) is one of the prominent laser cutting applications in the medical device industry. For years, production relied on laser fusion cutting with lamp-pumped solid state lasers, providing pulse widths in the µs-range. Newly developed modulated fiber lasers with peak power levels above 1 kW have substituted lamp-pumped lasers for that application area. But even with an optimum setup, fusion cutting processes are not completely free from burr and recast formation inside the tube. Therefore, post-processing steps are necessary, including brushing and chemical etching in order to remove oxide layers as well as electrochemical polishing to round-off edges. Whereas such post-processing methods are tolerable for standard materials like stainless steel and cobalt-chromium alloys, sensitive materials, like the shape memory alloy Nitinol, are prone to chemical and mechanical damage. Here, the use of ultra short pulsed fiber lasers is a viable way to significantly reduce heat affected zones and melt generation and thus eliminating recast layer and burr formation.

Whereas for metal stents ultra short lasers are still in competition with modulated-cw fiber lasers, there is no other way to cut bio-absorbable polymer materials, like polylactic or polyglycolic acids. Suffering from low melting temperatures, low absorption and low heat conductivity, machining of those materials with traditional cutting lasers is impossible. Microstructural changes cannot be tolerated, as they would not allow for the necessary precision and mechanical properties of those implants. Here, femtosecond lasers already have achieved excellent results with vascular stents showing high-precision cuts with perfect edge quality.

Also, for metal welding applications on medical devices like endoscopes, probing devices or surgical knifes, fiber lasers are prepared to substitute lamp-pumped Nd:YAG lasers on the long run. There are two different approaches to do that: seam welding with cw-fiber lasers using different concepts to enlarge the weld pool size or spot welding with kW-pulsed fiber lasers.

Laser ablation processes of thin films can be found on various products throughout different industry sectors. Those fiber laser applications range from nanosecond down to the femtosecond pulse width regimes, depending on the amount of heat affection that can be tolerated. Whereas those ablation processes typically started with the help of standard solid state laser technology, the trend into fiber lases is obvious. For industrial applications requiring quasi-zero heat affected zones, femtosecond fiber lasers are inevitable.

The presentation will give an overview on the variety of fiber laser applications for manufacturing of medical devices, solar cells, automotive or electronic components, covering standard fusion cutting with modulated fiber lasers, the specifics of “cold” processing with ultra short pulsed fiber lasers as well as the characteristics of fiber laser welding.

8237-13, Session 12

Distributed light scattering model for the SBS and SRS threshold powers in small and large mode area passive optical fibers

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The stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS) threshold powers in passive small mode area optical fibers (SMAFs) and large mode area optical fibers (LMAFs) is determined from a distributed light scattering model. The model employs the pump and Stokes rate equations together with the equivalent thermal Brillouin and Raman noise powers to provide a numerical solution for the evolution of the pump and Stokes powers along the fiber length without approximation and is applicable to the non-depleted and depleted pump regimes. It is found that the Smith relations do not apply in the pump-depletion regime, although they are defined for pump-to-Stokes conversion efficiencies eta of 1.0 and 0.5 for backward and forward stimulated light scattering, respectively. It is found that the threshold powers rapidly increase by two orders of magnitude for SBS and increase by ~3 dB for SRS in the depleted pump regime as approaches 1.0. Simple transcendental equations for the threshold powers are obtained in the non-depleted pump, low fiber loss regime that are of similar form to the standard threshold relations first derived by Smith: Pth=kappa*Aeff/g*Leff where Pth is the threshold power, g is the non-linear gain coefficient, Aeff is the optical effective area and Leff is the fiber effective interaction length. The numerical coefficient kappa=ln(PS/PN) is found to be a weak function of the Stokes power PS and the thermal noise power PN and is independent of Aeff and Leff. Differences in kappa are attributed to the differing order-of-magnitude Stokes and noise powers that apply to SBS and SRS in SMAFs and LMAFs. It is found that the SRS threshold power of the LMAF at eta=0.1 exceeds that first derived by Smith by 1.7 dB. The SRS threshold in SMAF and the SBS thresholds in the SMAF and LMAF at eta=0.1 are in agreement to within <1.0 dB with the Smith relations. The transcendental approximations are useful for rapidly estimating the SBS and SRS threshold powers in all fibers at any pump power and pump-to-Stokes conversion efficiency eta<<0.1.

8237-14, Session 12

Frequency domain analysis of dynamic refractive index changes in fiber amplifiers

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Gain dynamics and corresponding refractive index changes in fiber amplifiers are important for low noise fiber amplifiers and when using doped fibers as phase actuators. Furthermore, self-induced refractive index changes are a possible explanation for mode fluctuations in high power fiber amplifiers, which currently represent a major challenge for high power fiber lasers. Since these processes are all time dependent, a dynamic model of the refractive index change is required. We will present measurements of the refractive index changes in a low power ytterbium fiber amplifier. We modulated an ytterbium amplifier's pump or seed power and measured a 1.5 µm probe beam's phase shift as a function of modulation frequency. The resulting transfer functions are essentially a combination of two low pass filters, which can clearly be distinguished by timescale. One is related to the heat deposit in the fiber. Its corner frequency was smaller than 100 mHz. The other low pass is caused by the fiber amplifier gain dynamics and the Kramers-Kronig-Relations (KKR) with a corner frequency in the kHz range. Using a simplified analytic model, which was originally developed to predict power (over-) modulation in telecom amplifiers, we were able to model the KKR phase shift transfer functions. Although the magnitude of the KKR phase shift is slightly different at 1 µm, the timescales and qualitative effects predicted by this model will help modeling of phase noise in low noise amplifiers and possibly mode fluctuations in fiber amplifiers.

8237-15, Session 12

All-fiber broad-range self-sweeping Yb-doped fiber laser

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The effect of broad-range self-sweeping narrow-line Yb-doped fiber laser has been demonstrated experimentally for the first time. The effect is observed in a widely used laser configuration with a double-clad Yb-doped fiber and a cavity formed by a fiber Bragg grating and Fresnel reflection from one cleaved end. The sweep range is limited by the bandwidth of fiber Bragg reflector.

In an all-fiver cavity formed by broad-band fiber loop mirror and Fresnel reflection the range is increased up to 16nm. It is found that the self-sweeping effect is related to the self-sustained relaxation oscillations. So the sweep rate increases with an increase in pump power and decreases with increasing cavity length. RF and optical spectra (linewidth is less than 1pm) shown that during the evolution of a single pulse small number of longitudinal modes takes part in lasing. Based on these results we propose a model describing dynamics of the laser frequency. The model is based on the spatial hole burning effect and the gain saturation in Yb fiber laser, and takes into account self-pulsing of the laser. Theoretical estimation for pulse to pulse change of lasing frequency is in good agreement with experimental data.

8237-16, Session 14

Gain-tailored SBS suppressing photonic crystal fibers for high power applications

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We present experimental studies of polarization-maintaining Yb-doped photonic crystal fibers possessing both acoustic and Yb-ion concentration tailoring. In the initial design, the concentrations of fluorine, aluminum, and germanium in two different regions of the core were selected such that the corresponding Brillouin shifts were sufficiently separated to allow for the introduction of a temperature profile along the fiber for further stimulated Brillouin scattering (SBS) suppression. The Yb-ion concentration was maintained uniformly throughout the entire core. When this fiber was utilized in a counter-pumped amplifier configuration, close to 500 W of near diffraction-limited single-frequency output was obtained in a fiber of length 10 m as compared to 160 W obtained in a non-acoustically tailored fiber of equal length. Further power scaling at the 500 W level was limited by the onset of power dependent modal instabilities. A second fiber design was developed in which the Yb-ion concentration was modified to have preferential overlap with the fundamental mode. In this case, our measurements of the Brillouin gain spectrum revealed three primay peaks. Furthermore, different iterations of this gain-tailored fiber were used to investigate the correlation between power dependent modal instabilities, spatial hole-burning, and thermal effects.

8237-17, Session 14

YAG-derived fiber for high-power narrow-linewidth fiber lasers

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We present experimental and modeling results demonstrating rare earth-doped (Er and Yb) YAG-derived silica fibers (RYDF) to be suitable candidates for use in high-power narrow-linewidth fiber lasers. Stimulated Brillouin scattering (SBS) suppression in this case results from desirable material characteristics that cooperate to yield a low Brillouin gain coefficient (BGC), namely reduced photoelastic constant and increased acoustic velocity, mass density, and Brillouin spectral width relative to silica. Fabrication of the RYDFs via a rod-in-tube method, starting from crystalline YAG, and its transformation to the amorphous state, is described. From measurements of the Brillouin gain spectrum (BGS), the BGC of a typical large-mode-area RYDF is ~ 0.5×10^-11 m/W. Utilizing an additive materials model, measurements on the multi-component RYDF system are extrapolated to compositionally-design further reductions to the BGC, including introducing other co-dopants to the mixture. Spectroscopically, the RYDFs are found to act similarly to more traditional rare earth-doped aluminosilicate fibers, with quenching concentrations similar to typical commercial fibers, suggesting laser properties can be preserved while decreasing the BGC. Amplifier experiments will be used to verify this conjecture. Finally, we focus on the Yb-doped RYDF (YYDF) and show that it is a good candidate for use in kW-class narrow-linewidth fiber lasers. We found that YYDFs offer improved compatibility with phase modulating the laser for further increases in the SBS threshold. Photodarkening investigations of this fiber will also be presented. Using novel fiber fabrication methods with less-common and low-silica materials can lead to promising glass recipes with ultra-low intrinsic BGCs.

8237-18, Session 14

High power single-frequency 780-nm fiber laser source for RB trapping and cooling applications

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We present here the realization and the full characterization of an all-fiber system producing more than 1.8W of single-frequency radiation at 780 nm. This source finds its major applications in the field of Rubidium atoms trapping and cooling, for which powerful, compact and robust single-frequency and single-mode laser sources are requested. The system is based on the frequency-doubling of an all-fiber 1560 nm amplifier, made of polarization maintaining (PM) fibers, seeded by a single-frequency linearly polarized semiconductor laser diode. The fundamental infrared PM fiber laser provides 12W at 1560 nm, for less than 40W of pump power, with a stable polarization extinction ratio of 17dB, a linewidth of 59 kHz and a perfect beam quality (M^2<1.1). A PP-MgO-LN is used in a compact single-pass frequency doubling stage to produce 1.8W at 780 nm. In order to accurately measure the narrow linewidth of the laser, we implement an alternative method for laser linewidth determination at 780 nm, based on frequency noise spectrum measurement. Indeed, when the frequency noise is not dominated by white noise, the standard delayed self-heterodyne interferometric technique results are problematic to interpret. Using the proposed method, based on a modified all-fibered Mach-Zehnder interferometer, that converts frequency fluctuations into intensity variations, we measured a linewidth of 153 kHz at 780 nm. We will present a full characterization of this fiber laser source, in terms of power and efficiencies, amplitude noise, frequency noise, linewidth measurements, beam quality and beam pointing stability.

8237-19, Session 14

Er-doped single-frequency photonic crystal fiber amplifier with 70 W of output power for gravitational wave detection

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To the best of our knowledge, we report for the first time on a large mode area Er-doped photonic crystal fiber laser system. The fiber has a core diameter of 40µm and a core NA of <0.04. In a kHz-linewidth single-frequency master oscillator power amplifier (MOPA) scheme more than 70W of output power at 1556nm could be demonstrated. This is the highest output power value ever reported from an Yb-free Er-doped fiber amplifier and also the highest value obtained with a 980nm pumped Yb-free Er-doped fiber laser system. The amplifier efficiency with respect to absorbed pump power at 980nm was slightly below 20%. The output power scaling was limited by the amount of available pump power. The fractional TEM00 content of the output beam has been analyzed with a non-confocal scanning ring cavity at various power levels. A fractional TEM00 content in excess of 90% was measured with only a slight degradation at high output power levels. This corresponds to M^2 values very close to unity. In addition, it was verified that no mode instability effects occurred at all power levels. Therefore, the presented Er-doped photonic crystal fiber MOPA system can almost maintain the output characteristics of a single-mode single-frequency laser source, while it also has the potential to be scalable to single-frequency output power levels beyond 100W. Thus, it is a promising candidate for the development of interferometric gravitational wave laser sources around 1550nm, which constitutes the goal of our research.

8237-20, Session 14

High-power single-frequency photonic bandgap fiber amplifier at 1178 nm

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Yb-doped fiber laser operating at the long-wavelength wing of the fluorescence (1150-1200nm) has been extensively investigated for yellow-orange sources by frequency doubling. We have been investigating Yb-doped solid-core photonic bandgap fiber (Yb-PBGF) laser and amplifier. The characteristic high-contrast wavelength-dependent distributed filtering enables elimination of amplified spontaneous emission (ASE) and thus significant scaling the power and gain to as high as 167W and 15dB at 1178nm, respectively.

In this paper we report, for the first time to our knowledge, an Yb-PBGF amplifier in a single-frequency operation, which is required in many applications such as laser guide star. The seed source was an external-cavity laser diodes (EC-LD), based on InAs/GaAs quantum-dot gain chip, generating narrow linewidth (~320kHz) single-frequency light at 1178nm. It was preamplified by a fiber Raman amplifier pumped by an 1120nm Yb fiber laser. The launched seed power of 1.6W was successfully amplified by an Yb-PBGF amplifier to 24.6W, without any sign of stimulated Brillouin scattering (SBS) and linewidth broadening. The ASE was also highly suppressed (> 45dB SNR).

The behavior of SBS in a PBGF is considered to be different from standard index-guided fibers. Since the acoustic velocity in the inclusions in PBG cladding (such as Ge-doped silica) is lower than in core silica, the Brillouin gain can be lower by acoustic antiguiding. The measured peak Brillouin gain coefficient of 0.06/m/W indicates 3dB suppression of SBS against an index-guided fiber with the same effective area. Further high-power operation and detailed study on SBS limit will be presented.

8237-21, Session 14

Characterization of a narrowband Raman MOPA with short master oscillator

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Raman fiber lasers (RFL) with a narrow spectral bandwidth are important light sources, e.g. for applications that require second-harmonic generation (SHG). Non-linear optical processes within the fiber like four-wave mixing (FWM) lead to spectral broadening, due to the generation of frequency components outside the initial laser bandwidth. This mainly results from FWM of the longitudinal modes (LMs) generated in the laser cavity. Consequently a reduced number of LMs with increased frequency spacing, which is obtained by using a short laser cavity, is expected to reduce the spectral broadening. We investigated a Raman MOPA (master oscillator power amplifier) configuration, consisting of a RFL with a very short cavity length of 17cm (MO) and a Raman amplifier of 55m length (PA). Pumping with 8W of a Ytterbium-doped fiber laser at 1100nm, the Stokes wave at 1151nm is generated within the MO, yielding 0.7W Stokes power with a narrow FWHM bandwidth of 60pm at the MO output. From the measured frequency spacing between the LMs of 607MHz a maximum number of 22 LMs can be calculated to oscillate within the bandwidth of the MO output. The residual pump power at the MO output is used to amplify the Stokes wave in the subsequent Raman PA. At the MOPA output the amplified Stokes power is 4.3W with a strongly broadened FWHM bandwidth of 328pm. Thus our results show that even for a Stokes wave with only few LMs at the MO output, strong FWM induced spectral broadening occurs within the PA.

8237-22, Session 15

Development of resonantly cladding-pumped holmium-doped fibre lasers

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The development of efficient, high power thulium fibre lasers has provided an attractive route for the demonstration of a range of laser sources in the 2um spectral region. This wavelength band provides advantages in terms of eye-safety, atmospheric transmission, reduced susceptibility to nonlinear effects and is of interest for applications in fields such as defence, medicine and remote sensing. Thulium fibre lasers have reached average powers over 1kW [1], and have proven suitable as robust pulsed sources for frequency conversion [2].

For some applications holmium-doped fibre lasers offer advantages over thulium lasers. Cladding pumped holmium fibre lasers can be tandem pumped by high power thulium fibre lasers with a very low quantum defect allowing further power scaling of 2um laser sources. Holmium also offers emission beyond 2.1um with high gain and efficiency compared with thulium which is advantageous for atmospheric propagation. These properties make resonantly pumped holmium fiber lasers an attractive candidate for the future development of 2um sources.

We have previously demonstrated an efficient resonantly cladding pumped holmium doped fibre laser producing 99W from a robustly single mode fibre [3]. The laser operated at 2.105um with good beam quality and a slope efficiency of 65% versus absorbed pump power. More recently 140W of output power was demonstrated from this fiber laser.

This presentation will discuss recent results in which we further power scale cladding pumped holmium doped fibre lasers using both single mode and large mode area fibre designs. Progress towards the development of narrow line-width and pulsed all-fibre sources using resonantly pumped holmium fibres will also be discussed.

[1] T. Ehrenreich et al.,"1-kW, All-glass Tm:fibre Laser" SPIE Photonics West 2010

[2] D. Creeden et al., "Multi-Watt Mid-IR Fiber-Pumped OPO", CLEO/QELS, 2008, CTuII2

[3] A. Hemming et al., "Resonantly Pumped Holmium Fibre Lasers", Advanced Photonics Congress, 2011

8237-23, Session 15

An all-fiber PM MOPA pumped high-power OPO at 3.82 µm based on large aperture PPMgLN

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High power optical parametric oscillators (OPO) operating in the mid-infrared wavelength range (3-5µm) are desirable for a wide range of applications, such as spectroscopy, atmospheric and environmental monitoring, LIDAR and missile counter-measures. Fiber laser pumped OPOs represent a new generation of compact, high power parametric devices due to the excellent beam quality, simple thermal management schemes and ultrahigh electrical-optical conversion efficiencies of such pump sources. Here we report a periodically poled magnesium oxide doped lithium niobate (PPMgLN) based OPO pumped by a high power PM pulsed Ytterbium fiber master oscillator power amplifier (MOPA).

We designed and fabricated the PPMgLN wafer with a channel size of 50mm x 2mm x 2mm, which allows a relatively large focused beam waist (1.2-1.3mm) so as to reduce the thermal-lens-effect. Using adaptive pulse shaping of the seed diode we demonstrate a reduction in the impact of dynamic gain saturation and optical Kerr/Raman nonlinearities within the fiber MOPA, obtaining shaped signal and idler pulses at the OPO output. A maximum single polarization average (peak) output power of 76W (38kW) was obtained from the MOPA at 1060nm (100kHz repetition rate, 20ns pulsewidth). Overall 21W of OPO output power at a slope efficiency of 45% was obtained of which 5.5W power was recorded at the idler wavelength of 3.82µm. Our results reveal that the OPO conversion efficiency can be increased further by minimizing rise/fall time of the pump pulse and operating the MOPA at 1030-1040nm which not only mitigates short wavelength ASE build-up but will allow enhancement of the pulse peak power.

8237-24, Session 15

High-energy monolithic single-frequency pulsed fiber laser at ~2 um in MOPA configuration

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We report a high pulse energy all-fiber-based 2 um pulsed laser with transform-limited linewidth and 10-100 ns pulse width. This monolithic MOPA-based pulsed fiber laser is based on the highly Tm-doped germanate fibers, which can be used for coherent LIDAR and laser remote sensing. In our experiments, two kinds of single-frequency pulsed fiber laser seeds were used. One is actively Q-switched fiber laser seed based on fiber birefringence induced by a piezo in the short fiber laser cavity. Another one is directly modulated single-frequency pulsed fiber laser seed by using electro-optic and acoustic-optic modulators. A new single-mode large core PM highly Tm-doped germanate fiber 25/250 um was developed based on rod-in-tube technique. The transform-limited fiber laser pulses in 10-100 ns regime has been successfully amplified by using the newly developed Tm-doped germanate fiber 25/250 um in the power amplifier stage. Based on the monolithic MOPA configuration, 0.543 mJ pulse energy has been achieved, which corresponds to a peak power of 36.2 kW for transform-limited fiber laser pulses.

8237-25, Session 15

Integrated 100-W polarized narrow linewidth thulium fiber MOPA system

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There has been rapid progress in the development of high power thulium fiber lasers in the past 10 years. However, the immaturity of system components such as pump combiners and optical isolators for use in the 2 µm wavelength regime continues to limit the development of fully integrated high power polarized thulium fiber laser systems. Here we report on the performance of a Tm:fiber master oscillator power amplifier (MOPA) system, which produces 100 W output with sub-200 pm linewidth. The oscillator is constructed using PM fiber with 10 µm diameter core and 130 µm diameter cladding, and is pumped with a 35 W diode at 793 nm through a pump combiner. The only free-space portion of the system achieves wavelength stabilization and polarization control using a guided-mode resonance filter (GMRF). The amplifier consists of large mode area (LMA) PM fiber with 25 µm core and 400 µm cladding diameters pumped with six 70 W 793 nm diodes through a 6+1:1 high power pump combiner. The oscillator is spliced to the amplifier after propagation through a fiber coupled optical isolator and mode field adaptor (MFA). This nearly completely spiced laser system produces high power, with >10 dB polarization extinction ratio (PER) and diffraction-limited beam quality. To the best of our knowledge this is the highest power produced from an integrated polarized Tm:fiber laser.

8237-26, Session 16

Mode-locked Tm and Ho fiber lasers

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Recently thulium(Tm) and holmium(Ho)-doped fiber lasers have attracted significant attention because near 2 micron fiber lasers are useful for a variety of applications including eye-safe LIDAR, medicine, spectroscopy, remote sensing, and generation of mid-infrared light source. Thulium and holmium fiber lasers exhibit a broad laser wavelength tuning range, implying that these fiber lasers could generate ultra-short pulses. In this presentation we will review our progresses in mode-locked Tm and Ho fiber lasers using saturable absorbers.

8237-27, Session 16

High peak and average power generation by cascaded nonlinear compression of fiber CPA system

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Fiber chirped pulse amplification systems have proven to be a source of high average power ultrashort pulses. Besides the potential to be used in industrial applications they have become an interesting source for high field physics. However, their use is hampered by the relatively long pulse duration of several hundreds of femtoseconds. The use of nonlinear compression in noble gas filled hollow core fibers is a simple way for post-compression of these laser pulses. By propagating the laser pulses in a noble gas they are spectrally broadened. When removing the chirp by chirped mirrors the pulses are shortened in time and their peak power is enhanced.

We show numerical and analytical considerations of such a compression scheme that allow us to optimize a single compression stage in terms of peak power or pulse duration. According to these findings experiments are presented that enhance the peak power of an existing fiber CPA system from 1.8 GW to 7.5 GW in a single stage. The pulses are already shortened from 480 fs to 45 fs. By sending these pulses into a second noble gas filled hollow fiber further pulse shortening and peak power increase is achieved. This has resulted in 25 fs pulses with a pulse energy of 430 µJ at 30 kHz equaling an average power of 13 W. The peak power is higher than 10 GW. Beyond that, we will discuss perspectives of average power scaling towards energetic few-cycle pulses with 100 W average power and above.

8237-28, Session 16

High energy 2 micron femtosecond fiber laser

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We, for the first time, have developed a high energy sub-picosecond fiber laser by using mode-locked 2 µm seed oscillator at 2.5 MHz repetition rate and high energy/power Tm doped fiber amplifiers. The MHz seed demonstrated stable self-started mode locked regime initiated by saturable absorbing mirror. The seed included a piece of dispersion compensating fiber to manage the cavity dispersion and emitted chirped pulses with duration of ~ 1 picosecond and spectrum bandwidth of 7 nm. Repetition rate as low as 2 MHz was achieved. This significantly facilitated pulse train amplification to high energy without adding a pulse picker to down select pulse repetition rate. After the seed pulses were stretched with dispersion managed fiber and amplified with multi-stage amplifiers. High energy at micro-J level has been achieved with a diffraction limited beam quality. The pulse can be compressed to sub-picosecond. During pulse amplification, its spectrum was slightly broadened to 10 nm, which helps balance gain narrowing effects and does not deteriorate compressed pulse quality. Energy and power scaling will also be discussed for our current design. Comparison and future perspectives will also be presented.

8237-29, Session 16

Stretcher fibers for chirped pulse amplifiers at 1030 nm and 1550 nm

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Dispersion managed fibers for stretching of ultra short pulses is a promising route to all-fiber chirped pulse amplification systems. The key challenge in designing a stretcher fiber is to match the dispersion requirements of the compressor unit in a broad spectral range defined by the ultra short pulse. A solid silica single mode fiber based on a triple cladding index profile can be designed to meet such requirements by controlling the ratios of beta3/beta2 and beta4/beta2. The stretcher fiber provides a highly dispersive element that can match the significant higher order dispersion inherent to pulse compressors made of traditional diffraction gratings.

We have previously published a stretcher fiber (Fiber A) for the 1030 nm wavelength range. Using this fiber, chirped pulse amplifiers with several micro Joule pulse energy have been demonstrated. In this paper we also present stretcher fiber solutions for the 1550 nm wavelength range. Two stretcher fibers have been fabricated (Fiber B and C). Fiber C has the double beta4/beta2 ratio compared to fiber B. Using fiber B good dispersion match up to fourth order dispersion is demonstrated to a 1200 lines per mm grating operating at an incident angle of 74°. When the 1200 lines per mm grating is operated at an incident angle of 68°, which is beneficial as this gives a numerical higher beta2 for the same physical space, fiber C in combination with a length of anomalous dispersion fiber gives a good dispersion match up to fourth order.

8237-30, Session 17

Toward kW nanosecond fiber lasers with rod type fibers

F. L. Salin, EOLITE Systems (France)

No abstract available

8237-31, Session 17

9-mJ pulse energy Q-switched large-pitch fiber laser system with excellent beam quality

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

Fiber lasers have demonstrated outstanding performances in high average power operation, but nonlinear effects and fiber damage typically limit the maximum pulse energy that can be extracted from them. This way, larger mode field areas are essential for a further pulse energy scaling. In this work we report on, to the best of our knowledge, the highest pulse energy obtained from an effectively single-mode Q-switched fiber laser system so far. The working principle of rare-earth-doped double-clad large-pitch fibers based on delocalization of higher-order transverse modes from the active region of the fiber. The presented work demonstrates the concept at core diameters well above 100µm.

We have built an actively Q-switched oscillator consisting of a 1.2m long large-pitch fiber with a mode field diameter of 50µm. This oscillator delivered up to 4W of average power with a repetition rate of 5kHz, resulting in a pulse energy of 800µJ. This seed pulses have been amplified in a single stage booster fiber amplifier pumped at 915nm. The fiber amplifier employs a 1.3m long large-pitch fiber with a hole-to-hole distance of 75µm. This structure results in a mode field diameter of about 130µm (at low power levels). However, under high power operation the mode field diameter is reduced to about 100µm due to thermally induced index changes. The setup can deliver average powers of up to 35W, resulting in 7mJ pulses with sub-20ns pulse durations. The beam quality is close to diffraction-limited.

8237-32, Session 17

MW+ peak power sub-nsec 10-kHz repetition rate polarization-maintaining fiber-amplifiers using tapered Yb-doped fibers

Y. Chen, J. Fouron, F. Kimpel, S. Gupta, Fibertek, Inc. (United States)

Fiber-laser based high peak power, reliable nsec and sub-nsec pulsed laser transmitters are of significant interest for precision Lidar mapping and dynamic ranging application. Unlike fiber-optic communication, airborne and space-based direct-detection lidar applications, as well as ranging of low cross-section fast-moving targets require much higher pulse energy (or peak powers), and low repetition rates for unambiguous returns. Such pulse energy scaling is challenging in fiber lasers, due to fiber nonlinearities, and self-focusing and fusing induced fiber damage. Similarly, efficient low duty cycle operation with stable pulse train is also challenging due to the pulse gain dynamics, and the amplified spontaneous emission.

We present results on precise and stable sub-nsec pulse energy scaling to mJ+ pulse energy, near 10kHz repetition rates, in advanced heavily Yb-doped fibers, that exhibit virtually no photo-darkening. To mitigate nonlinearity and damage issues, large-mode-area (LMA) fiber designs with core diameters ranging from 30-60um were used to demonstrate pulse energy scaling to 1.7mJ, for 0.7nsec pulses at ~12.5kHz repetition. However, mode-quality, power and polarization stability, is observed to degrade. Using precisely controlled variable fiber draw, 3.5m long novel tapered Yb-doped polarization-maintaining (PM) LMA Yb-doped fiber was fabricated, with 25/250um and 40/400um core/clad at each end, and used in the last stage of a multi-stage Yb-fiber MOPA. The fiber-MOPA is controlled by high-speed FPGA for real-time control of the seed laser diode, electro-optic modulator and acousto-optic modulator. Stable 0.3nsec pulses at 10kHz rate is demonstrated with 0.3mJ pulse energy (1MW peak power). At 1nsec pulsewidth, scaling to >0.5mJ pulse energy is demonstrated. Polarization extinction of >16dB is obtained with diffraction limited beam quality and excellent (<3%) power stability. Such compact and robust pulsed fiber amplifiers enable next generation of airborne and space lidar transmitters.

8237-33, Session 17

High-power fiber based architecture providing extensive temporal and spectral pulse format control

F. Di Teodoro, T. S. McComb, E. C. Cheung, Northrop Grumman Aerospace Systems (United States)

We report on a master-oscillator/power-amplifier (MOPA) affording active continuous adjustment of the output pulsewidth, pulse repetition frequency (PRF), and central wavelength along with the efficient generation of multi-mJ/multi-MW pulse energy/peak power, within a spatially/spectrally bright output. The MOPA includes a seeder comprising gain-switched distributed Bragg reflector diode laser and high-saturation-power semiconductor optical amplifier. The seeder can generate single-frequency pulses of continuously tunable central wavelength (in the 1060nm spectral region). Its pulsewidth and PRF can be independently, continuously, and precisely adjusted in the 0.1 to >5ns and 5-1000 kHz ranges, respectively, via direct fire commands with diminutive electronic-to-optic pulse jitter (1ns, the seeder is completed by a phase modulator driven by a structured noise source, which permits to continuously adjust the spectral width from 1 to >10X the Fourier transform limit. The pulses are then injected in a gain-staged amplifier terminated by a novel adiabatically tapered Yb-doped ~12cm-diameter-coil fiber with output core diameter >40um. From this all-fiber amplifier, we obtain peak powers >200kW and robust beam M2 ~ 1.1. Further pulse energy/peak power scaling is obtained in large-core standard or mode filtered rod-type photonic crystal fiber amplifiers, which also retain excellent spatial brightness. Among our results is the SBS-free generation of ~2mJ-energy, ~1.5MW peak power in ~2ns pulses of ~2GHz spectral FWHM (10kHz PRF) and M2 < 1.3 in a compactly packaged (< 15-liter volume) embodiment of the described fiber-based architecture.

8237-34, Session 17

High energy in-band pumped erbium doped pulsed fibre laser

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High energy Er-based 1550nm pulsed fiber lasers are highly desirable in applications such as remote sensing and material processing where light scattering off a target can cause safety concerns. At present, the state-of the-art approach to generate high energy pulses is by 9xx-nm cladding pumped Erbium-doped fiber (EDF) or Erbium/Ytterbium-codoped fiber (EYDF) lasers/amplifiers [1,2]. Recently, inband-pumped Erbium doped fiber amplifiers have attracted considerable interest. For example, an optical-to-optical conversion efficiency of ~80% at "multi-watts" level has been demonstrated in a continuous-wave, core-pumped MOPA. The core-pumped scheme is attractive for pulse laser system due to the shorter pump absorption length resulting in an inherently shorter device and reduced effective nonlinear lengths.

Here, we demonstrate for the first time an all-fiber, high-energy inband, core-pumped nanosecond MOPA capable of generating pulses with energies of 1.56mJ at a repetition rate of 1.25kHz. The MOPA was seeded by a fiber Bragg grating (FBG) stabilized, actively Q-switched EYDF fiber ring laser producing ~105ns pulses at ~1562.5nm. A 40µm core diameter Er^{3+}-doped LMA fiber was used as the gain medium while a 1535nm single-mode EYDF laser was used as the pump source. The width of the Gaussian shaped output pulses increased from ~105ns to ~150ns during the amplification process. The output beam quality (M2) was measured to be <1.5. By optimizing the cavity architecture both the multi-peak pulse phenomenon [2] and modulation instability within the MOPA have been mitigated. Further enhancement in pulse energy is primarily limited by the saturation of the pump absorption and the build-up of inter-pulse ASE.

[1] E. Lallier and D. Papillon-Ruggeri, "High energy pulsed eye-safe fiber amplifier," Paper CJ1.5, CLEO Europe, May 22-26 May, Munich, Germany, 2011.

[2] V. N. Philippov, J. K. Sahu, C. A. Codemard, W. A. Clarkson, J.-N. Jang, J. Nilsson and G. N. Pearson, "All-fiber 1.15-mJ pulsed eye-safe optical source," Proc. SPIE 5335, 1, 2004.

8237-35, Session 17

Q-switched and mode-locked pulses amplified with short thulium-doped silicate fibers

Q. Wang, J. Geng, T. Luo, S. Jiang, AdValue Photonics, Inc. (United States)

250-word text abstract

30ns, 3µJ Q-switched pulse laser with the repetition rate of 10 kHz at 1950 nm was demonstrated. By amplification with a 50cm long piece of single-mode thulium(Tm)-doped silicate fiber, 300µJ pulses with 15kW peak power were obtained. The heavily Tm-doped silicate fiber has the cladding-pump absorption of 22dB/m at 793nm. The core diameter is 22um and the first cladding is 125um. With the core NA of 0.06, the fiber maintains solid single-mode operation at 1950nm. The 50cm long piece of fiber can provide 20dB gain for nanosecond pulses at 10 kHz.

An all-fiber mode-locked thulium fiber oscillator was demonstrated. With dispersion compensation in the ring cavity, self-starting and stable stretched-pulse mode-locking was achieved. The bandwidth of output pulse is 15 nm and the pulse energy is 0.3 nJ. Its amplification to 665mW average power, 16kW peak power and 20nJ pulses with a 30cm long piece of single-mode Tm-doped silicate fiber are demonstrated. The Tm-doped silicate fiber used for mode-locked pulse amplification has the core diameter of 10 µm, which enables low splicing loss between our silicate fiber and SMF-28. The amplified high peak power pulses at 2 µm reported in this paper are very useful for mid-IR generation.

Extended abstracts

Comparing to previous works on 2µm Q-switched pulse amplification, this contribution demonstrates several strengths.

1. Very short piece of heavily Tm-doped silicate fiber. Only 50cm long fiber can provide 20dB gain under cladding pump.

2. Single-mode fiber design instead of LMA fiber. 22um core and 0.06 NA enable solid single-mode operation.

3. All-fiber configuration for the whole system is compact and robust.

4. 300uJ and 15kW pulses at 1950nm are strong enough for many nonlinear applications.

Very short (30cm) Tm-doped silicate fiber was used for amplifying mode-locked pulses. To achieve output delivery with SMF-28 fiber, 10um diameter fiber was used in amplifier. With shorter Tm-doped silicate fibers with larger core can lead to amplified pulses with much larger pulse energy and peak power. The whole system is also in all-fiber configuration.

Conference 8238A: High Energy/Average Power Lasers and Intense Beam Applications VII

Sunday 22 January 2012

Part of Proceedings of SPIE Vol. 8238A High Energy/Average Power Lasers and Intense Beam Applications VII

8238A-01, Session 1

Chemistry of I* excitation in a hybrid catalytic electric-discharge oxygen-iodine laser

W. T. Rawlins, S. Lee, S. J. Davis, Physical Sciences Inc. (United States)

In electrically driven oxygen-iodine laser systems (EOIL), I_2 is injected into active-oxygen flows containing O(3P), O_2(a1□g), and NO/NO_2 to produce excitation and lasing on the $I(^2P_{1/2} \rightarrow {}^2P_{3/2})$ line at 1315 nm. We have investigated the excitation of $I(^2P_{1/2})$ and optical gain for both homogeneous (all-gas-phase) and heterogeneous (gas-surface catalytic) discharge-flow conditions. The catalyst is a unique iodine oxide coating prepared by reactions of active oxygen species with iodine vapor over a specially prepared substrate. The results reveal several reactions not previously considered which contribute to $I(^2P_{1/2})$ excitation and quenching, and significantly revise the previously accepted view of the active-oxygen-NO_x-iodine reaction system.

8238A-02, Session 1

ElectricOIL performance enhancement via increases in g_0L

D. L. Carroll, G. Benavides, J. Zimmerman, CU Aerospace LLC (United States); B. Woodard, Univ. of Illinois at Urbana-Champaign (United States); A. D. Palla, J. T. Verdeyen, CU Aerospace LLC (United States); W. C. Solomon, Univ. of Illinois at Urbana-Champaign (United States)

Experiments and modeling have led to a continuing evolution of the Electric Oxygen-Iodine Laser (ElectricOIL) system [1-6]. This continuous wave (cw) laser operating on the 1315 nm transition of atomic iodine is pumped by the production of $O_2(a)$ in a radio-frequency (RF) discharge in an $O_2/He/NO$ gas mixture. New discharge geometries have led to improvements in $O_2(a)$ production and efficiency. There are unidentified kinetic processes that are occurring in the ElectricOIL system [7, 8]. As understanding of the ElectricOIL system continues to improve, the design of the laser is systematically evolving. The gain has improved by more than 100-fold from the initial demonstration of 0.002% cm^{-1} to 0.30% cm^{-1}, and similarly the outcoupled laser power has improved more than 500-fold from 0.16 W to 109 W. Recent experiments and modeling are presented. Increases in the product of g_0L are presently showing a super-linear growth in performance.

8238A-03, Session 1

XPAL theory and modeling with comparison to experiments

D. L. Carroll, J. T. Verdeyen, A. D. Palla, CU Aerospace LLC (United States)

The exciplex pumped alkali laser (XPAL) system has bee demonstrated [1-5] in mixtures of Cs vapor, Ar, with and without ethane, by pumping Cs-Ar atomic collision pairs and subsequent dissociation of diatomic, electronically-excited CsAr molecules (exciplexes or excimers). The blue satellites of the alkali D2 lines provide an advantageous pathway for optically pumping atomic alkali lasers on the principal series (resonance) transitions with broad linewidth (>2 nm) semiconductor diode lasers. Because of the addition of atomic collision pairs and exciplex states, modeling of the XPAL system is more complicated than classic diode pumped alkali laser (DPAL) [6-9] modeling. Recent XPAL data include four-level demonstrations (without any relaxer gas) in Rb-Ar and Cs-Ar-Xe. The development of a simple theoretical analysis of CW XPAL systems is presented and compared with some experimental data, along with the latest high-fidelity modeling using the BLAZE-V code [10].

8238A-04, Session 1

Optical gain and excitation phenomena in optically pumped alkali atom-rare gas mixtures

K. L. Galbally-Kinney, D. L. Maser, W. J. Kessler, W. T. Rawlins, S. J. Davis, Physical Sciences Inc. (United States)

Diode-pumped alkali laser (DPAL) technology offers an attractive means of achieving high-energy laser output through optical pumping of the D-lines of Cs, Rb, and K. The exciplex effect, based on weak attractive forces between alkali atoms and polarizable rare gas atoms (Ar, Kr, Xe), provides an alternative approach via broadband excitation of exciplex precursors (XPAL). We have developed an approach for measuring both spectrally and spatially resolved optical gain in these systems, based on tunable diode laser absorption/gain spectroscopy. We have also observed multi-quantum excitation within the alkali manifolds which result in infrared emission lines between 1 and 4 um.

8238A-05, Session 2

Investigation of radial temperature gradients in diode pumped alkali lasers using tunable diode laser absorption spectroscopy

C. D. Fox, G. P. Perram, Air Force Institute of Technology (United States)

Diode Pumped Alkali Lasers (DPAL) are often pumped with spatially non-uniform excitation rates, possibly leading to temperature and alkali density gradients within the gain medium. Decreases in local alkali atom densities will modify the pump rate and can lead to decreased power efficiency. In the present work, a 0.8 W/cm^2 pump laser at the D1 frequency heats the medium in a T=50-100°C cesium heat pipe with 5 Torr nitrogen used for quenching. A 31μW/cm^2 diode laser probes the spectral absorbance of the cesium cell on the D2 transition with radial spatial resolution. The 300 kHz linewidth probe laser is scanned 20 GHz across the optically thick hyperfine structure, revealing absorbances of 1-5. The absorbance outside of the pumped volume is modulated by up to a factor of 2 when the pump beam is blocked, suggesting significant temperature gradients. The radial temperature profile is observed across the 1.5 cm pipe with resolution of 2 mm. The dependence of the temperature profiles on pump power, nitrogen pressure, and heat pipe temperature has been characterized.

8238A-06, Session 2

The kinetics of optically excited Ne* and Kr* metastables in helium at high pressure

M. C. Heaven, J. Han, H. Kabir, Emory Univ. (United States)

Excited rare gas atoms may be used for optically pumped laser systems that operate on the np5(n+1)p↔ np5(n+1)s transitions. Rg(np5(n+1)s) metastable states are readily produced using low-power electrical discharges. Knowledge of the rate constants for collisional energy transfer from the np5(n+1)p states is required to evaluate the laser potential for various Rg + buffer gas combinations. We have used discharge excitation of Ne or Kr in He buffer gas to produce metatstables at total gas pressures of 0.2-1.0 bar. Pulsed laser excitation has been used to study excited state relaxation kinetics and transition lineshapes.

8238A-07, Session 2

Potential energy surfaces for the interactions of excited Rb and Cs atoms with methane

M. C. Heaven, Emory Univ. (United States)

Diode pumped alkali vapor lasers (DPAL's) rely on collisional energy transfer to move population from the optically pumped level (2P3/2) to the upper level of the laser transition (2P1/2). Small hydrocarbon molecules such as methane and ethane have proved to be very effective transfer agents. It is thought that the primary mechanism is electronic to rotational (E-R) energy transfer, but this has yet to be proven. In the present study we use electronic structure calculations to determine the potential energy surfaces for Rb(2P) and Cs(2P) interacting with methane. These surfaces are used to estimate the probabilities for transfer by E-R and by surface hopping at seams of intersection.

8238A-08, Session 3

Maritime HEL efficacy analysis

S. M. Hammel, Space and Naval Warfare Systems Command (United States)

My thesis is that atmospheric degradation is the dominant indeterminate factor impeding an accurate power-in-bucket determination for an HEL. This indeterminacy is intensified by the fact that for maritime use, there is no measurement package that can assess extinction or turbulence along the beam path, and no model with sufficient accuracy or resolution to predict beam extinction or scintillation on slant paths in a maritime environment. I will discuss the strengths and weaknesses of component propagation models.

This paper will emphasize work to assess beam propagation efficiency in various maritime environments. We developed a power-in-bucket climatology to enable a comparison of environmental factors such as geographical location and season of year. The results are collected into standalone software widget that allows the user to choose environmental factors and system parameters to assess beam propagation efficacy.

8238A-09, Session 3

Average power scaling of UV excimer lasers drives flat panel display and LIDAR applications

L. Herbst, R. F. Delmdahl, R. Paetzel, Coherent GmbH (Germany)

A new concept for high-average power upscaling of excimer lasers has been developed enabling as much as 1.2 kW of stabilized UV-laser average output power at a wavelength of 308nm. The output power of 1.2 kW was achieved by external beam merging and temporally synchronizing two high power UV-oscillators each capable of 1 Joule energy per pulse and 600 Hz pulse frequency.

Upscaling 308nm excimer laser output power to above a kW

Similarly, the cost-effective production of flexible displays is driven by high output power 308 nm excimer laser upscaling. Flexible displays have enormous commercial potential and can largely use the same production equipment as is used for rigid display manufacturing. In a crucial process step a 308 nm excimer laser is directed through the glass substrate. The UV photons are strongly absorbed within a thin evaporating interface layer, thus separating the flexible circuitry on polymer from the rigid glass carrier. Avoiding chemical separation the laser lift-off processing of flexible displays also works towards a greener production.

Higher average output power of 308 nm UV laser sources aid reduces measurement time and improves the signal-to-noise ratio in Raman lidar stations. The availability of kW-class 308 nm excimer lasers will thus also contribute to increase the level of understanding our chiefly man-made climate change.

8238A-10, Session 3

Development of a double TIG laser process

J. Hermsdorf, Laser Zentrum Hannover e.V. (Germany)

TIG welding is a common industrially established process. Its main advantage is the weld quality. The drawback is the low process speed which leads to high heat affects, irreversibly destroyed material properties and work piece distortion. To overcome these process limits, two common TIG processes were combined with low power laser radiation. This double TIG laser process enables 50 % higher process speed and lower distortion without compromise in weld quality and penetration depth. Two electrodes are integrated into one welding head with the laser beam in the center. During the process the laser combines and guides the two electrical arcs to one common foot point on the workpiece. Due to this increase of electric energy density good process stability is given, even at higher welding speeds. The guiding of both electrical arcs with 400 W laser power and a beam diameter of 1.6 mm on the material surface will be demonstrated. Welding speeds up to 3 m/min and 1 m/min were possible on aluminium and stainless steel, respectively.

The paper shows first process results on stainless steel with a material thickness of 2 mm. Welding pieces, cross-sections, process videos and the new welding head will be presented.

8238A-11, Session 3

Phase controlled stimulated Brillouin scattering phase conjugation mirrors and its applications to the laser fusion driver

H. J. Kong, S. Park, S. Cha, KAIST (Korea, Republic of); M. Kalal, Czech Technical Univ. in Prague (Czech Republic)

The inertial fusion energy is noted as the one of the future energy sources. To realize the inertial fusion energy, the output energy of 500 kJ@10 Hz@10 ns pulsed laser is required. However, it is hard to achieve both high energy and high repetition rate because of the heat problem of the gain medium and the parasitic oscillation. One of the solutions is the beam combination laser using stimulated Brillouin scattering phase conjugation mirrors (SBS-PCM). Its phase conjugation property has the advantage to make laser fusion driver.

Figure 1 is the setup of the beam combination laser using SBS-PCMs. The laser beam passes spatial filter and the size of the beam is expanded by ten times. The beam is separated by 4-beam aperture mask to 4 sub-beams. Each sub-beam passes through PBS, and is reflected by mirrors and prisms. Each sub-beam is amplified by amplifiers, and passes through the Faraday rotators. The self-phase-controlled SBS-PCMs reflect sub-beams, and the sub-beams pass the Faraday rotators, the amplifiers, the mirrors and the prisms. One of the sub-beams is divided by beam splitter, and the part of the sub-beam is expanded by beam expander. This expanded beam serves as a reference beam. The sub-beams are combined to the output beam, and the part of the output beam and the reference beam make an interferogram to measure the relative phases between each sub-beams. We will present the experimental result, and its application to the laser fusion driver.

8238A-12, Session 4

MOPA carbon monoxide laser system emitting nanosecond pulses

A. A. Ionin, I. Kinyaevskiy, Y. Klimachev, A. Kotkov, A. Kozlov, P.N. Lebedev Physical Institute (Russian Federation)

Master Oscillator - Power Amplifier (MOPA) carbon monoxide laser system emitting nanosecond pulses around the fundamental band wavelength of ~5.2 micron and frequency doubled band wavelength of ~2.6 micron was developed. Amplification of the nanosecond pulses in the active medium of fundamental band CO laser amplifier was experimentally studied. Gain parameters including saturation ones of the CO laser active medium were measured for different experimental conditions. High peak power of the nanosecond pulses emitted by the MOPA system enabled us to increase efficiency of frequency doubling in nonlinear optical crystal up to 25 percent.

8238A-14, Session 4

A simplified model for HF chemical laser amplifier

W. G. Liu, X. Chen, H. Wang, W. Li, W. Hua, National Univ. of Defense Technology (China)

HF chemical laser with MOPA configuration is a good solution to achieve high output power with high reliability. Kinetic models for HF amplifier are important for prediction and optimization of the performance of MOPA chemical lasers. In this paper, a simplified model for HF chemical laser amplifier is presented. The main processes which are included in the model are: (a) chemical pumping of HF (v=2) and HF (v=1), (b) stimulated transitions and spontaneous emission. (c) collisional relaxation of vibration excited HF molecule by H2,N2 and HF.

Some assumptions are taken in this model: (a) the density of H2, N2, HF, translational temperature and velocity of gas mixture are averaged across the laser cross section, (b) only two vibration-rotational transitions (2P6, 1P7) occurs in the amplifier, (c) gas temperature does not change during the lasing process in the amplifier.

Based on these assumptions, a set of three-level rate equations is formulated and then solved by an iterative technique. Comparison is made with recent experimentally obtained data from a low power discharge-driven CW HF laser with MOPA configuration. It is shown that experimental results are consistent with the calculation from the simplified model.

Conference 8238B: Atmospheric and Oceanic Propagation of Electromagnetic Waves VI

Tuesday 24 January 2012

Part of Proceedings of SPIE Vol. 8238B Atmospheric and Oceanic Propagation of Electromagnetic Waves VI

8238B-20, Session 5

Creating a Cn2 profile as a function of altitude based on scintillation measurements along a slant path

L. C. Andrews, Univ. of Central Florida (United States); R. L. Phillips, D. Wayne, P. Sauer, T. Leclerc, R. Crabbs, Florida Space Institute (United States)

Using a three-aperture scintillometer system (TASS) to measure irradiance fluctuations along a slant path, it is possible to create a Cn2 profile model as a function of altitude up to the maximum altitude of a laser beam along some propagation slant path. This technique was demonstrated in June 2011 on a beacon beam transmitted between Hollister Airport in California to a position on Fremont Peak at a slant range of 17 km. Although the primary experiment was to test a hybrid optical RF communication system, the beacon signal at the transmitter was intercepted by the TASS from which weighted path-average values of Cn2, inner scale l0, and outer scale L0 were determined. Path-average values were then entered into an algorithm that determines the parameters of the HAP Cn2 profile model (a variation of the HV profile model). In this paper we report on these recent measurements and how this method of constructing the HAP model can be used over other propagation paths.

8238B-21, Session 5

Target-in-the-loop adaptive laser beam projection on an extended target: turbulence speckle effects mitigation

M. A. Vorontsov, E. E. Polnau, M. Gatz, T. Weyrauch, Univ. of Dayton (United States); S. L. Lachinova, Optonicus (United States); D. Marker, Air Force Research Lab. (United States)

It is well-known that the outgoing beam scattering off a target's randomly rough surface results in strong speckle-modulation of the return wave. This speckle modulation is the major bottleneck for the existing two major types of adaptive optics techniques (phase-conjugate and power-in-the-bucket metric optimization) and hence represents a serious obstacle for directed energy applications. In the presented study the speckle-noise problem is addressed using the following two approaches: (a) the speckle-average ("SA") phase conjugation control technique that allows mitigation of speckle-effects by measuring the SA wavefront slopes of the target return wave using a modified Shack-Hartmann wavefront sensor, and (b) the stochastic parallel gradient descent (SPGD) wavefront control based on the target-in-the-loop optimization of a set of selected speckle-field statistical characteristics (speckle metrics), that are proportional to the target hit-spot power density. We show that the fiber-array technology offers a unique potential for practical implementation of the speckle-metric based SPGD adaptive optics technique in the fiber-array HEL systems under development. Results of both analysis and the concept-proof experiments are presented.

8238B-22, Session 5

Experimental demonstration of target-in-the-loop coherent beam combining over a 7-km propagation path

T. Weyrauch, Univ. of Dayton (United States); M. A. Vorontsov, Univ. of Dayton (United States) and Optonicus (United States); G. W. Carhart, L. A. Beresnev, U.S. Army Research Lab. (United States); A. P. Rostov, Optonicus (United States); J. J. Liu, U.S. Army Research Lab. (United States)

Coherent combining, i.e., phase locking, of laser beams, which originate from a fiber-based multi-channel master oscillator power amplifier (MOPA) laser system, at a remotely located target in the atmosphere requires adaptive compensation of both random phase shifts introduced by the MOPA system and atmospheric turbulence-induced phase aberrations. In this paper, we report on the results of, to our knowledge, first successful target-in-the-loop (TIL) coherent beam combining experiments over an extended-length atmospheric propagation path in a TIL setting with a non-cooperative, unresolved target. Seven laser beams emerging from an adaptive fiber-collimator array were projected to a corner-cube retro-reflector located at distances up to 7 km. The power of the return light, collected by a telescope placed next to the collimator array, was used as performance metric for adaptive control of piston, tip and tilt wavefront phase at each fiber-collimator sub-aperture using iterative stochastic parallel gradient descent (SPGD) techniques. Optimization of the metric resulted in automatic focusing of the combined beam onto the target with pre-compensation of quasi-static (e.g., from windows in the propagation path) and atmospheric turbulence-induced phase aberrations. The round-trip propagation delay - one of the major obstacle for the TIL adaptive optics techniques - has been overcome in these experiments by utilizing a recently proposed SPGD wavefront control technique that allows the duration between sequential wavefront control updates to be shorter than the round-trip propagation delay. The new technique resulted in a significant increase of phase-locking and atmospheric compensation bandwidth.

8238B-23, Session 5

Atmospheric transmission for cesium DPAL using TDLAS

C. A. Rice, G. P. Perram, Air Force Institute of Technology (United States)

The Cesium Diode Pumped Alkali Laser (DPAL) operates near 894 nm, in the vicinity of atmospheric water vapor absorption lines. An open-path Tunable Diode Laser Absorption (TDLAS) system composed of narrow band (~300 kHz) diode laser fiber coupled to a 12" Ritchey-Chrétien transmit telescope has been used to study the atmospheric transmission characteristics of Cs DPAL over extended paths. The ruggedized system has been field deployed and tested for propagation distances of greater than 1 km. By scanning the diode laser across many free spectral ranges, many rotational absorption features are observed. Absolute laser frequency is monitored with a High Fineese wavemeter to an accuracy of 2 MHz. Phase sensitive detection is employed with absorbance of < 1% observable under field conditions. Water vapor concentrations are accurately retrieved from Lorentzian profiles using the HITRAN database.

8238B-24, Session 5

Probability density function of partially coherent beams propagating in the atmospheric turbulence

O. Korotkova, Univ. of Miami (United States); S. Avramov-Zamurovic, C. Nelson, R. Malek-Madani, U.S. Naval Academy (United States)

Experimental results are presented for the histograms of the fluctuating intensity of a scalar stochastic light beam propagating in weak atmospheric turbulence, along horizontal links above both ground and water. The probability density function [pdf] of the intensity is reconstructed from the calculated statistical moments on the basis of the Gamma-Laguerre model (introduced by R. Barakat) and compared with histograms. The stochastic beam is generated by a Gaussian laser source and is reflected from a phase Spatial Light Modulator [SLM] to result in a Gaussian Schell-model beam. The change in the pdf shapes with the initial beam parameters, ground/water links and propagation distance is demonstrated. Stochastic beams have been recently suggested to be used for communications and remote sensing through the atmosphere, instead of laser beams, due to their ability to efficiently suppress atmospheric perturbations. The knowledge of the intensity pdf is crucial for the accurate prediction of the communication errors and the LIDAR returns.

8238B-25, Session 6

Turbulence-corrected adaptive laser beam focusing on a remote image-resolved target

A. I. Khizhnyak, V. B. Markov, Advanced Systems & Technologies, Inc. (United States)

Focusing of the laser beam on a remote target through turbulent atmosphere remains a difficult problem to resolve. Two methods have been extensively studied to address this problem: the computer-controlled adaptive optics (AO) and self-aligned non-linear optical phase conjugation (OPC). Both methods have proven to perform well with a localized beacon on the target. However, with no beacon the laser beam cannot be tightly focused, resulting in a large area spot. Consequently, the target-scattered light field is transformed it into a fully-developed speckle field, making it difficult to apply the AO technique to control the laser beam. This problem though have been extensively studied over last several decades still is lacking a reliable solution.

This presentation discusses a novel approach in addressing the problem of the impact of the speckle field on the performance of AO and OPC methods used to improve focusing of the laser beam on a remote image resolved target through turbulent atmosphere. Examples of different operational scenarios have been analyzed using a computer simulation technique. Two study cases were considered, namely the horizontal and the slant path for the ground and airborne based laser system often considered as the up- and down-link propagation geometry. Proof of the concept experimental studies were performed in the laboratory environment using a specially designed target-in-the-loop simulator. The results of the performed analysis and experimental studies allow to conclude that the use of the proposed algorithm to control the AO system result in an improved focusing of the laser beam on a remote image-resolved target.

8238B-26, Session 6

Scintillation-resistant wavefront sensing based on a multi-aperture phase reconstruction (MAPR) technique

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A scintillation-resistant sensor that allows retrieval of an input optical wave phase using a multi-aperture phase reconstruction (MAPR) technique is introduced and analyzed. The MAPR sensor is based on a low-resolution lenslet array (not exceeding 7x7 lenslets) in the classical Shack-Hartmann arrangement and two high-resolution photo-arrays for simultaneous measurements of pupil and focal plane intensity distributions. Pupil and focal measurements are used for retrieval of the wavefront phase using a two stage process: (1) phase reconstruction inside the sensor pupil sub-regions corresponding to lenslet sub-apertures, and (2) recovery of sub-aperture averaged phase components (pistons). Numerical simulations demonstrate the efficiency of the MAPR technique even in conditions of strong intensity scintillations making it a good candidate for applications requiring optical wave propagation over near horizontal or slant atmospheric paths. Since both phase and amplitude functions of the optical wave can be computed from the MAPR sensor measurements, the sensor described can be also referred to as complex-field sensor.

8238B-28, Session 6

Turbulent flow characterization using OCT

M. Mujat, R. D. Ferguson, N. V. Iftimia, D. X. Hammer, E. P. Plumb, Physical Sciences Inc. (United States); I. Nedyalkov, M. Wosnik, The Univ. of New Hampshire (United States); H. H. Legner, Physical Sciences Inc. (United States)

The objective of this project was to develop and demonstrate a novel system based on Fourier-Domain Optical Coherence Tomography (FD-OCT) to measure with high spatial resolution the near-wall velocity profile and turbulence characteristics in a high Reynolds number fluid flow. The velocity profile near the wall provides direct information on the wall shear stress or skin-friction, a quantity of paramount interest to researchers to understand turbulent flow and its contribution to drag reduction for large naval vehicles. Turbulent boundary layers dominate ship and submarine flowfields. OCT is a non-invasive depth-resolved imaging method with a micron-level axial resolution. As opposed to other particle velocimetry techniques, OCT provides depth resolved velocity measurements with excellent depth discrimination within 1-2 mm from the boundary where other techniques, like Laser Doppler Velocimetry, cannot make such measurements. Our preliminary results demonstrate the feasibility of performing depth-resolved velocity measurement in various conditions such as parabolic flow in a 200 µm flow cell, or turbulent flow over 1 mm in the boundary layer of a 6' deep water tunnel. Fluctuations in the streamwise and normal velocity components can be quantified for more complete characterization of the turbulent flow statistics. Our direct measurements of near-wall mean velocity are consistent with previous turbulent boundary-layer velocity profile measurements. Consequently, the prospects for measuring skin friction directly in the marine environment with or without drag-reducing flow additives are quite good. Naturally occurring particulates in sea water and drag-reducing elements provide excellent scattering centers for OCT to measure velocity values and skin friction.

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8238B-29, Session 6

Laser beam propagation in oceanic turbulence

N. H. Farwell, O. Korotkova, Univ. of Miami (United States)

Light propagation though oceanic turbulence is a relatively unexplored topic compared to that of atmospheric turbulence. Many models have been developed and used to describe the power spectrum of atmospheric turbulence whereas until recently many predictions in the ocean were still made with the simple Kolmogorov model. A recently developed spectral model describing oceanic optical turbulence is used to investigate the properties of a Gaussian beam upon propagation through oceanic turbulence. The analytical model combines the effects of temperature and salinity fluctuations on the refractive index resulting in a two bumped power spectrum at high wave numbers. The exact profile of the spectrum is affected by the rate of dissipation of turbulent kinetic energy, the rate of temperature dissipation, and the relative strength of temperature and salinity fluctuations. Absorption and scattering are ignored and only the effects of optical turbulence, which for certain wavelengths can be significant in comparison to absorption, are analyzed. Using the Rytov method and Belen'kii and Mironov's method of effective beam parameters for strong turbulence regimes, the intensity, coherence, and scintillation properties of a Gaussian beam are explored. Due to the complicated nature of the oceanic turbulence spectrum, the analysis is restricted to numerical computations.

Conference 8239: High Power Laser Materials Processing: Lasers, Beam Delivery, Diagnostics, and Applications

Tuesday-Thursday 24-26 January 2012

Part of Proceedings of SPIE Vol. 8239 High Power Laser Materials Processing: Lasers, Beam Delivery, Diagnostics, and Applications

8239-36, Poster Session

Controlling the thermally induced focal shift in laser processing heads

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We present a system being able to in situ measure and control the true focal position on the workpiece including the thermally induced focal shift in the laser processing head.

The development of multi-kilowatt solid-state lasers with continuously growing brilliance leads to a significant increase of the thermally induced focal shift in all transmissive optics. Our system does not simply keep the distance between the workpiece and the focussing optics constant. It measures and controls the real focal position on the workpiece, taking also into account the thermally induced focus shift.

This is done by using six astigmatic measurement beams which are aligned coaxially around the welding beam and which follow the same optical path as the high-power beam and therefore underlie the same thermally induced influences. The orientations of the elliptical profiles on the workpiece depend on the focal distance. The beams scattered from the workpiece surface are analyzed by a camera and a corresponding software algorithm which allows to control the focal position of the welding beam by a feedback loop including a stepper motor. All required additional optical components except the measurement beam sources were integrated into a TRUMPF LLK-D plug. First experiments show that the software algorithm is capable of controlling the focal position within a range of 4 mm. The resolution ranges between 150 µm and 500 µm, depending on the workpiece material.

Additional experiments are in progress to test the system under various realistic conditions in a laser welding process.

8239-37, Poster Session

Process reliability of critical weldings

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Process reliability is an essential precondition for manufacturing a product in persistently high quality and quantity - over the entire manufacturing time of product, in particular, as far as varying process conditions are concerned.

Definition of design in terms of function, production technology and, if need be, aesthetics is an important part of product development.

The construction of complex components from preferably lightweight single parts which can be manufactured with high cost efficiency makes sense as regards economic aspects. As a consequence thereof, constantly higher demands are made on joining technology where materials of various material groups must be combined to create a functional component.

Even in the design phase, the draftsman must also consider the subsequent production technology i.e. product design shall also comprise demands made on a constructive design suited for use of laser apart from the very product function. This includes accessibility to laser beam and other relevant features, such as material selection, seam geometry and location.

This is of particular importance for critical materials and material pairings which are increasingly in use - driven by the economic pressure in the use of expensive raw materials and, last but not least, by the advance of electric mobility.

This is strongly evidenced by the beam sources of high brilliance current available which offer far more versatile applications as a few years ago with established laser-beam sources. Thanks to the use of highly brilliant laser-bear sources, special seam geometries can be purposefully created and heat-affected zones kept to a minimum.

The process-engineering possibilities of material machining with highly brilliant lasers shall be demonstrated here such as e.g. joining of high-carbon steels, highly reflecting materials such as copper or aluminum etc. under use of different kinds of process monitoring equipment.

8239-39, Poster Session

Study of a fiber laser assisted friction stir welding process

G. Casalino, S. L. Campanelli, A. D. Ludovico, N. Contuzzi, A. Angelastro, Politecnico di Bari (Italy)

Friction Stir Welding (FSW) is a relatively new joining technique. This technique has many advantages: the welding procedure is relatively simple with no consumables or filler metal; joint edge preparation is not needed; oxide removal prior to welding is unnecessary; high joint strength has been achieved in different innovative materials; FSW can be used with alloys that cannot be fusion welded due to crack sensitivity.

The drawbacks of FSW include the need for powerful fixtures to clamp the workpiece to the welding table, the high force needed to move the welding tool forward, and the relatively high wear rate of the welding tool.

To overcome these drawbacks, a hybrid Laser-Friction Stir Welding (LFSW) system was developed in this work. The experimental set-up combined a commercial FSW machine and a fiber laser system. The key advantage of fiber lasers over other laser technologies are its high beam quality, that enables the beam to be focused to a small spot with a correspondingly high energy density. Laser power can be used either to preheat or to postheat the workpiece at a localized area ahead of and behind the rotating probe.

The effects of the set-up of the welding hybrid machine (tilt angle, blocking system, design of the tool) and some of the welding parameters (tool force, RPM tool, plunge speed, dwell time, welding speed, laser power) on the weld quality was studied. The evaluation of the weld quality was performed through the weld external defects and mechanical and microstructure characterization.

8239-40, Poster Session

Parameters in selective laser melting for processing metallic powders

T. Kurzynowski, E. Chlebus, B. Kuznicka, J. Reiner, Wroclaw Univ. of Technology (Poland)

The paper presents results of studies on Selective Laser Melting. SLM is an additive manufacturing technology which may be used to process almost all metallic materials in the form of powder. Types of energy emission sources, mainly fiber lasers and/or Nd:YAG laser with similar characteristics and the wavelength of 1,06 - 1,08 microns, are provided primarily for processing metallic powder materials with high absorption of laser radiation. The paper presents results of selected variable parameters (laser power, scanning time, scanning strategy) and fixed parameters such as the protective atmosphere (argon, nitrogen, helium), temperature, type and shape of the powder material. The thematic scope is very broad, so the work was focused on optimizing the process of selective laser micrometallurgy for producing fully dense parts. The density is closely linked with other two conditions: discontinuity of the microstructure (microcracks) and stability (repeatability) of the process. Materials used for the research were stainless steel 316L (AISI), tool steel H13 (AISI), and titanium alloy Ti6Al7Nb (ISO 5832-11). Studies were performed with a scanning electron microscope, a light microscopes, a confocal microscope and a µCT scanner.

8239-01, Session 1

Laser plasma sources for EUV lithography

M. C. Richardson, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

The development of EUV sources of sufficient brightness for HVM operation still remains the most critical challenge to EUV lithography. Laser plasma sources are one of the two primary concepts being pursued towards solving this need. These sources have centered on the use of high power, high-repetition rate pulsed laser systems irradiating mass-limited tin-containing droplet targets that produce band emission in the 13 nm range. The challenges to this approach are the efficient conversion of laser light to useful EUV emission with minimal particle and plasma debris affecting the transmission performance of the EUV collecting and imaging optics, dose control and stability, system reliability, spatial footprint efficiency, and its cost-competitiveness with laser-assisted discharge sources.

In this talk we will review the primary physical processes involved in laser plasma sources, the technical approaches being adopted, the laser technologies being employed, and the future these sources have for producing EUV powers required for HVM operation. We will discuss the differences in laser illumination being used, the different types of droplet targets, and the approaches being adopted for debris mitigation. In addition, the costs of ownership and operation will be addressed, and projections made on possible future developments.

8239-02, Session 1

The story of laser brazing technology

P. Hoffmann, ERLAS Erlanger Lasertechnik GmbH (Germany)

The presentation opens with a review in the year 1992, when fundamental research work in laser brazing technology started at German institutes. Obviously limitations were given by available laser system technology and missing process knowhow. Until 1998 it was a new technology without noticeable use for applications. But with first implementations in automobile production, the advantages became evident and from that time the number of automakers using laser brazing technology for body in white production has grown rapidly.

Besides a better understanding for the sensitivity of the process against joint irregularities and misalignment, the key to successful launch was an advanced system technology. Special working heads with wire feeding device, seam tracking systems and tactile sensors for an automated teaching have been developed.

With the help of actual examples the laser brazing adapted design of joints and boundary conditions for safe processing are discussed.

The presentation closes with an outlook on actual developments of technology specific system technology. Novel laser heads providing a two beam technology will allow improved penetration depth of the filler wire and a more ecological processing by means of energy consumption.

8239-03, Session 1

Innovations in laser cladding and direct metal deposition

C. Leyens, Technische Univ. Dresden (Germany)

The present paper will review recent progress in productivity, precision and quality of laser-based cladding and direct metal deposition. Laser cladding has proven to be an outstanding tool for surface modification aiming at excellent precision and tunable properties of the clad. However, limits for this technology are set by high costs of the laser equipment and the low energy efficiency of the laser beam leading to low deposition rates; for simple and large-scale components laser cladding is therefore often neglected for economical reasons. Typically, around 80-90% of the absorbed laser energy is lost by conductive heating of the component. In case of brittle materials high laser-related cooling rates can generate undesirable cracks within the clad. Recently, we have demonstrated the great benefits obtained by induction heating-assisted laser cladding. This novel hybrid technology combines high deposition rates with excellent cladding properties. For example, crack free deposition of INCONEL 625 on steel was achieved at 14,5 kg/h deposition rate using 8 kW diode laser power and 12 kW induction power.

Laser-based direct metal deposition is a novel concept for the fabrication of components and repair as well as geometrical surface modifications. Great advantages of the technology are an almost dense coating and beneficial material properties combined with low heat input and low distortion of the work piece. Material deposition with lateral resolution down to 30µm is possible for 2D and 3D geometries by means of precise system components and multiaxial CNC-machines.

An in-depth understanding of the processes and the resulting materials properties is key for the development of technically viable and economically reasonable customized solutions in many field of applications, such as aerospace, energy, oil and gas as well as off-shore technology.

8239-04, Session 1

Structural strengthening of rocket nozzle extension by means of laser metal deposition

M. Honoré, Force Institute (Denmark); L. Brox, M. Hallberg, Volvo Aero Corp. (Sweden)

Commercial space operations strive to maximize the payload per launch in order to minimize the costs of each kg launched into orbit; this yields demand for ever larger launchers with larger, more powerful rocket engines. Volvo Aero Corporation in collaboration with Snecma and Astrium is developing a new, upgraded Nozzle extension for the Vulcain 2 engine configuration, denoted Vulcain 2/2+ NE. The manufacturing process for the welding of the sandwich wall and the stiffening structure is developed in close cooperation with FORCE Technology. The upgrade is intended to be available for the European Space Agency's (ESA) highly successful commercial launch vehicle, the ARIANE 5.

The upgraded Vulcain 2/2+ Nozzle Extension features a novel, thin-sheet laser-welded configuration, with laser metal deposition built-up 3D-features for the mounting of stiffening structure, flanges and for structural strengthening, in order to cope with the extreme load- and thermal conditions, to which the rocket nozzle extension is exposed during launch of the 750 ton ARIANE 5 launcher. Several millimeters of material thickness has been deposited by laser metal deposition without disturbing the intricate flow geometry of the sub-millimeter wall thickness of the nozzle cooling channels.

The laser metal deposition process has been applied on a full-scale rocket nozzle demonstrator, and in excess of 15 kilometers of filler wire has been successfully applied to the rocket nozzle. The laser metal deposition has proven successful in two full-throttle, full-scale tests, firing the rocket engine and nozzle in the ESA test facility P5 by DLR in Lampoldshausen, Germany.

8239-05, Session 2

The role of high power lasers in macro trends affecting product design and manufacturing in heavy industry

E. Hansen, ESAB North America (United States)

The products and production processes found in our traditional "heavy industries" have remained essentially unchanged since the 1950s. The products they build, the tools used to build them and the methods of construction, while certainly refined, have experienced little fundamental change over the last 60 years. Recently, however, there have emerged several "macro" trends influencing the way products are designed and manufactured in heavy industry. The most common macro trends include:

- Affordable, High Performance Materials
- Emphasis on Mass Reduction
- New Integrated Structures
- Precision Cutting and Forming Operations
- Forward Shifting of Added Value
- Reduction or Elimination of High-Skill Craftwork
- 5th Generation Joining Technologies
- Flexible Automation for Low Volume/ High Mix Production

These trends can be found across a spectrum of market segments from transportation and mobile equipment to civil engineering and shipbuilding. They are fundamentally changing these industries from essentially low-tech, high-craft operations towards the kind of high-tech, low-cost production that we more commonly associate with automotive and light manufacturing. One of the most important tools in these emerging macro trends are efficient, high energy, solid-state lasers and the new design and production methods that they enable. This presentation will look at these emerging trends and how high power lasers are being used to bring about fundamental change.

8239-06, Session 2

Frequency doubled high-power disk lasers in pulsed and continuous-wave operation

A. Hangst, TRUMPF Laser- und Systemtechnik GmbH (Germany); S. Weiler, TRUMPF Inc. (United States); D. H. Sutter, C. Stolzenburg, I. Zawischa, S. Kalfhues, A. Killi, TRUMPF Laser GmbH & Co. KG (Germany); M. Holzer, U. Kriegshaeuser, TRUMPF Laser- und Systemtechnik GmbH (Germany)

The disk laser with multi-kW output power in infrared cw operation is widely used in today's manufacturing, primarily in the automotive industry. The disk technology combines high power (average and/or peak power), excellent beam quality, high efficiency and high reliability with low investment and operating costs.

Additionally, the disk laser is ideally suited for frequency conversion due to its polarized output with negligible depolarization losses. Laser light in the green spectral range (~515 nm) can be created with a nonlinear crystal. Pulsed disk lasers with green output of well above 50 W (extracavity doubling) in the ps regime and several hundreds of Watts in the ns regime with intracavity doubling are already commercially available whereas intracavity doubled disk lasers in continuous wave operation with greater than 100 W output are in test phase.

In both operating modes (pulsed and cw) the frequency doubled disk laser offers advantages in existing and new applications. Copper welding for example is said to show much higher process reliability with green laser light due to its higher absorption in comparison to the infrared. This improvement has the potential to be very beneficial for the automotive industry's move to electrical vehicles which requires reliable high-volume welding of copper as a major task for electro motors, batteries, etc.

8239-07, Session 2

Lasers for industrial production processing: tailored tools with increasing flexibility

W. Rath, ROFIN-SINAR Laser GmbH (Germany)

High-power fiber lasers are the latest generation of diode pumped, solid-state lasers. Due to their all-fiber design they are compact, efficient and robust. Rofin's fiber lasers are available with highest beam qualities but the use of different process fiber core sizes enables the user additionally to adapt the beam quality, focus size and Rayleigh length to his requirements for best processing results. Multi-mode fibers from 50µm to 600µm with corresponding beam qualities of 2.5 mm.mrad to 25 mm.mrad are used. The integrated beam switching modules allow the operation of up to 4 different manufacturing systems or can share the power to two processing heads for parallel processing.

Also CO2 Slab lasers combine high power with either "single-mode" beam quality or higher order modes. The well established technique is in use for a large number of industrial applications, processing either metals or non metallic materials. For many of these applications CO2 lasers remain the best choice of possible laser sources either driven by the specific requirements of the application or because of the cost structure of the application.

The actual technical properties of these lasers will be presented as well as an overview over the wavelength driven differences of application results using examples of current industrial practice taking into account cutting, welding, surface processing in 2D and 3 D applications including the flexible use of scanners and classical optics processing heads.

8239-08, Session 2

High power diode lasers: generation of line focus geometries and its applications

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There are arising several applications for laser surface modifications of large areas, e.g. for processing flat panel displays, solar cells or drying processes. All these applications have two major requirements in common: i) melting of the surface with low heat impact on the bulk material and ii) processing of several square meters per minute in production lines. Scanning of line focus geometries across the surface is the approach of choice since scan and repeat approaches of laser spots are easily driven to not feasible parameter sets of scan speed, power or brightness level.

The requirements from the application point of view can be transformed to following key parameters of the laser system. High power density of > 1 kW/mm², extended line length exceeding several hundreds of mm to a couple of meters and small line width well below 100 µm, respectively. The overall power requirements ranges typically from a few kW to multiple hundreds of kW. Direct diode laser approaches do well fit due its high electro-optical efficiency and uneven brightness in fast and slow axis of broad area laser bars.

Concepts, data of lasers systems characterization as well as application results of diode lasers with line focus geometries are presented. Several distinct configurations are evaluated in detail, for instance for line length up to 520 mm or power level of 10 kW. Special emphasize on all these systems is given on modular and scalable concepts as well as on investigations of components and mounting procedures for large size optics.

8239-09, Session 2

High-power transmission characterization of Chalcogenide glasses using a Tm:fiber laser system

P. Kadwani, J. D. Bradford, R. A. Sims, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); J. D. Musgraves, K. A. Richardson, Clemson Univ. (United States); L. Shah, M. C. Richardson, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

Chalcogenide glasses have many potential applications owing to their transparency in mid-IR regime extending far beyond other oxide and fluoride based glasses. In order to characterize the high-power capabilities of chalcogenide glasses, we utilize a Tm:fiber laser providing up to 50 W average power at 2 µm wavelength. We have performed transmission measurements on 1 mm thick samples of $As_{10}Se_{90}$, $As_{30}Se_{70}$, $As_{40}Se_{60}$, and $As_{50}Se_{50}$. The Tm:fiber laser is an oscillator consisting of a LMA fiber with 25/400 µm core/cladding end pumped with 200 W, 793 nm pump. The output beam is collimated to a 2 mm beam-diameter and transmitted through the sample. No signs of damage are evident for powers up to 23 W, but thermal lensing is observed in $As_{30}Se_{70}$ at ~15 W. Further experiments will include more precise measurement of thermal lensing in the samples and surface damage threshold with 150 nanosecond pulses with ~ 2 kW peak power from a Q-switched Tm:fiber oscillator.

8239-10, Session 3

Advantages of fibre lasers in 3D metal cutting and welding applications supported by a ‘beam in motion (BIM)’ beam delivery system

T. Scheller, JENOPTIK Automatisierungstechnik GmbH (Germany)

Modern laser technology is continuously opening up new fields of applications. Driven by the development of increasingly efficient laser sources, the new technology is successfully entering classical applications such as 3D cutting and welding of metals.

Especially in light weight applications in the automotive industry laser manufacturing is key. Only by this technology the reduction of welding widths could be realised as well as the efficient machining of aluminium and the abrasion free machining of hardened steel.

The paper compares the operation of different laser types in metal machining regarding wavelength, laser power, laser brilliance, process speed and welding depth to give an estimation for best use of single mode or multi mode lasers in this field of application.

The experimental results will be presented by samples of applied parts. In addition a correlation between the process and the achieved mechanical properties will be made.

For this application JENOPTIK Automatisierungstechnik GmbH is using the BIM beam control system in its machines, which is the first one to realize a fully integrated combination of beam control and robot. The wide performance and wavelength range of the laser radiation which can be transmitted opens up diverse possibilities of application and makes BIM a universal tool.

8239-12, Session 3

T-joints of Ti alloys with hybrid laser-MIG welding: macro-graphic and micro-hardness analyses

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Titanium alloys are characterized by high mechanical properties and elevated corrosion resistance that make them very attractive for aeronautic, aerospace and naval applications. However, these good characteristics of titanium alloys are limited to the difficulty to be cut, welded and heat treated.

Focusing the attention on laser welding, an efficient shielding of the molten weld pool is required due to the increased reactivity with atmospheric elements at high temperatures. Laser welding has considerable flexibility for joining titanium alloys with or without filler wire/powder. The laser welding produced narrower joints than other jointing techniques, with mechanical resistance of the welded joints equivalent and sometimes exceeding those of same parts made of base material only. However, disadvantages of the wider use of this process are the insufficient gap bridging ability and the required precision in positioning. The combination of laser welding with MIG/GMAW has proven to resolve these drawbacks of laser welding, while maintaining the key advantages and even improving the welding speed and penetration.

In this paper, the hybrid Laser-MIG welding of Ti-6Al-4V is investigated. The welded joints were obtained from with 3-mm thick sheets, accurately polished and pickled to reduce the oxide contamination in the molten pool. The joint geometry was the double

fillet welded T-joint. A specific trailing shield was designed for this joint geometry to eliminate weld discoloration and oxidation. The resulting microstructures and mechanical properties (micro-hardness) of welds were evaluated and compared to those achieved for the base metals.

8239-13, Session 3

Improvements of the welding performance of plasma arcs by a superimposed fibre laser beam

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Details and results of experimental investigations of a laser-supported plasma arc welding process are presented. The particular feature of the realised experimental set-up is the coaxial arrangement of a single-mode fibre laser beam through a hollow tungsten electrode in combination with a modified plasma welding torch design. The analysis of the welding capabilities of the combined laser-arc source comprises high-speed video recordings of the arc shape and size, corresponding simultaneous measurements of the arc voltage as well as an evaluation of the resultant weld seam geometries. Results of welding trials on different types of steels and aluminium alloys are discussed. The corresponding investigations revealed that a fibre laser beam with a wavelength of 1.07 microns can have a crucial impact on the arc and welding characteristics for both categories of materials even at very low laser power output levels. Beneficial effects are especially observed under high welding speed conditions. In that particular case the arc root and therefore the arc column can be substantially stabilised and guided by the laser-induced hot spot.

8239-38, Session 3

Through the Optical Combiner Monitoring in remote fiber laser welding of zinc coated steels

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Due to the high power and high beam quality offered by fiber and disc lasers, the remote laser welding process has become more practicable. However laser welding of zinc coated steels in lap joint configuration is still problematic because of the violent vaporisation of zinc.

Monitoring during remote laser welding of overlapped zinc coated steels can be helpful to the comprehension of the welding phenomena and to the identification of defects generated during the welding process. In this study, a new monitoring configuration for remote fiber laser welding (RFLW) processes is proposed. In this solution, referred as Through the Optical Combiner Monitoring (TOCM), the optical emissions from the welding process are directly observed through the optical combiner of the fiber laser source. Key feature of the TOCM solution is the possibility to have a direct feedback from the process coaxially to the laser beam path thus avoiding the insertion of monitoring devices inside the scanner head used in RFLW.

The TOCM solution discussed in the paper is integrated in an IPG YLS 3000 fiber laser source whose beam is focused via an El.En. ThetaFiber scanning system with an equivalent focal length of 1 m.

After the definition of the right welding process conditions, spectroscopic tests were exploited to evaluate the optical emission from the welding plasma/plume for the identification of the most relevant wavelength ranges related to process behaviours. After that, photodiodes were filtered in the identified wavelength emission ranges for time and frequency analysis of the welding process.

Former test in RFLW of overlapped zinc coated plates proved the possibility for on-line measure of the gap between the plates in TOCM configuration. Together with these results, in the paper attention will be focused on the on-line evaluation of the welding quality in terms of lack of penetration and presence of welding defects.

8239-41, Session 3

Bead characterization of disk-laser butt welding of thin AA 2024 sheets

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Higher productivity, lower distortion and better penetration are the main advantages which laser welding provides in comparison with conventional processes. A Trumpf TruDisk 2002 Yb:YAG disk laser is used in this work, as it increases productivity and quality.

Materials with many technological issues in welding, resulting in shallow penetration and defects, are aluminum alloy. In particular, AA 2024 behavior is investigated in the paper, being this alloy extensively used in automotive and aerospace industries.

Defocusing has been considered, as it allows to produce deeper key-holes so to reduce porosity content. Speed influence on key-hole stability and porosity has been noticed, since the welding mode changes from key-hole to conduction regime.

Bead-on-plate and butt autogenous welding tests on 1.25 mm thick sheets have been examined from morphological and microstructural point of view. Geometric and mechanical features of the welding bead have been evaluated via a 3-levels experimental plan with power, speed and defocusing as governing factors.

8239-15, Session 4

Identification of phase transformation using optical emission spectroscopy for direct metal deposition process

L. Song, J. Mazumder, Univ. of Michigan (United States)

The microstructure of an alloy, which is related to the characteristics of its phase diagram, is strongly correlated to its mechanical properties. However, the analysis of microstructure of an alloy has been limited to the postmortem analysis such as optical or scanning electron microscopes. We report an in-situ identification of phase transformation by diagnosing the laser induced plasma during direct metal deposition process. Within the same microstructure range, the spectral line intensity ratio is proportional to the composition ratio; however, when there is a phase change, the linear relationship is broken and another linear relationship within the range of the new phase is formed. This phase related plasma change reflects the initial nucleation of the crystallography of the alloy in early stage and will be applicable for in-situ phase transformation identification during any process where plasma is generated.

8239-16, Session 4

A novel additive manufacturing process of using direct diode lasers to hard-face and repair of components for enhanced surface wear and corrosion resistance

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The objective of this presentation is to introduce large area heat treat and cladding processes using novel free space diode lasers as a means to reduce re-manufacturing costs and extend field lifetime of components. Lasers have been explored as an option for hard-facing and repair of metal surfaces for several years. Recent advances in diode laser use have resulted in enhanced process yield, improved quality and throughput while minimizing operating cost. This paper will examine how the novel diode laser compares with other laser and non-laser technologies for cladding of various metal alloys onto industry components.

In cladding, a heat source melts a powdered metal or wire placed onto the work surface to produce a metallurgical bonded continuous high-alloy layer. The natural rectangular cross-section of the diode laser array output can be easily re-imaged as a line of laser light well suited to large-area processing; the line rapidly "paints" across the surface as it is moved in a direction perpendicular to its long axis. The diode laser has the unique advantage of high absorption into the base metal surface. As a result, the diode laser has been documented to be almost twice as efficient as a CO2 laser for the cladding process.

When it comes to large area and high deposition rate cladding various arc welding or overlay technologies are used today. Comparing this process with diode laser cladding it becomes obvious that the electrical and powder use efficiency of the direct diode laser is superior. Laser clad samples show lower material dilution and part distortion. Hardness of the cladding is often higher due to shorter quench rates. Results of high-deposition rate cladding with high-alloy coating specifically to enhance surface wear and corrosion resistance will be discussed.

8239-17, Session 4

Laser heat treatment with latest system components

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Laser beam heat treatment has been established during the last years as a complementary technology for local hardening treatment tasks at tool manufacturing, automotive industry and many others. Especially new high power diode lasers and a lot of process supporting systems, what have been developed in recent years, are responsible for the increase of industrial laser hardening applications. The paper starts with information about the basics of laser heat treatment. After that a review about suitable lasers and recommended systems for reliable and well adapted laser heat treatment processes is given. Examples of last ten years transfer of laser beam hardening into industry are presented and discussed.

8239-18, Session 4

Local heat treatment of high strength steels with zoom-optics and 10kW-diode laser

M. Baumann, V. Krause, Laserline GmbH (Germany)

High strength steels enable new solutions for weight optimized car bodies without sacrificing crash safety. However, cold forming of these steels is limited due to the need of high press capacity, increased tool wear, and limitations in possible geometries. These drawbacks can be compensated for by local heat treatment of the blanks. In high-deformation areas the strength of the material is reduced and the plasticity is increased by diode laser irradiation.

Local heat treatment with diode laser radiation could also yield key benefits for the applicability of press hardened parts. High strength is not desired all over the part. Joint areas or deformation zones for requested crash properties require locally reduced strength.

In the research project "LOKWAB" founded by the German Federal Ministry of Education and Research (BMBF), heat treatment of high strength steels was investigated in cooperation with Audi, BMW, Daimler, ThyssenKrupp, Fraunhofer ILT, IWU and others. A diode laser with an output power of 10kW was set up to achieve acceptable area treatment rates. Furthermore a homogenizing zoom-optics was developed, providing a rectangular focus with homogeneous power density. The focus size in x- and y-direction can be changed independently during operation. With pyrometer controlled laser power the surface temperature is kept constant, thus the laser treated zone can be flexibly adapted to the needs. Deep-drawing experiments showed significant improvement in formability. With this technique, parts can be manufactured, which can conventionally only be made of steel with lower strength. Locally reduced strength of press hardened serial parts was demonstrated.

8239-19, Session 4

Laser cladding by using solid-state and direct diode laser sources

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The laser cladding technique is applied for coating production and reparation of damaged parts in the automotive, aerospace, petrochemical and biomedical industries. Depending on the required coating properties, different materials including iron alloys, cobalt alloys, titanium alloys and various nickel based superalloys can be deposited. During the process, not only the deposit material is melted, but also a thin layer of the substrate. Since the laser radiation wavelength determines the absorption rates of deposit and base materials, the type of laser source used (predominantly solid-state or direct diode lasers) has an influence on the process costs and deposition rates which can be obtained.

In the present work, solid-state and direct diode laser sources are compared in terms of electrical/optical efficiency, laser beam quality, process costs and performance in cladding applications.

8239-20, Session 4

Multi-kW laser cladding using cylindrical collimators and square-formed fibers

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In industrial laser cladding applications various new possibilities have opened up by introduction of laser sources with powers over 10 kW. High laser power allows higher deposition rates, which enables new applications for example in heavy engineering. However, for best efficiency and cladding results, the laser beam should be focused to rectangular shape instead of a circular one. In case of many lasers, this may require complicated processing optics as the beam is usually circular. In this paper we present results from cladding applications using a 12 kW disc laser coupled into a square-formed fiber with a 1000x1000 µm-core. The output of the fiber is collimated by a newly developed collimator based on cylindrical lenses with an 1:3.3 aspect ratio. The asymmetrically collimated beam is then condensed to the workpiece using an f=500 mm focusing unit. With this setup we reach a spot size of 7.4x2.2 mm = 16.3 mm2, implying laser power densities up to 740 W/mm2.

The asymmetric collimator is based on efficiently water-cooled cylindrical lenses with different focal lengths. Having interchangeable fiber connector interfaces and Optoskand's standard exit interface, the collimator can easily be implemented in optical heads. We present results on the optics performance including power transmission, image quality and focal shifts at power levels up to 12 kW. Results of preliminary cladding tests using the asymmetrical optics and off-axis powder feeding will also be presented. Deposition rate and efficiency using high power levels will be investigated. Analyses of cladding bead geometry and microstructure will be performed.

8239-21, Session 5

Wavelength dependency in high power laser cutting and welding

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Laser cutting and welding have been around for more than 30 years. Within those three decades there has never been a greater variety of high power laser types and wavelengths to choose from than there is today. There are many considerations when choosing the right laser for any given application - capital investment, cost of ownership, footprint, serviceability, along with a myriad of other commercial & economic considerations. However, one of the most fundamental questions that must be asked and answered is this - “What type of laser is best suited for the application?”.

Manufacturers and users alike are realizing what, in retrospect, may seem obvious - there is no such thing as a universal laser. In many cases there is one laser type and wavelength that clearly provides the highest quality application results. This paper will examine the application fields of high power laser welding & cutting and will provide comprehensive guidelines for selecting the laser that is best suited for the application. Processing speed & edge quality serve as key criteria for cutting. Whereas speed, seam quality & spatter ejection provide the paradigm for welding.

8239-22, Session 5

Energy balance in disk and CO2 laser beam inert gas fusion cutting

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In recent years, several studies on laser beam fusion cutting demonstrated significant differences in the characteristics of the CO2 laser cutting and cutting with solid-state disk and fiber lasers. The reasons for the observed differences in cutting speed performances and cut edges quality are still the object of the current research activities and not finally clarified. Recently, numerical models based on the governing conservation equations of energy, mass and momentum transfer have been already developed in order to get more insights into the dynamics of the cutting process. However, despite this considerable progress in process simulation, many current cutting problems of practical interest, can be still more efficiently tackled by a thermodynamical analysis.

In this paper a thermodynamic analysis is carried out in order to achieve a deeper understanding of the relevant interactions between the absorptivity behavior of metals on inclined cutting front and disk and CO2 laser radiation and to give a possible explanation of the differences in cutting quality detected for cuts performed with different laser sources.

The particular feature of the applied experimental setup was the similar geometry of both the CO2 and the disk laser beam with comparable values of the focus diameter and the Rayleigh length. Cutting trials on cold work steel test specimens with different sheet thicknesses were performed. The thermodynamic analysis is based on experimentally primary losses evaluation, on the numerical calculation of conductive power losses and analytical calculation of the remaining terms of energy balance.

8239-23, Session 5

Applicability of various beam sources for high power laser cutting of non-oriented electrical steel

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In some cases, gas assisted laser fusion cutting of non-oriented electrical steel laminations for electrical machine applications has been investigated for decades but with unsatisfactory success. Although a wide range of experiments on solid state laser cutting of alloys and metals with various thickness have been carried out successfully, laser processing of electrical sheet metal might still be considered as a niche application. Industrial manufacturing requirements usually deal mainly with geometric dimensioning and tolerancing with the consequence of loosing sight of the original product requirement power efficiency increase. Therefore, the mechanical induced stress that causes a reduction of the magnetic capability of each lamination is not considered. Indeed, recent laser beam technology seems to be a promising step forward and opens up the manufacturer new fields of application. Basically, this innovative technology has to be characterized about its utilization capability to obtain sufficient power efficiency of the whole electrical machine at low manufacturing costs. In this paper, laser cutting of electrical sheet metal applying various beam sources with regard to the magnetic property deterioration is compared with conventionally manufactured samples. The obvious correlation of beam profile and affected magnetic parameters such as the total power loss, the coercive field strength and the remanent induction is characterized by using a commercialized measurement system. The magnetic properties degenerating effects, by means of plasticity localized along the cutting edge and residual stresses which may spread over the whole lamination are investigated by SEM analysis.

8239-24, Session 5

Tailor cutting of crystalline solar cells by laser micro jet

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Coupling a laser into a hair thin micro jet (Laser Micro Jet, LMJ) for cutting solutions offers a wide range of applications that are quite unique. As the laser beam is guided by internal reflections inside of a liquid cylinder, the cuts are naturally straight and do not reflect any divergence as otherwise occurs with an unguided laser beam. Further, having a liquid media at the point of contact ensures a fast removal of heat and eventual debris ensuring clean cuts, which are free of any burrs. Many applications have indeed been developed for large variety of materials, which are as different as e.g. diamond, silicon, aluminium and hard metals, though certainly by tailoring process parameters, but nonetheless relying on the same proven principle of confining the laser’s power within the LMJ.

The photovoltaic industry has enjoyed in the last decades tremendous growth rates’, which are still projected into the future. We focus here on the segment of BIPV (Building Integrated PV), which requests tailored solutions to actual buildings and not one fits it all standardized modules. Having the option to tailor cut solar cells opens a new field of applications.

For the first time, finished crystalline solar cells have been cut with LMJ into predetermined shapes. First results show that the cut is clean and neat and preliminary solar performance measurements are positive. This open a new avenue of tailored made modules instead of having to rely on the one fits allow approach necessarily used so far.

8239-25, Session 5

Combining remote ablation cutting and remote welding: opportunities and application areas

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Remote Ablation Cutting (RAC) is a most promising process for cutting thin metal sheets in the automotive and consumer industry. Characteristically for the RAC are high cutting velocities for metal foils as well as material processing of box structures without spatter contamination at the inner surface. Furthermore, the system technology for RAC can also be used for other processes, like welding and marking. Thereby, the flexibility of a production unit is increased, compared to a conventional cutting system. Despite several advantages, the RAC is not yet state of the art in industrial production. Reasons are lacking knowledge in the process itself and in possible application areas.

In this paper a conceptual model of the ablation and the ejection mechanism is presented. It consists of the laser beam absorption within the processing zone, the melt acceleration inside the kerf and the resulting spatter formation above the part surface. Besides the model, the process boundaries and limitations are identified using empirical data.

Addressing possible applications, the following samples of different industrial areas are introduced to show the potential of the process: Cutting of heat exchanger plates, cylinder head seals, cathode and anode material for Li-Ion-Batteries and CFRP. Furthermore, a concept and first results of the combined processing of remote cutting and welding with one laser and one scanner are presented.

8239-26, Session 6

Mid-infrared imaging Fourier transform spectrometry for high power fiber and CO2 laser irradiated plexiglass, fiberglass, and painted metals

R. Acosta, K. C. Gross, M. A. Marciniak, G. P. Perram, Air Force Institute of Technology (United States)

New measurement techniques to study CW, high power laser-material interactions are emerging with the ability to monitor the evolving, spatial distribution of the state of the surface. In particular, fast framing hyperspectral imagery is just becoming available with sufficient temporal, spatial and spectral resolution to monitor the oxidation of metal and carbon rich materials. An imaging Fourier Transform Spectrometer operating in the mid infrared with high framing rate has recently been developed at the Air Force Institute of Technology in collaboration with Telops Inc. A 320 x 256 InSb focal plane array with spectral response from 1.5 - 5.5 μm is mated with a Michelson interferometer to achieve spectral resolutions as high as 0.25 cm-1. The very fast 16-tap InSb array frames at 1.9 kHz for the full 320 x 256 frame size. The single pixel field of view of 0.3 mrad provides a spatial resolution of 1 mm at the minimum focal distance of 3 m. Gas phase plumes above the surface of laser-irradiated black plexiglass, fiberglass and painted thin metals have been spectrally resolved. High-speed imagery is obtained using a low-pass filter for the interferograms and illustrates significant turbulent behavior. Brightness temperatures exceed 600 K. Selective emission in the region 2800 -3100 cm-1 is readily evident and is used to develop a time-dependent spatial map of both temperature and plume constituents.

8239-27, Session 6

Spectroscopic closed loop control of penetration depth in laser beam welding process

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In-process monitoring and feedback control are fundamental actions for stable and good quality laser welding process. In particular, penetration depth is one of the most critical features to be monitored. In this research, overlap welding of stainless steel is investigated to stably reproduce a fixed penetration depth using both CO2 and Nd:YAG lasers. The plasma electron temperatures of Cr(I) and Fe(I) are evaluated as in process monitoring using the measurements of intensities of emission lines with fast spectrometers. The system is calibrated using a quantitative relationship between electron temperature and penetration depth in different welding conditions. In particular the electron temperature is calculated by varying the laser power and the welding speed during the trials, which corresponds to a relationship between the electron temperature and penetration depth as well. Finally closed loop control of the weld penetration depth is implemented by acquiring the electron temperature value and by adjusting the laser power to maintain a pre-set penetration depth. The PI controller is successfully used to stabilize the electron temperature around the set point corresponding to the desired penetration depth starting from a wrong value of laser power or welding speed. Optical inspection of the weld surface and macroscopic analysis of cross sections verify the results obtained with the proposed closed-loop system based on a spectroscopic controller and confirms the reliability of our system.

8239-28, Session 6

NIR-camera-based online diagnostics of laser beam welding processes

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Novel high-brightness lasers enable new welding processes that take advantage of the smaller spot size and the slimmer beam waist. But these processes also require a more precise process control and process qualification. One instrument for laser welding process diagnostics, which is under consideration for quite a while, is detecting the thermal radiation that is emitted from the melt and the still hot weld seam. Nowadays, inexpensive, robust and compact NIR (near infra red)-sensitive cameras allow their integration into laser beam welding sensor systems. These sensors allow the 2-dimensional monitoring and evaluation of laser welding processes at high resolution.

We have integrated an NIR-sensitive camera into a laser welding head for coaxial process monitoring of the proximity of the weld spot in the 1...2 μm wavelength range. A fast real-time image processing system evaluates the laser spot area, the weld pool and the heat effective zone. The evaluation of the various zones and the proper correlation of the different characteristics are the basis for failure detection and weld seam qualification.

We present examples of laser beam welding of various materials and process parameters and the respective process sensor evaluation, using a multi-kW Yb:YAG thin disk laser. The results are compared with other online and offline evaluation methods.

8239-29, Session 6

High-power fiber optic cable with integrated active sensors

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In industrial applications using high-brilliance lasers at power levels up to and exceeding 20 kW and similarly direct diode lasers of 10 kW, there is an increasing demand to continuously monitor component status even in passive components such as fiber-optic cables. With fiber-optic cables designed according to the European Automotive Industry fiber standard interface there is room for integrating active sensors inside the connectors. In this paper we present the integrated active sensors in the new Optoskand QD fiber-optic cable designed to handle extreme levels of power losses, and how these sensors can be employed in industrial manufacturing. The sensors include photo diodes for detection of scattered light inside the fiber connector, absolute temperature of the fiber connector, difference in temperature of incoming and outgoing cooling water, and humidity measurement inside the fiber connector. All these sensors are connected to the fiber interlock system, where interlock break enable functions can be activated when measured signals are higher than threshold levels. It is a very fast interlock break system as the control of the signals is integrated in the electronics inside the fiber connector. Also, since all signals can be logged it is possible to evaluate what happened inside the connector before the interlock break instance. The communication to the fiber-optic connectors is via a CAN interface. Thus it is straight forward to develop the existing laser host control to also control the CAN-messages from the QD sensors. As an alternative, we present a software shell developed to easily monitor and control the sensors.

8239-30, Session 7

Beam delivery systems and processing heads for 1µm high brightness laser cutting systems

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Near infrared thin disc and fiber lasers with optical output powers in the multi Kilowatt range have reached industrial maturity during the past decade, and appear to be the only candidates in the field to address high power macro applications that have been dominated by less efficient CO2 lasers so far. The inherent advantages of those beam sources are higher wall-plug efficiency, compactness and the general possibility for a loss less beam delivery to the work piece through an optical fiber. The higher brightness of these sources will enable customers to investigate novel processes as e.g. precise high speed fine sheet 2D metal cutting or remote metal cutting in the near future.

One critical component of the cutting system is the beam delivery fiber and the connected processing head. Within this chain several optical free-space components as e.g. fiber end-caps, lenses or mirrors contribute to a laser power induced thermal focus shift on the work piece leading either to an undesired movement of the focal position or even to a deterioration of the beam quality. Since the build-up of the focus shift is time-dependent the customer will experience a direct slow-down of the process if stable working conditions are required.

We present a novel, highly optimized laser processing head that allows for precise control of the focus diameter and position on the work piece by means of a novel optical system that utilizes a minimum number of optical elements. Further, we will report on the laser beam induced focus shift in diverse optical elements and ways of its reduction.

8239-31, Session 7

Unique beam delivery and processing tools for high power solid state laser processing

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The advent of high power, high brightness solid state lasers within the past several years has necessitated new tools for use with laser material processing. These lasers pose an increased challenge on the beam delivery components, such as focusing optics and fiber optic cables. Thermal focus shift can negatively influence the application results and therefore must be minimized. A new reflective focusing optic (RFO) and associated high power thermal focus data will be presented, as well as a new fiber optic cable with optimized cooling.

Although dealing with thermal issues is a necessity, there are several unique tools that have also been developed in association with high power, high brightness laser beam sources. Among them is the dual core fiber optic cable. This unique and patented fiber literally has two concentric cores, enabling both cutting (100 micron core diameter) and welding (400 or 600 micron core diameter) via a single cable. The physical concept and means by which the beam is directed through either fiber core will be presented. Also discussed will be latest advances in remote scanning optics (i.e. Programmable Focusing Optic (PFO)), as well as new drift compensation calibration tool for the PFO.

8239-32, Session 7

Maximum uptime and minimum focus shift in high-power 1µm laser beam delivery

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High Power (3kW to 20kW) 1um lasers can show problems related to thermal focus shift, optical contamination, and subsequent optical damage if not designed and maintained properly in production. Other issues are related to correct optical assembly and optic orientation in the beam delivery system.

Even low to medium power lasers can have problems where the power density on the optics becomes excessive, especially where single mode lasers are employed.

This paper discusses methods and hardware developed to minimize thermal focus shift in medium and high power beam delivery by first analyzing the standard issues and measuring improvements by the use of proper designs with reflective and transmissive systems by employing seals, active purge, optimized layouts, and direct-cooled optics. Results for systems in the 1-3kW and 15-20kW range will be discussed.

8239-33, Session 7

Ultra low absorption glasses and optical coatings for reduced thermal focus shift in high power optics

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A study has been performed of the factors leading to thermal focus shift in high power optics. Using advanced low absorption optical materials from Heraeus and state-of-the-art Ion Beam Sputtered coatings from Precision Photonics, a variety of thermal effects have been studied using optical windows. Results will be presented for bulk absorption, surface absorption, surface micro-roughness, index homoegeneity, stress-induced birefringence, bubble density, and coating absorption.

8239-34, Session 7

Self-compensation of thermal lensing in optics for high-brightness solid-state lasers

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

Modern diode-pumped solid-state lasers such as the thin-disk laser and the fiber laser provide high output power in the kW-range with excellent beam quality. The use of these high-brightness laser sources for material processing purposes, however, poses problems arising from the optics used to guide the beam to the workpiece: Thermally induced effects in the individual elements of the focusing optics and the beam guidance system sum up to a severe transient focus shift and a significant deterioration of the beam quality. To further enhance the possibilities for the application of modern high-brightness laser systems, it is crucial to reduce the impact of these thermally induced effects.

In this contribution, a principle design approach for thermally compensated refractive optics will be discussed. Analogous to achromatization, an optimal combination of multiple elements of different shapes and materials has to be found, so that the individual thermally induced effects in each element are compensating for each other. Provided the elements are in good thermal contact and have similar thermal conductivities and thermal capacities, the resulting optical system will be self-compensating. To achieve this self-compensation, several combinations of different materials are evaluated by means of thermo-mechanical FEM-simulations. The calculated wavefront deformation a laser beam is experiencing when traversing through the thermally influenced optical system serves as figure of merit for an optimization process. An optimization has been carried out for different designs of thermally compensated laser windows. Recent experimental results achieved with these thermally compensated windows will be presented in this contribution.

8239-35, Session 7

Fabrication and characteristic of a new multicore fiber for high power delivery

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We fabricated a new type of multicore fiber using the PCVD process and stack-and-draw method. The fabrication process is discribed in detail in this work. This fiber core is composed with 91 GeO_2-doped micro-rods arranged in the hexagon shape and is measured up to 50µm, very suitable for low loss splicing with the multimode fiber. The attenuation is measured only 3dB/km at 1064nm and lower than 10dB/km at 1550nm, the water-loss peak at 1383nm is about 90dB/km; The fiber mode properties were also measured that shows a gaussian shape mode. Our multicore fiber might have the potential application such as the delivery of high power, the multiparameter fiber sensor, etc. according to our design.

Conference 8240: Nonlinear Frequency Generation and Conversion: Materials, Devices, and Applications XI

Tuesday-Thursday 24-26 January 2012

Part of Proceedings of SPIE Vol. 8240 Nonlinear Frequency Generation and Conversion: Materials, Devices, and Applications XI

8240-01, Session 1

Controlling of sub-cycle pulse in UV-Vis-IR by multilayer optics

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The short laser pulse generation to the limit set by the single cycle of light has been pursued ever since the discovery of lasers. The controlled superposition of light frequencies extending over more than one octave paves the way to shaping the sub-cycle evolution of light fields (along with carrier-envelope phase control) in laser pulses.

The result of the continuous development of dispersive optics permits pulse compression down to almost single cycle pulses of 3 fs duration. The dispersive mirrors together with the recently developed wave synthesizer technology [1] pave a way to sub-2 fs pulses. A sub-2 fs pulse has a spectrum of 350-1050 nm and corresponds to a sub-cycle optical pulse. During the last decade, we demonstrated that the broader the spectrum for which the group delay dispersion (GDD) has to be controlled the lower the nominal value of the GDD that can be obtained. In other words, relaxing the requirement on the bandwidths allows for higher values of GDD. Low amount of dispersion which can be compensated for a broad spectrum, can be overcome by a wave synthesizer which splits light into different spectral channels. Each channel has a smaller bandwidth thus simplifying the optics and allows for precise control of the wave package.

Reference:

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8240-02, Session 1

Generation of yellow-orange picosecond pulses at 595 nm by sum-frequency mixing of fiber-amplified gain-switched laser diodes

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Gain-switching of laser diodes is an ideal method for the generation of picosecond pulses in the milliwatt range at arbitrary repetition rates. However, the wavelength range covered by semiconductor lasers is still limited. Especially between 520 and 635nm no direct emitting laser diodes exist yet, while this range is of high importance for fluorescence applications in life sciences. Frequency conversion of infrared laser diodes is one way to bring the comfort of diode lasers to the green-yellow wavelength range.

Our paper describes a compact 595 nm laser generating picosecond (ps) pulses. A freely triggerable gain-switched distributed feedback (DFB) laser diode emits ps-pulses at 1532 nm with a narrow spectral line-width. These pulses are amplified by an Erbium-doped fiber amplifier (EDFA) which is core-pumped by a 976 nm, narrow line-width, single-mode laser diode. The active fiber is dimensioned to absorb only a fraction of the launched pump power. Thus, the amplifier's output contains both, the amplified picosecond pulses at 1532 nm and the remaining cw pump light at 976 nm. Both components are then coupled into a highly efficient, periodically poled potassium titanium phosphate (PPKTP) waveguide, where ps-pulses at 595 nm are generated through sum-frequency mixing.

This setup, which is featured by a dual use of the pump light, is, to our knowledge, a method for efficient frequency conversion with the lowest possible number of components. By adapting this idea to other materials, many more wavelengths in the visible range can be generated by mixing of signal and pump light.

8240-03, Session 1

Highly efficient Q-switched green microchip laser based on second harmonic generation in MgO-doped PPLN

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Pulsed sources of green radiation based on frequency-doubled microchip lasers are attractive for many industrial, scientific and medical applications that require sub-nanosecond pulse width, high peak power, high repetition rate, compactness and low cost. In particular, such laser systems have already found widespread application in spectroscopy, micromachining, fluorescence imaging, and laser displays. One of the challenges in the development of such laser systems is to achieve high conversion efficiency of near-IR light into its second harmonic.

Quasi-phase-matched nonlinear materials present an attractive alternative to the conventional bulk crystals to enhance frequency conversion efficiency. Among several available periodically poled crystals such as LiNbO3 (PPLN), stoichiometric LiTaO3 (PPSLT), and KTiOPO4 (PPKTP), the first one has the highest nonlinearity (deff $\approx$ 17 pm/V). Moreover, doping of PPLN with MgO significantly increases its threshold of photorefractive damage at room temperature.

In this work we report on highly efficient (60%) pulsed second harmonic generation (SHG) in MgO:PPLN with compact sub-ns microchip laser which is, to the best of our knowledge, the highest value for MgO:PPLN in the pulsed regime. The microchip laser operating at 1064 nm delivered 10 uJ, 560 ps long pulses at 6.9 kHz with an average output power of 69 mW. The single pass SHG was carried out in a 5 mm long MgO:PPLN crystal (C2C Link Corp.). Under the optimum focusing conditions, the maximum output power of 40 mW was obtained, corresponding to a conversion efficiency of 60%. A direct comparison with LBO, KTP, and BiBO crystals was also made and will be reported in detail.

8240-04, Session 1

Power-scalable tunable UV, visible, and NIR generation from an ultrafast fiber OPA based on four wave mixing in PCF

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High power, high repetition rate, ultrafast laser sources at novel wavelengths or with wavelength tunablity have numerous scientific applications such as CARS microscopy and FLIM. Wavelength conversion using chi^3 nonlinearity (four wave mixing, FWM) in optical fibers offers a highly robust, simple and low cost alternative to bulk OPO, OPA systems and enables conversion with high efficiency to wavelengths not attainable in a single stage bulk chi^2 device. An ultrafast fiber MOPA was developed which delivered ps pulses with high average power (>10 W) at 20MHz repetition rate and rapid and continuous tunability over the wavelength range 1040 - 1070 nm with narrow spectral linewidth. Through FWM in a single PCF, this source generated greater than 30% conversion efficiency to a narrow linewidth signal with tunability from 720 to 875 nm and a corresponding idler tunable from 1370 to 1880 nm by simple tuning of the master oscillator wavelength. The signal, idler and residual pump beams exit the PCF with excellent beam quality, spatial and temporal overlap and the same polarisation state allowing a number of subsequent non-linear conversion processes to give tunable output in the UV and visible range. Generation of tunable signal SHG, signal-pump SFG, pump SHG and pump-idler SFG were demonstrated in a single angle tuned BBO crystal. The combined system delivered tunability over large portions of the UV, visible and NIR spectral range from 370 - 1900 nm with a very simple setup. There is scope for power scaling of the source and extending the wavelength coverage.

8240-05, Session 1

Continuous-wave fourth harmonic generation in a whispering-gallery resonator

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High quality factor whispering-gallery resonators enhance the intensity of light continuously in time via multiple recirculations, resulting in large light-matter interaction distances. This intensity enhancement mechanism has allowed demonstration of various nonlinear phenomena in whispering-gallery resonators, including 4-wave mixing, Raman-lasers, Erbium-lasers, Brillouin-lasers, visible-light emission through second and third harmonic generation, and excitation of mechanical vibration. In this work, we experimentally demonstrate simultaneous generation of continuous-wave UV (4th harmonic), visible (3rd harmonic), and near-IR (2nd harmonic) from a telecommunication-compatible IR pump in a millimeter-scale lithium niobate whispering-gallery resonator at the record-low pump power of 200 mW. In the absence of the whispering-gallery resonator intensity enhancement, such cascaded harmonic generation in lithium niobate could only be achieved by use of high peak-power pulsed pump sources. Our resonator is fabricated from a periodically poled lithium niobate disk and edge-polished to an ultra-smooth profile. Light is coupled into the device via a diamond prism, and a quality factor greater than 10^7 was measured. A non-uniform poling-period allows quasi-phase matching for cascaded harmonic generation up to the 4th harmonic at input pump powers as low as 200 mW. Cascaded harmonic generation is observed by recording the wavelength of residual scattered light with an optical spectrometer. Additionally the power dependence of the harmonics on the IR pump is measured, confirming the expected 2nd, 3rd, and 4th order dependence of the respective harmonics on the pump. Finally, the harmonics are spatially separated at the prism output and recorded on a CCD camera for direct observation.

8240-06, Session 2

Intracavity generation of continuous wave terahertz radiation

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Continuous wave (CW) terahertz (THz) waves find a plethora of applications in spectroscopy, biosensing, quality inspection as well as in THz astronomy. However, it is still challenging to access the frequencies between 1 and 5 THz with high power levels using room temperature THz sources. Nonlinear frequency conversion is one promising approach for generating CW THz radiation. Here, infrared laser light is down converted into THz waves by difference frequency generation (DFG). But an efficient conversion requires high laser intensities typically generated by employing Q-switched laser sources. This results in narrow band THz radiation with pulse durations of tens to hundreds of nanoseconds.

To generate pure CW THz waves we use a different approach. We utilize the high intensities within a dual color vertical external cavity surface emitting laser (VECSEL). This laser provides hundreds of Watts intracavity power while oscillating simultaneously on two laser lines. The frequency spacing of the laser lines that determines the frequency of the generated THz waves can freely be adjusted within the frequency range of 100 GHz to several THz. Thus, the entire terahertz gap can be covered. As nonlinear medium we employ a periodically poled lithium niobate crystal due to its high nonlinear coefficient.

In the presented results we focus exemplarily on the two frequencies 820 GHz and 1.9 THz. We characterize the beam shape, the linewidth and the power scalability of the source. We also discuss the potential to use the THz source as local oscillator for a hot electron bolometer (HEB) mixer.

8240-07, Session 2

Terahertz-induced optical modulation in quantum-well microcavity

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Strong exciton-photon coupling in a high-Q microcavity leads to the formation of two new eigenstates, called exciton-polaritons. We present the quantum dynamics of exciton-polaritons driven by strong few-cycle THz pulses. Our study focuses on an intriguing question of how THz radiation interacts with the strongly coupled light-matter system. We performed THz-pump and optical-probe experiments to answer the question: we observed the time-resolved optical reflectivity of the lower and higher exciton-polariton (LEP and HEP) modes in a QW microcavity in the presence of strong few-cycle THz pulses. In a previous study with a bare QW, a strong THz field tuned to the 1s-to-2p intraexciton transition induced an excitonic Rabi splitting. Since THz radiation interacts only with the excitonic components of exciton-polaritons and has no impact on cavity modes, it is an interesting question how THz radiation drives the exciton-polariton states to higher energy states in the microcavity system. Our study shows that THz radiation resonantly drives the exciton-polariton polarizations giving rise to LEP-to-2p or HEP-to-2p transitions. LEP-to-HEP transition is forbidden because they have the same symmetry. Our experimental and theoretical investigations demonstrate that LEP, HEP, and 2p-exciton states form a three-level Λ system in an optically excited QW microcavity.

8240-08, Session 2

Efficient parametric THz generation pumped by monolithic pulsed fiber lasers at ~2 um in MOPA configuration

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In this paper, we report the first demonstration of the parametric THz generation based on DFG in ZGP and QPM-GaAs crystals pumped by ~ 2 um pulsed fiber lasers. We have implemented two-channel pulsed fiber laser system in MOPA configuration with different wavelengths (1.92 um and 1.937 um) in order to generate DFG THz radiation. Two kinds of single-frequency pulsed fiber laser seeds were used: one is actively Q-switched single-frequency fiber laser seed; another one is directly modulated single-frequency pulsed fiber laser seed. After two pre-amplifier stages, the output peak/average power is about 10's W/10 mW-level. The pre-amplifier stages use commercial Tm-doped double cladding fiber with core diameter of around 7 um. A new developed single-mode large core PM highly Tm-doped germanate fiber 25/250 um was used in the power amplifier stages for two pulsed fiber laser pump channels. For the single-pass DFG THz radiation pumped by the new developed ~ 2 um pulsed fiber lasers, the THz average power can be up to 6.65 uW pumped by ~ 70 uJ ~ 2 um fiber laser pulses, which is over 5 times higher than the THz power generated by using QPM-GaP crystal pumped by C-band pulses with the same pump power level. Therefore, more efficient parametric THz generation can be expected by using QPM-GaAs or ZGP crystals pumped by ~ 2 um fiber laser pulses, especially, based on the external cavity enhancement and collinear THz OPO schemes.

8240-09, Session 2

Coherent electro-optical detection of THz-wave generated from synchronously pumped picosecond THz parametric oscillator

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Terahertz (THz) radiation based on nonlinear frequency conversion in nonlinear optical crystals is one of the most reliable methods for developing tunable, high-power, and compact THz-wave sources. In particular, THz-wave parametric sources are able to generate the THz-wave of 0.7 to 3.0 THz continuously by properly selecting the noncollinear phase-matching geometry. The parametric source, however, so far needs to use a high peak-power pulsed pumping source, such as a Q-switched nanosecond Nd:YAG or Nd:YVO4 laser, to obtain sufficient THz-wave output power. Therefore, we have been focusing on developing the low-laser-power-pumped parametric source and successfully demonstrated a synchronously-pumped picosecond THz parametric oscillation in doubly-resonant external cavity with a bulk 5 mol% MgO-doped lithium niobate crystal. The pumping source was a mode-locked picosecond Ti:sapphire laser with 900-mW average output power, 780-nm center wavelength, 1.1-ps pulse width, and 81.7-MHz repetition rate. Furthermore, our THz-wave parametric source has the performance of wide frequency tunability from approximately 0.7 to 3.0 THz by slightly changing the resonant frequency of Stokes wave which was resonated as well as the pump wave automatically. For the purpose of the realization of THz spectroscopy and imaging applications using our THz-wave source, we constructed the coherent THz-wave detection system via electro-optical effect with a ZnTe crystal. As a result, we obtained the temporal waveform and the relatively broad spectrum of the THz-waves generated from our parametric oscillator. Also, we compared this electro-optical detection system with a Fourier transform Michelson interferometer using a high-resistance silicon beam splitter, from the viewpoints of availability, ease of use, and signal-to-noise ratio.

8240-10, Session 2

Single-cycle terahertz pulses with amplitudes exceeding 1 MV/cm generated by optical rectification in LiNbO_3 and application to nonlinear optics

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Using the tilted-pump-pulse-front scheme, we generate single-cycle terahertz (THz) pulses by optical rectification of femtosecond laser pulses in LiNbO_3. In our THz generation setup, the condition that the image of the grating coincides with the tilted-optical-pulse front is fulfilled to obtain optimal THz beam characteristics and pump-to-THz conversion efficiency. The designed focusing geometry enables tight focus of the collimated THz beam with a spot size close to the diffraction limit, and the maximum THz electric field of 1.2 MV/cm is obtained[1]. Furthermore, the nonlinear interactions of GaAs quantum wells with intense THz pulses have been studied. Here we show that the intense terahertz pulse, unlike a DC bias, can generate a substantial number of electron-hole pairs forming excitons that emit near-infrared luminescence. The bright luminescence associated with carrier multiplication suggests that the carriers coherently driven by a strong field can efficiently gain enough kinetic energy to induce a series of impact ionizations, which we demonstrate for the first time can increase the number of carriers by about three orders of magnitude on picosecond timescale.

[1]H. Hirori, A. Doi, F. Blanchard, and K. Tanaka, “Single-cycle terahertz pulses with amplitudes exceeding 1 MV/cm generated by optical rectification in LiNbO3,” Appl. Phys. Lett. 98, 091106 (2011).

8240-11, Session 3

Optical parametric oscillation in orientation patterned GaAs waveguides

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Orientation patterned GaAs (OPGaAs) ridge waveguides have been fabricated by MOCVD growth on OPGaAs templates. The waveguides (WGs) were designed for parametric frequency conversion from 2µm to mid-IR. Monolithic, signal resonating, OPO cavity was formed by dielectric coating of the chip facets, HR at the signal wavelength, and AR at the pump and idler wavelengths. In a 13mm long chip, the threshold for parametric oscillations was 4.6W of 2µm CW power launched into the waveguide. OPO characteristics were investigated using a tunable pulsed source in the wavelength range of 1.95-2.15um. Both type I (TM→TE+TE) and type II (TE+TM→TE) parametric interactions have been observed, differing in QPM wavelength. The observed QPM frequencies of both types are in good agreement with the predicted values based on WG effective index calculations. Strong dependence of parametric power on pump wavelength is observed and explained by the balance between internal cavity and mirror losses at each wavelength. For pump peak power of 13W coupled into the WG, idler peak power of 0.6W at a wavelength of 4.4um was obtained. This 4.6% optical conversion efficiency is about half of the predicted value for such waveguides and operating condition. This may be a result of insufficient coupling of the pump power into the WG fundamental mode. Methods for increasing the output power and improving conversion efficiency will be discussed.

8240-12, Session 3

Sub-nanosecond 1-kHz low-threshold non-critical OPO based on periodically poled KTP crystal pumped at 1064 nm

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Highly nonlinear materials used in non-critical phase-matching, can be implemented in a short cavity optical parametric oscillator (OPO) to produce sub-ns signal and idler pulses as recently demonstrated with CdSiP2 in the 6.1-6.5 micron range. In the present work we employed a 9-mm long periodically-poled KTiOPO4 (PPKTP) with a domain inversion period of 37.8 micron to generate such pulses around 2.8 micron. The sample was 3-mm thick along the z-axis and the grating pattern was 8 mm (along x) to 2 mm wide (along y-axis), in a plane-plane, 1-cm long OPO cavity. The rear mirror reflected ~97% at all three wavelengths while the output coupler totally reflected the signal transmitting >95% of the idler (singly resonant OPO with double pass pumping). The pump source was a diode-pumped 1-ns Nd-laser system at 1064 nm. The maximum energy was 1.4 mJ at 1 kHz, of which up to 0.89 mJ were incident on the PPKTP crystal.

The measured OPO threshold was ~110 microJ (~10 MW/cm2 average pump intensity). The maximum idler output energy reached 110 microJ (quantum conversion efficiency of 32.5%). The signal pulse duration (FWHM) was 0.72 ns. No fast detectors exist above ~2 micron but we frequency doubled the idler pulse and correcting the result for the second harmonic by a factor of square root of 2 obtained an idler pulse duration of 0.76 ns. At room temperature the signal and idler wavelengths were at 1717 and 2799 nm, respectively but tuning should be possible by temperature and/or multiple gratings.

8240-13, Session 3

Comparison of linear and RISTRA cavities for a 1064-nm pumped CdSiP2 OPO

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We compared the beam quality of the idler from 1064-nm pumped optical parametric oscillators based on CdSiP2 (CSP) for linear and Rotated Image Singly-Resonant Twisted RectAngle (RISTRA) cavities. The pump source was a 14-ns Q-switched Nd:YAG laser at 100 Hz. Both cavities were operated in single pump pass with an output coupler highly transmitting the pump and idler (6125 nm) waves. Only the signal wave was resonated with the output coupler having 70% reflectivity at 1288 nm. The physical RISTRA cavity length was 128 mm while the linear cavity was 55-mm long, resulting in equal round trip times taking into account the refractive index and the number of passes through the 9.5 mm long 90°-cut CSP crystal. The 6.75□6 mm2 faces of the crystal were triple AR-coated. An aperture was used to create a flat-top like pump spatial profile and the maximum incident energy was 21.5 mJ, roughly 2 times above the threshold for both cavities. The maximum idler output energy was 64 µJ for the RISTRA and 34 µJ for the linear cavity. The divergence of the idler beam was about 2 times higher in the case of the linear cavity. At distances corresponding to equal and almost optimum filling of the aperture of a 1”-diameter, 10-cm focal length MgF2 lens, the focal spot diameter achievable with the linear cavity was about 1 mm while the intensities achievable with the RISTRA cavity were roughly 2 times higher. The idler beam from the RISTRA cavity had also smoother spatial profile.

8240-14, Session 3

Improved space bandwidth product in image upconversion

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Recently, the feasibility of image upconversion based on SFG has been proven to be a promising technology [1, 2]. For instance, by appropriate choice of material and operation parameters, it is possible to obtain phase-matching for virtually any wavelength. For imaging, the space bandwidth product is a key parameter. However, in order to obtain large images with good resolution large angles of propagation through the nonlinear material is necessary, thus resulting in different phase-match conditions when compared to the on-axis rays of the system. This may not be very significant for broadband emitting objects, however, for narrow spectrally emitting object, e.g. using laser illumination or emission from a narrow energy transition of a gas; this limits the space bandwidth product of the upconversion process.

We show that the space bandwidth product for upconversion of monochromatic objects can be increased by appropriate control of the phase-match condition and subsequent image reconstruction. Scanning the phase-match condition, while acquiring images, corresponds to making a conical scan of the object. We show that by super position of each acquired concentric region from the conically scans the entire upconverted image can be restored resulting in an image with significantly increased space band width product. The scanning of the phase-match condition is realized by changing the temperature of the nonlinear material, but could equally well be obtained by tuning of the mixing wavelength, resulting in a much faster image acquisition speed.

We present the theory and an experimental demonstration of spectral imaging resulting in an increase of the space bandwidth of the system, by a factor of >10, as compared to a system based on fixed phase-match conditions.

8240-15, Session 3

Image upconversion: a low noise infrared sensor?

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Low noise upconversion of IR images by three-wave mixing, can be performed with high efficiency when mixing the object radiation with a powerful laser field inside a highly non-linear crystal such as periodically poled Lithium Niobate. Since IR cameras are expensive and have high levels of intrinsic noise, we suggest to convert the wavelength from the mid infrared to the visible/NIR wavelength for simple detection using CCD cameras. The intrinsic noise in cameras has two main contributions. First, read noise originating from the charge to signal read-out electronics. This noise source is usually measured in number of electrons. The second noise source is usually referred to as dark noise, which is the background signal generated over time. Dark noise is usually measured in electrons per pixel per second. For silicon cameras certain models like EM-CCD have close to zero read noise, whereas high-end IR cameras have read noise of hundreds of electrons. The dark noise for infrared cameras based on semiconductor materials is also substantially higher than for silicon cameras, typical values being thousands of electrons per pixel per second for cryogenically cooled cameras. An ideal solution thus suggest the combination of an efficient low noise image wavelength conversion system combined with low noise silicon based cameras for low noise imaging in the IR region. We discuss image upconversion as a means to do low noise conversion of IR light to visible light. We demonstrate system noise performance orders of magnitude lower than existing cryogenic cooled IR cameras.

8240-16, Session 4

Coherent quasi-CW 153-nm light source at high repetition rate

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Narrowband lasers in vacuum ultraviolet regions have a diverse range of applications in various scientific fields such as photoelectron spectroscopy and high precision spectroscopy. Although such radiation with 7 eV of photon energy has been already demonstrated, even higher photon energy is desired in fields such as angle-resolved photoelectron spectroscopy, where higher photoelectron energy would allow the observation of a broader region in the momentum space.

Here we demonstrate generation of coherent quasi-cw VUV radiation at 153.4 nm (8 eV) at 33 MHz repetition rate, which is the shortest wavelength generated through phase-matched processes in nonlinear optical crystals to our knowledge. This is achieved through successive frequency conversion of the infrared pulses from ytterbium (Yb)-fiber laser system using two LBO crystals and two $KBe_2BO_3F_2$ (KBBF) crystals.

Our Yb-fiber-based laser system consists of an oscillator and three amplifier stages, which delivers 7 W of output with 20 ps pulse duration at the center wavelength of 1074 nm at the repetition rate of 33 MHz. The infrared beam is frequency-converted by two LBO crystals into the third harmonic (TH) beam. The TH beam is focused onto a KBBF prism-coupled device (KBBF-PCD) to generate the sixth harmonic (6H) beam of the original IR beam through a second harmonic generation process. The 6H beam and the remaining fundamental IR beam are focused onto another KBBF-PCD to generate the seventh harmonic (7H) radiation through sum-frequency generation process. A clear 7H signal is observed with a phototube and a lock-in amplifier.

8240-17, Session 4

Designable nonlinear optical device: QPM quartz for VUV spectrum

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Ferroelectrics-based nonlinear optical devices have been attracting much attention since quasi-phase matching is satisfied by reversing spontaneous polarization. QPM nonlinear optics, enabling arbitrary setting of phase-matching point at desired wavelength and temperature, produces designable phase-matching properties by elaborating lithographic patterns. The QPM concept can be even combined with a waveguide technology, where >100 times higher efficiency is expected by strong confinement and extended interaction length of lights.

A novel technology called twinning, brings the possibility to introduce QPM to non-ferroelectric crystals. Twinning in quartz breaks ferroelectrics' limit: large absorption in UV region and low damage threshold to laser pulse. Crystal quartz also exhibits excellent chemical-and thermal stability, together with wide transparent window from mid-IR to vacuum UV (~150 nm). Pressure-induced twinning allows us to flip the sign of the crystallographic X axis, leading to QPM by nonlinear coefficient of d11 (=d12). Twin aspect ratio (depth /width) around several hundred allows a deep and fine QPM structure applicable to short wavelength generation with a mm-scale aperture. Walk-off-free collinear SHG was achieved at 193 nm wavelength by 5th order QPM with 9.6 um periodicity. Vacuum UV (VUV) NLO finally acquired a new degree of freedom, phase control by twinning. History and progress of QPM quartz will be reviewed, with demonstration of SHG ranging from visible to VUV.

This work is partially supported by Ministry of Science and Education, Japan (Project #: 23360037).

8240-45, Session 4

Frequency-doubled diode laser for direct pumping of ultrashort Ti:sapphire lasers

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In this work, we present a simple and robust diode laser system emitting 1.28 W in the green spectral range, suitable for pumping an ultrafast $Ti:Al_2O_3$ laser. To classify the results, our laser is compared to a commercially available diode pumped solid-state (DPSS) laser system pumping the same oscillator.

Due to their absorption characteristics, $Ti:Al_2O_3$ laser crystals are directly pumped mostly by frequency doubled solid state lasers. These pump lasers offer multiple watts of green light but very often increase both dimensions and costs of Ti:sapphire laser systems. As high power diode lasers have become available, more than 1.5 W of green light could be generated by single-pass frequency conversion, enabling competitive direct optical pumping.

Using our laser for optical pumping of a Ti:sapphire laser reduces the optical conversion efficiencies to 75 % of the values achieved with a commercial solid-state laser system pumping the same oscillator. However, the superior electro-optical efficiency of the diode laser still improves the overall efficiency of the Ti:sapphire laser by a factor > 2. Autocorrelation measurements show that pulse widths of less than 20 fs can be expected when using our laser. This opens the opportunity of using diode laser pumped Ti:sapphire lasers for applications like pumping of photonic crystal fibers for CARS (coherent anti-stokes Raman spectroscopy) microscopy or retinal optical coherence tomography.
We will present our first results applying this new, compact Ti:sapphire source.

8240-46, Session 4

Mode hop free tunable blue laser

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We report on a mode hop free tunable blue laser based on an external cavity system. Continuous-wave blue laser is generated by direct intra-cavity frequency doubling (ICFD) of edge-emitting diode laser using MgO-doped periodically poled lithium niobate (MgO: PPLN) bulk crystal. Ultra-low reflectivity coating on the output facet of the diode laser gives less than 0.1% in the wavelength range of ±15 nm, which eliminates the original diode laser cavity allowing the extended longer laser cavity to dominate. An external dichroic mirror is used as output coupling mirror. A rotating etalon combined with a angle placed silica plate is inserted into external cavity. A narrowband pass filter is inserted between etalon and output coupling mirror to control the laser longitudinal modes outside of the free spectral rang of the etalon. By using combination the etalon, silica plate and filter will only allow one lasing longitudinal mode and operating wavelength tuning for fundamental light. The single longitudinal mode second-harmonic generation (SHG) blue laser was generated using quasi-phase matching (QPM) based MgO: PPLN by fine control of the crystal working temperature. We investigated the length changes as a function of angle of the external cavity and see how will they match with the optical properties of an etalon combined with an angel placed silica glass plate. An experimental tuning range in excess of 100 GHz has been obtained without causing a frequency error or mode hop. 30 mw blue light was obtained at wavelength of 465 nm with beam quality better then M2 =1.3.

8240-47, Session 4

High-power compact green laser source based on wavelength-stabilized pump laser diodes

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Using proprietary BrightLock® monolithic chip wavelength stabilization technology and a unique cavity design, our next generation of high brightness, compact green laser modules was realized. We present recent results including stability over temperature and time, pulsed rise times of less than 2 nano-seconds, and powers up to 8W coupled into a 50um fiber. The Ultra-G is able to maintain power levels of 6W over a baseplate temperature range of 20-30C. Over time, at all power levels from 50mW to 6W, the Ultra-G exhibits <2% RMS noise. And, over all power levels and all pulse trains, the Ultra-G shows rise times of <2 milli-seconds with an overshoot of <5%.

We also present stability after putting the modules through a battery of environmental testing - including shock and vibration, extreme temperature cycling and humidity testing. After five 24-hour temperature cycles from -40 to +70C, the Ultra-G exhibited <5% change in output power. After going through shock and vibration testing according to DIN ISO 10109-6, the Ultra-G still showed <5% overall change in output power. Finally, after humidity cycling from 0-95%, <5% change was maintained.

8240-42, Poster Session

Bright soliton propagation in inhomogeneous N-coupled nonlinear Schrödinger system using Darboux-transformation

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The recent advances in using the possibility of ultra short pulses in long distance communication via optical fibers have motivated an intense study on optical solitons. Optical communication plays vital role in the rapid growing information technology, in which optical solitons have become the subject of intense studies. We present analytic solitary-wave solutions for N coupled nonlinear Schrödinger (CNLS) equations. The model is described by system of Nonlinear Schrödinger (NLS) equations for the envelopes of optical pulses propagating in a single-mode nonlinear fiber.

The Laxpair is explicitly constructed for 3-coupled nonlinear Schrödinger equation and the N-soliton solution is obtained. Now by extending this for N-coupled nonlinear Schrödinger equation, we obtain Bright N-soliton solution using Darboux Transformation Technique. Based on the Ablowitz-Kaup-Newell-Segur (AKNS) technology, the Darboux transformation method is successfully applied to two coupled nonlinear Schrödinger systems. With the help of symbolic computation, the bright one and two soliton solutions with amplified distribution solitons, interaction of classical solitons are further constructed via Darboux transformation. These kinds of bright solitons are discussed and the possible applications are pointed out in optical communications and relevant optical experiments. According to the solution, plots are obtained with different spectral parameters and the same is discussed.

It is hoped that our investigation might be helpful in optical communications such as optical computing, optical switching, relevant optical experiments, and will be useful for further investigation of muti-mixed CNLS systems. The properties we have discussed in this manuscript are of particular interest in optical WDM telecommunication systems of inhomogeneous media.

8240-43, Poster Session

Multilayer core asymmetric Bragg reflection waveguides for monolithic three-wave mixing

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Mono-stack matching-layer enhanced Bragg reflection waveguides (MS-BRWs) are investigated as a platform for all-semiconductor parametric devices based on second-order optical nonlinearity. Designs that are composed of a multi-layer core surrounded by asymmetric cladding are examined. The upper cladding in MS-BW is a single layer dielectric with low refractive index. The lower cladding separating the structure from the substrate is a quarter-wave transverse Bragg reflector. A phase-tuning layer, referred to as the matching-layer, is located between the multi-layer core and the Bragg reflector.

Propagation of the Bragg mode in MS-BRW is a combination of total internal reflection, at the upper cladding where the fields are evanescent and Bragg reflections at the lower periodic cladding. Using electromagnetic field transitions at the boundary of the matching-layer and the Bragg reflector, we derive analytical expressions for the modal dispersion of TE- and TM-polarized Bragg modes and the design equations of the matching-layer requirement.

Compared to BRWs with symmetric periodic cladding, the mono-stack BRWs benefit from reduced structure thickness, which eases the growth requirements. Also, the existence of evanescent field at the upper cladding in addition to the small thickness of this layer facilitates patterning longitudinal periodic structures such as grating couplers and Bragg reflectors/filters.

To illustrate the new design, the efficiency of second-harmonic generation is examined in an AlGaAs structure to highlight the nonlinear performance of MS-BRWs and to compare it with symmetric BRWs which have been conventionally used to achieve phase-matching for chi(2) processes.

8240-44, Poster Session

Cerenkov third harmonic generation via cascaded chi(2) processes in a periodic-poled LiTaO3 waveguide

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We present a type of quasi-phase-matched Cerenkov third-harmonic (CTHG) generation in a nonlinear LiTaO3 waveguide. The CTHG results from a guided-to-guided second-harmonic generation cascading a guided-to-radiated sum-frequency generation (SFG) in the waveguide. In the guided-to-radiated SFG process, nonlinear interactions with participating and nonparticipating reciprocal vectors would lead to different CTHG radiations. In addition, the power and temperature detuning characters of QPM CTHG were studied. Theoretical predictions were in good agreement with experimental results.

8240-45, Poster Session

Nonlinear wideband optical filters for laser protection applications

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The design of artificial nanostructured materials for the use in non-linear devices and integrated photonic systems is very challenging as it involves the need to incorporate the nanoparticles, nanomaterials and quantum physics equations. Near-field interactions in artificial nanostructured materials can provide a variety of functionalities useful for optical systems integration. For example, nanoparticles embedded within a dielectric host are known to have a field enhancement effect and therefore lower the threshold of laser induced damage within the material. We are taking advantage of the unique capabilities of nanoparticles guest embedded within dielectric host matrices for field enhancement effect in developing next generation of non-linear components and devices to passively control and regulate optical power.

We report on passive optical power control devices based on a range of photonic nanostructures, including mainly nanostructures for spatial field localization to enhance optical nonlinearities. We present the two main optical power control mechanisms: blocking and limiting, as well as their corresponding nano-scale phenomena. Our blocking mechanism is enabled by catastrophic breakdown of the material when over power occurs. It is performed by novel nanostructures that are used as threshold trigger at relatively low powers according to the nanoparticles and nanostructure design. The limiting of optical transmittance is done mainly by non-linear scattering based on novel nanostructures that are used as the non-linear scattering medium. We present the design, manufacturing and tests of novel generic optical power control components with applications such for optical power regulating for cameras, sensors and other optical systems.

8240-46, Poster Session

Generation of white-light through frequency upconversion in praseodymium-ytterbium codoped nano-structured fluorogermanate glass

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Novel materials suitable for the development of solid-state visible and white-light sources based upon near-infrared excited rare-earth doped frequency upconverters have drawn much scientific and technological interest lately, owing to potential application in color displays technology. Therefore it is of great interest to study frequency upconversion processes in novel alternative rare-earth doped phosphor materials. Considering solid-state hosts, nano-structured glasses have recently emerged as a viable alternative for photonics and biophotonics applications. They are obtained by suitable heat treatment of the precursor glass samples produced by standard oxide glass fusion and casting methods. The advantages of the nanocomposites reside in the fact that the rare-earth ions are confined in nano-scaled crystalline environments of low phonon energy, producing high quantum efficiencies and low optical absorption cross sections when compared to vitreous environments.

Praseodymium-ytterbium codoped fluorogermanate 75GeO3:25PbF2 nano-structured phosphors for solid-state lighting were synthesized by thermal treatment of precursor glasses. Room temperature luminescence features of praseodymium-ytterbium ions incorporated into low-phonon-energy PbF2 nanocrystals dispersed into the fluorogermanate glass matrix and excited with near-infrared light emitting diode laser was evaluated. The luminescence spectra exhibited emission signals peaked around 490, 525, 613, 643 nm. White-light emission was observed in ytterbium-sensitized praseodymium-doped phosphor excited at 980 nm. The dependence of the luminescence emisson intensity upon annealing temperature, and rare-earth concentrations was also evaluated. The results indicated that there exist an optimum annealing temperature and activator ion concentration in order to obtain efficient upconversion emission signals with CIE 1946 chromaticity coordinates within the white-light borderline region. Results indicate that the nanocomposite fluorogermanate glassy phosphor is a promising novel contender for application in white-light solid-state display technology

8240-47, Poster Session

Modeling parametric waveguide terahertz generation

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Terahertz (THz) generation by means of difference frequency generation (DFG) is a versatile approach to generating narrow bandwidth and tunable THz frequencies. However, using commonly available laser sources in the near-infrared (NIR) leads to inherent inefficiencies in the process. These inefficiencies stem from the large wavelength difference between the NIR inputs and the THz output. Because the NIR inputs have a much smaller wavelength than the THz, they also have a much smaller divergence and hence lower beam overlap and low efficiency. The efficiency of the process is greatly enhanced by using a waveguide structure. We present two numerical models designed to optimize narrow-bandwidth THz generation in waveguides. One model is based on a rectangular grid and allows for modeling arbitrary structures. The second model assumes cylindrical symmetry, which allows for fast calculations. Both models automatically include waveguide dispersion effects, and both show enhanced THz generation in waveguides when compared to bulk structures. The numerical results compare well to published THz waveguide experiments.

Another inefficiency associated with the wavelength difference between the THz and the NIR inputs is a large quantum defect. A way to improve over this defect is with a cascaded structure, which amplifies the THz at the expense of the first stage signal. We use the numerical models to study the performance enhancement when adding a cascaded interaction to the waveguide. Our models let us optimize the cascaded structure and show improved performance over a single-stage waveguide structure.

8240-48, Poster Session

Second harmonic generation and optical parametric amplification using fan-shaped optical superlattice

X. Lv, G. Zhao, S. Zhu, Nanjing Univ. (China)

We experimentally demonstrate continuous tuning of central wavelength and bandwidth of second harmonic generation and optical parametric amplification, using a periodically poled lithium tantalate with fanshaped grating and oblique-incident light. The fan-shaped structure are composed of two periods, 7.4884 and 7.6338 micron. Using a foundamental laser of 1064nm, we compared the temperature tolerance of uniform grating and fan-shaped grating. By changing the incident beam position, the SHG temperature can be tuned from 140 to 200 degree Celsius. By changing the incident angle, the temperature tolerance is increased from 1.2 to 11 degree Celsius. In the optical parametric amplification, pumped by a 532nm pulsed laser, the central signal wavelength can be tuned from 920nm to 1064nm, and bandwidth is enlarged from 4.6nm to 40nm around 940nm.

8240-49, Poster Session

High amplification of BEFWM with the liquid fluorocarbon

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Stimulated Brillouin Scattering (SBS) is a nonlinear optical effect that is broadly used for correcting the beam quality of the laser beams, their mode control, amplification and phase conjugation. Two factors are essential when it comes to selection of the nonlinear medium for SBS, i.e. its efficiency or gain coefficient and safety. For example, a low SBS gain coefficient in the fluorocarbon liquid C8F18 that is at least one order of the magnitude lower than in other nonlinear media, typical limits its application in the high-power laser systems. However, a highly purified C8F18 is a very safe and stable nonlinear medium, and in combination with a high optical breakdown threshold it is becoming attractive for practical applications.

This report discusses the phase conjugate mirror (PCM) using the SBS effect in C8F18. The PCM reflectivity better than 90% has been achieved at an optimized experimental geometry of the incoming beam. The output energy of the phase conjugated pulse linearly increased with an increase of the energy of the input pulse after reaching the threshold level at about 3.3 mJ. The estimated slope efficiency is about 95%. As applied to a weak signal amplification, we have realized higher than 10^5-fold amplification when we use the Brillouin enhanced four wave mixing (BEFWM) with an input signal at the level of several nJs. The reflected energy as high as 11 mJ has been achieved with the 400 uJ incoming input signal. Further lowering of the signal energy should result in a higher amplification.

8240-51, Poster Session

Supercontinuum generation in standard telecom fiber using picoseconds pulses

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We reported Sepercontinuum generation (SC) in standard telecom fiber using picoseconds pulses of microchip laser. The pulses width is 700 ps at 1064 nm and operates with a repetition rate of 9 Mhz, Using 57 m long of standard fiber, the spectra extend from 700 to above 1700nm, some 100nm further into the visible. The physical processes leading to the formation of the continuum spectrum were studied by monitoring the growth of the SC while increasing the input power. We could conclude that the mechanisms leading to the continuum in this case rely primarily on the processes of cascaded stimulated Raman scattering and four-wave mixing for this type of telecom fiber. Three Raman lines centered respectively at ~1115 nm, ~1175 nm and ~1239 are observed. The coupling efficiency of ours experimental setup between the laser Microchip and the telecom fiber helped us to obtain this wide spectrum. We used different lengths of fiber and we show evolution of spectra each length.

8240-52, Poster Session

Parametric down conversion in one dimensional-photonic band gap structure

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Abstract

In this paper, we have numerically investigated the parametric down conversion in one dimensional-photonic band gap (1D-PBG) structure, which is composed of two different types of dielectric layers, for terahertz wave generating application. The first one is ordinary dielectric material with linear refractive index and the other one is nonlinear optical material. We have used the multiple-scale analysis to derive a complete set of the nonlinear coupled mode equations (NLCMEs) for four wave mixing (FWM) process with pump field depletion for steady state case. From numerical simulation, we have observed that the conversion efficiency can be enhanced with the increasing of the number of periodicity of 1D-PBG structure, however the efficiency is falling off with higher laser detuning.

Keyword: photonic band gap structure, parametric process, four wave mixing, nonlinear coupled mode equation

8240-53, Poster Session

Analyses of optical packet switching techniques based on nonlinear materials with respect to various label formats

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All-optical networks discarding slow and power-demanding electronic processing introduce the indisputable solution for future networking. Ultrafast data communications ultimately head towards all-optical packet data transfer and optical IP routing. Nonlinear phenomena and materials then could serve as the core building block of these networks.

The paper focuses on two main research aspects. At first, nonlinear switching techniques (utilizing cross-phase modulation and four-wave mixing) are evaluated with respects to nonlinear fiber types and their parameters. In the second part, optical packet label format analysis is carried out, considering spectral efficiency and packet recognition. Simulation models have been developed to provide comparison with measured data. Main goal was to optimize high-speed data switching with combination of particular nonlinear element while utilizing more complicated forms of packet labels.

The experimental setup included a high-speed data source, several label generators (to enable evaluation of both out-band and in-band labeling methods), a label processing unit and a nonlinear switching element together with fiber Bragg gratings at each output. Incorporation of a highly-nonlinear fiber, untapered and tapered chalcogenide (ChG) fibers into the switch was investigated theoretically as well as by measurements. Thanks to ultrafast response of the ChG medium, switching speeds in orders of nanoseconds were obtained. Simulations showed very promising implementations of such a ChG As2Se3 fiber taper for ultrafast optical switching. Influence of the label format was also evaluated and results will be thoroughly discussed in the paper. Different labeling approaches were considered in contrast to spectral efficiency and setup robustness.

8240-54, Poster Session

Sum-frequency generation of continuous-wave tunable ultraviolet coherent light in BBO-installed external cavity

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Recently, a continuous-wave (CW), high-power, tunable, and ultraviolet (UV) light source is required strongly in many applications such as material engineering, photochemistry, spectroscopy, and micro fabrication. However, there has been no UV light source to emit directly CW, high-power, tunable, and UV lights. Therefore, we developed a CW, high-power, tunable, and UV light source through sum-frequency generation (SFG) with a BBO nonlinear crystal. Most of CW laser doesn't have high peak-power enough to cause nonlinear optical phenomenon, so we built up two-stage frequency-conversion system using two external cavities for the enhancement of CW light. In the first stage, we obtained 532-nm coherent light by second harmonic generation (SHG) of a 1064-nm light source. The 1064-nm light source was a fiber laser which was able to output up to 10 W. We employed a bow-tie external cavity incorporating four mirrors, whose length was controlled by a Hänsch-Couillaud frequency stabilization method. The mirrors of the cavity were placed on a monolithic brass board to away from any environmental fluctuations. In the second stage, we successfully obtained 312-nm coherent light by SFG of 532-nm light from the first stage and 754-nm light from a single-frequency CW Ti:Sapphire laser. Considering a nonlinear coefficient, it is preferable to use BiBO crystal for high-efficient SFG, but 312-nm light might be absorbed by BiBO crystal. Although the nonlinear coefficient is lower than BiBO crystal, we chose BBO as a nonlinear crystal to avoid the adsorption of the 312 nm light.

8240-55, Poster Session

Tunable terahertz parametric oscillator synchronously pumped by mode-locked picosecond Ti:Sapphire laser with MgO-doped LiNbO3

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In recent years, terahertz (THz) waves have attracted extensive attentions for use in many applications including imaging, spectroscopy, astronomy, and communications. Although there are various ways to generate THz waves such as quantum cascade lasers, photoconductive switching, and optical parametric process, the nonlinear frequency conversion technique in nonlinear optical (NLO) crystals is one of the most promising methods for realizing a tunable, high-power THz source. Especially in the frequency conversion, the optical parametric process is able to generate tunable, monochromatic, and high-power THz waves with a single pumping laser in room temperature. Therefore, we built a THz parametric oscillator (TPO) in doubly-resonant external enhancement cavity synchronously-pumped by a mode-locked picosecond Ti:sapphire laser with 780 nm of center wavelength. Our TPO cavity including a 5 mol% MgO-doped LiNbO3 (MgO:LN) crystal with Si-prism coupler for the output coupling of the THz wave was designed so as to circulate both pump and idler wave in the same cavity simultaneously. We selected the MgO:LN crystal as a NLO crystal because of its large nonlinear coefficient and high damage threshold. As a result, we developed a widely tunable picosecond TPO just by selecting the resonant idler wavelength. The resonant idler wave was continuously tunable from 781.5 to 786.0 nm by varying the noncollinear phase-matching condition, corresponding to the THz frequency range from 0.7 to 3.0 THz according to the law of energy conservation. In addition, the measured angle between the pump and idler waves inside the crystal showed the good agreement with the theoretical calculation.

8240-56, Poster Session

Nonlinear optical properties of Er3+ ions doped TeO2-Li2O-W2O glass by 800nm femtosecond laser excitation

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The Yb3+-Er3+ codoped lithium tungsten tellurite(TWL) glasses with good quality are grown by solid state reaction method. The unpolarized uv-visible- nir optical absorption spectra of the glass samples have been measured at room temperature. The green and red upconversion emission properties are analyzed with respect to steady- state spectra and decay behaviors under100femtosecond 800nm laser excitation. Change of the glass network of Er-Yb:TWL glass after femtosecond laser modification was studied systematically for the pulse energy between 80 and 320nJ repetition rates between 250KHz and 2.2MHz and scan speeds between 50µm/s and 100mm/s. The third-order nonlinear optical susceptibilities of the glass were investigated by z-scan measurement using the 100 femtosecond laser pulses and observed the large value of n2 for different compositions. The relationship between the nonlinear optical properties and the glass structures estimated by Raman spectroscopy was discussed. The nonlinear susceptibilities of these tellurite glasses increased as the stretching Raman band of TeO4increased, while the stretching band of TeO3 decreased. This indicate that amount of TeO4 units was deeply related to the third order non-linear susceptibilities. The measured three- photon absorption is originated from the glass host, with contribution of the nonbridging oxygen and nonlinear electronic polarization. Results indicate that large potential of the TWL glasses for photonic device in the near infrared.

8240-57, Poster Session

Influence of losses induced by macrobends in the supercontinuum generation using standard fiber

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Supercontinuum generation is being widely studied due to its applications in communications, medicine and metrology. Usually, special fibers, such as photonic crystal fibers and dispersion-shifted fiber, have been utilized. However, there is few information about the potential use of standard fiber with this purpose, which shows some advantages: low cost and availability. In this work, the influence of losses due to induced macrobends on the supercontinuum generation using standard fiber was studied. The losses were introduced by coiling 27 m in length of standard fiber on cylinders with different diameter, a nanosecond microchip laser and 1064 nm of wavelength were employed. The continuum was recorded at the fiber output by using an optical spectrum analyzer and its dynamics was analyzed by tuning the launched power. In a first stage, the fiber was used without bends generating strong firs-order Raman Stokes and a supercontinuum spectrum of 660 nm. When the fiber was rolled in a cylinder of 1.27 cm of diameter to induce macrobends, the Raman Stokes of high order were attenuated and the output spectrum was reduced to 240 nm. Also, a signal peak was observed, around 1030 nm, that means new frequencies were generated in the near infrared region. Thus, induced macrobends affect the supercontinuum broadening

8240-58, Poster Session

Experimental and numerical investigation of highly absorbing nonlinear organic chromophores

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We have developed a mathematical/numerical model and measured ultrafast laser light propagating through nonlinear materials. The numerical model can optimize photo-physical parameters of otherwise unknown photo-activated transitions in multi-photon absorbers. Two photon (TPA) processes are particularly useful in many applications including fluorescence imaging, optical data storage, micro-fabrication, and nanostructured quantum dots for optical limiters. Laser transmission measurements of the organic molecular chromophore, AF455-known TPA material-were taken with a 175 fs, λ_0=780nm, plane-polarized light pulses from Ti:S regenerative amplifier into a 5.1mm thick PMMA slab doped with the chromophore. The energy of the pulses was varied using a variable attenuator consisting of a rotatable waveplate (λ/2) and fixed polarizer. The range of input energies (intensities) in this experiment was 0.01µJ (0.97 GW/cm2) to 25 µJ (2.4 x103 GW/cm2. Experiments showed that as the incident laser intensity increased beyond several µJ, the material did not saturate as predicted by traditional theory. We included excited-state absorption (ESA), as demonstrated by the absorption spectrum, which still could not account for the additional deviation. In order to understand this result we used our numerical method-incorporating an optimization algorithm-to show that an unexpected/unknown higher energy level was being populated. Additionally, we calculated the absorption parameter and relaxation time of this additional level, the population of every energy level and the contribution of every state to the total absorption at each energy. We then calculated the entire transmission curve from 0.01µJ (0.97 GW/cm2) to 25 µJ (2.4 x103 GW/cm2) and found excellent agreement with the experimental data.

8240-59, Poster Session

Arrangement of an advanced acousto-optical processor for modeling the triple correlations of low-power optical pulse trains

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Measuring the train-average parameters inherent in low-power optical pulses with asymmetric envelopes, which are arranged in high-frequency repetition trains, is an actual problem for modern optics. It can be provided via shaping triple auto- or cross-correlations, then their bi-spectra and recovering pulse parameters. The advantages of triple correlations in comparison with correlations of even orders consist in their capability of recovering signals almost unambiguously, revealing asymmetry of train-average pulse envelope, and identifying the frequency chirp and phase. In the case of low-power optical pulses from semiconductor laser systems, a three-wave mixing is not efficient enough to be detected reliable. Consequently, one needs new algorithms for shaping triple correlations of optical signals, but each found algorithm should be comprehensively tested via comparably simple experimental modeling procedure. This is why the acousto-optics and special method for modeling with the time-frequency scaling of pulse parameters are involved. Practically, triple correlations originate within an optical scheme including the modulated light source, representing the first input port, and two wide-aperture acousto-optical cells forming two other input ports. Due to a lens system, initially modulated light beam is crossing sequentially apertures of these cells oriented at right angle to each other. A CCD-matrix integrates the received optical signal with respect to time and registers the resulting triple correlations. In a view of arranging similar acousto-optical processor for modeling triple correlations, we characterize the components for lens system, light source and acousto-optical cells exploiting tellurium-dioxide crystals. Finally, performances of the designed processor are estimated and the needed algorithm is determined.

8240-60, Poster Session

Quasi phase matching through periodic step structure

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Periodic inversion of spontaneous polarization in a ferroelectric substrate has realized quasi phase matching (QPM) and thereby revolutionized nonlinear optics. In the presentation, we report on a new way to generate the second harmonic (SH) by QPM. In ordinary, QPM is achieved by polarization inversion, but we suggest the periodic step structure to achieve QPM. Polarization inversion is generally formed by superimposed voltage. However, the shorter wavelength region we treat, the shorter inversion cycle is. Therefore, if we wish to use the vacuum ultraviolet region, it becomes more difficult to form periodic inversion. The periodic step structure should be made by chipping off the region which might be ordinary inversion structure by Focused Ion Beam (FIB). Therefore, it has several merits such as it is not necessary to form periodic inversion, it is easy to process short cycle and it can make use of all crystal's transparency region without feeling shackled by angle phase matching of birefringence phase matching (BPM). We processed several optical crystals such as lithium triborate (LBO) crystal and then tried to generate SH. The process cycle was calculated theoretically considering the refractive index of crystals and substances of fillings and conversion efficiency was simulated.

8240-61, Poster Session

Optical parametric generation and amplification in 2.7-3.1 µm spectral range using periodically poled lithium niobate with femtosecond pumping

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We report results of the experimental investigations and theoretical simulations on the generation and amplification of the femtosecond pulses tunable in 2.7-3.1 um range in periodically pumped lithium niobate (PPLN) under pumping by high repetition rate femtosecond pulses from Yb:KGW laser. The femtosecond light pulses tunable in 2.7 - 3.1 µm spectral range could be useful for analyzing properties of the water rich biological objects and for laser micromachining of those biological tissues. On the other hand PPLN due to high nonlinearity and wide transparency range is attractive material for parametric generation and amplification in case of pumping by high repetition rate femtosecond pulses with low energies. Parametric generation and amplification experiments were performed in PPLN structures with 27 gratings, whose periods varied in 0.25 µm step from 25 µm to 31.5 µm. For the generation of the idler wave in 2.7 - 3.1 µm spectral range we used grating with 29.5 µm period. The PPLN structures with different length were used in experiments. The crystal was heated to 120ºC temperature in the copper oven in order to minimize a photorefractive effect. First of all, the laser-induced damage threshold of the PPLN structure was found. Measurements showed that damage threshold for S on 1 test with S=106 pulses at 1030 nm with 290 fs duration at repetition rate 100 kHz was ~0.02 J/cm2. Measured data showed, that quite low optical parametric generation efficiency (9 % in 8 mm long PPLN) was caused by a competitive process of second harmonic generation, which was twice more efficient. The spectral, spatial and temporal properties of the OPG and OPA which used two PPLN crystals were investigated. Theoretical simulation including many competitive nonlinear processes in PPLN pumped by femtosecond pulses showed similar futures as experiments.

8240-62, Poster Session

Fabrication and characteristic of long photonic crystal fiber taper

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Up to several handred meters long photonic crystal fiber taper was directly fabricated on the industry drawing tower. The long fiber taper had good uniformity of structure as the outer diameter decreased from ~170 µm to ~70 µm. We describe the fabrication technique detailly in this work. The fiber taper's optical attenuation was carefully measured and the zero dispersion wavelengths were calculated. Watt-level supercontinuum was obtained as the fiber taper pumped. The nonlinear mechanisms of spectral broadening are carefully investigated with the support of numerical simulations.We believe our work can provide some helpful information for mass-produce of hundred-meter-long photonic crystal fiber taper for supercontinuum source system.

8240-63, Poster Session

A multi-phonon light scattering and resolution of acousto-optic devices

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Rather specific type of a multi-phonon light scattering in the condensed matters is considered. Besides of its scientific novelty, studying this phenomenon promises a progress in applications, because practical exploiting N-phonon processes in acousto-optical spectrum analyzers will lead to improving their characteristic spectral resolution by about N times. The simplest case, corresponding to an effective multi-phonon acousto-optical processes and being limited by a moderate divergence of acoustic beam, is preliminary investigated here. The analysis shows that under some conditions it may be possible to expect appearing various multi-phonon processes of light scattering in a regime, which is very close to the commonly used Bragg scattering case. However, realizing so-called almost-Bragg regime restricts the Klein-Cook factor by an inequality Q > 4P, which limits a ratio of the acoustic and light wave numbers, i.e. K and k. With the optical wavelength 500 nm in a medium with the interaction length L = 0.5 cm and the refractive index n = 2.0, the almost-Bragg regime is provided when K/k > 0.01. When L is large enough for supporting the almost-Bragg regime, but acoustic beam divergence has already significant effect, the well-determined width F of an acoustic lobe can be identified. In isotropic media, rather effective two-phonon light scattering in the almost-Bragg regime can be observed with F(2) = K/k, while originating similar three-phonon processes of light scattering requires already F(3) = 2.1 K/k. Preliminary experiments with both two- and three-phonon light scattering in the almost-Bragg regime have been successfully performed using flit-glass acousto-optical cells. Potentially expected improving the spectral resolution in the case of exploiting these cells as optical filters has been measured as well.

8240-18, Session 5

Mid-IR supercontinuum generation from chalcogenide fibers

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No abstract available

8240-19, Session 5

Photonic crystal fibers for supercontinuum generation pumped by a gain-switched CW fiber laser

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Supercontinuum generation in photonics crystal fibers (PCFs) pumped by CW lasers yields high spectral power densities and average power. However, such systems require very high pump power and long nonlinear fibers and generally produce less broad output compared to pulsed pumping. By on/off modulating the pump diodes for the fiber laser in the 100 kHz range, the relaxation oscillations of the laser can be exploited to produce pulses with high peak power. The increased peak power enhances the broadening process in the nonlinear fiber, resulting in more efficient use of the CW fiber laser without the need for high average pump power.

Using a gain-switched fiber laser for pumping, the present study experimentally and numerically analyzes the influence of fiber design and fiber length on the supercontinuum process. The modal properties of the PCFs are analyzed and the dispersion properties are calculated and measured. The nonlinear propagation is modeled by the generalized nonlinear Schödinger equation and quantitatively compared to the experimental results.

The involved physics are investigated by sweeping the fiber length and the zero group velocity dispersion wavelength, which is of great importance to the modulation instability process. Furthermore, influence of the nonlinearity of the PCF is analyzed by comparing germanium doped and pure silica fibers.

Finally we show that by applying gain-switching, the fiber length can be reduced considerably compared to CW pumping while maintaining spectral width and high spectral power density, thereby providing a simple and robust alternative to picosecond or nanosecond pumped supercontinuum sources.

8240-20, Session 5

Single frequency acoustically tailored Raman fiber amplifier

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We report for the first time on an acoustically tailored single-frequency Raman fiber amplifier (RFA) for guide star application. SBS suppression was achieved through the control of the core dopants of a polarization-maintaining single-mode conventional fiber. The distribution of the dopants in the transverse direction was chosen such that a non-uniform acoustic index of refraction was achieved while preserving the homogeneity of the optical index. Furthermore, the core was doped for enhanced Raman gain. Pump-probe measurements were conducted on this fiber yielding a Brillouin gain coefficient of approximately 5×10-12 m/W and a 2.5 MHz/°C shift of the peak Brillouin gain with temperature. The acoustically tailored fiber was utilized in a counter-pumped single-stage monolithic amplifier configuration. An 1178 nm DFB laser provided 15 mW of seed power to the RFA which was pumped with an 1120 nm Raman fiber laser. A system of high power polarization-maintaining WDMs was used to combine or separate the signal and pump light. Due to the SBS suppressing characteristics of the fiber, we obtained 12 W of power that could be used for frequency doubling into the D2a sodium line. As an initial demonstration, a non-optimized thermal gradient was used to generate >15 W for further power scaling. Using a Fabry-Perot interferometer, we measured the signal linewidth at the highest power to be 50 W output power, which could potentially lead to a >40 W sodium guide star beacon.

8240-21, Session 5

Higher-order modulation instability in nonlinear fiber optics

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Modulation instability (MI) plays a key role in the nonlinear Schrödinger equation (NLSE), and is intimately linked to the theories of four-wave mixing and parametric wavelength conversion. Most approaches to describing MI, however, have been approximate, using numerical simulations or considering energy exchange between a limited number of waves. It has recently been realized, however, that analytic Akhmediev breather solutions of the NLSE describe modulation instability almost exactly, and this has led to a series of significant results in interpreting supercontinuum generation, MI spectral dynamics, and the observation of the Peregrine soliton.

In this paper, we extend the powerful framework of Akhmediev breather to describe a new regime of multiple wave interaction in optical fibers which we refer to as higher order modulation instability. The signature of higher-order MI corresponds to the simultaneous excitation of multiple sidebands under the fundamental MI gain curve. We show the resulting complex dynamics can be described analytically using the mathematical technique of the Darboux transformation.

Experimentally, we show how the excitation of higher-order MI is observed in fiber-optics using a single initial frequency modulation on a plane wave when the modulation frequency is below a critical low frequency limit such that multiple instability harmonics fall under the primary gain curve. These results represent the first quantitative study of higher-order MI dynamics in any NLSE system, and we anticipate that the analysis developed will provide new insights into optimizing technologies such as high repetition rate pulse train generation, wavelength conversion and broadband fiber parametric amplifiers.

8240-22, Session 5

Demonstration of minute continuous-wave triggered supercontinuum generation at 1 µm for high-speed biophotonic applications

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Ultra-broadband supercontinuum (SC) at the 1-µm wavelength range, which is regarded as a diagnostic window in biophotonics, represents a versatile light source for a wide range of bioimaging and spectroscopy applications. In particular, applications which require high-speed and high-throughput operations, such as real-time high speed spectroscopy based on dispersive Fourier transform (DFT) and serial time-encoded amplified microscopy (STEAM), demand for the robust SC source with not only a broadband spectrum but also a good temporal stability. In the context of the DFT-based techniques, we here demonstrate, for the first time, the 1-µm DFT which is enabled by the SC generation based on a minute continuous-wave (CW) triggering mechanism. By introducing an extremely weak CW (~200000 times weaker than the pump power), we observe that the temporal stability of the filtered SC can be considerably improved. Specifically, the standard deviation of SC shot-to-shot amplitude variation is reduced by 65%. Furthermore, wider SC spectral range which spans from 900 nm to 1200 nm and more than 25-dB enhancement in SC power on both red-shifted and blue-shifted regions are achieved with the CW-triggering. This 1-µm CW-triggered SC helps extending the operation regime of prior works on DFT to the 1-µm window. We demonstrate that both the wavelength-time mapping quality and spectral stability in 1-µm DFT show reasonably good improvement in the CW-triggered case compared with untriggered case. Hence, the CW-triggered SC at 1 µm enables robust DFT operation - making it possible to realize real-time, ultrafast and single-shot spectroscopy and imaging in biophotonics.

8240-23, Session 6

Three-dimensional light bullets

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Three dimensional light bullets (3D-LB) are the most symmetric solitary waves - nonlinear wavepackets propagating without diffraction and dispersion. Since their theoretical prediction, the observation of 3D-LB has constituted a long-lasting challenge in nonlinear science. The difficulty arises from their instability, triggering catastrophic collapse in conventional, homogeneous, cubic nonlinear media. Various methods have been proposed to stabilize 3D-LBs in the last two decades. Among them, was the prediction that a periodic modulation of the transverse refractive index would arrest collapse of 3D-LB even in cubic nonlinerar media. Indeed, we observed for the first time genuine 3D-LB in two dimensional arrays of coupled waveguides arranged in a hexagonal lattice. The observation was possible thanks to the combination of highly regular samples, a spatiotemporally resolved imaging system for ultrashort pulses, and the support of a sophisticated simulation code based on the Unidirectional Maxwell Equations. Both experiments and simulations showed that intrapulse Raman scattering continuously shifts the central wavelength of the 3D-LB and forces them to adiabatically adapt to changing diffraction and dispersion conditions along the propagation path. The 3D-LB decay when the wavepacket's energy is no longer sufficient to support solitonic propagation. Surprisingly, we also found that non-trivial spatiotemporal effects are taking place during the evolution and decay of 3D-LB. These effects, being the analogue to space-time focusing, lead to superluminally propagating wavepackets, which accelerate measurably during decay. Going far beyond existing theories on 3D-LB, the experiments opened a new, exciting chapter in nonlinear science.

8240-24, Session 6

High-energy 450-MHz CdSiP2 picosecond optical parametric oscillator near 6.3 microns for biomedical applications

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Mid-infrared (mid-IR) spectral range, 5900-6600 nm, constituting absorption bands of amide-I (6000 nm), water (6100 nm) and amide-II (6450 nm), is of great interest for human surgery, due to simultaneous absorption by both proteins and water. In the absence of conventional lasers at these wavelengths, the free electron laser is the only source capable of delivering sufficient energy for such applications. But high complexity and cost preclude its practical utility.

Here we report a compact, efficient, high-energy and high-repetition-rate mid-infrared picosecond optical parametric oscillator (OPO) based on the new nonlinear material CdSiP2 (CSP). The OPO is synchronously pumped by a master-oscillator power-amplifier system at 1064.1 nm, providing 1-µs-long macro-pulses constituting 8.6 ps micro-pulses at 450 MHz, and can be tuned over 486 nm across 6091-6577 nm, covering technologically important wavelength range for surgical applications. Using a compact cavity as small as ~30 cm and high-quality CSP crystal, an idler macro-pulse energy as much as 1.5 mJ has been obtained at 6275 nm at a photon conversion efficiency of 29.5%, with >1.2 mJ over more than 68% of the tuning range, for an input macro-pulse energy of 30 mJ. Both the signal and idler beams are recorded to have good beam quality with TEM00 spatial profile, and the extracted signal pulses are measured to have durations of 10.6 ps. Further, from the experimentally measured transmission data at 1064 nm, we have estimated the two-photon absorption coefficient of CSP to be =2.4 cm/GW, corresponding to an energy band gap of Eg=2.08 eV.

8240-25, Session 6

Ultrafast mid-IR generation in CdSiP2 (CSP) using a mode-locked near-IR fiber laser pump source

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Ultrashort pulse laser technology has expanded the ability for physicist and scientists to investigate and demonstrate subjects from optical non-linearity to complex light-matter interactions. The recent advances in ultrashort fiber optic sources have made exploration in ultrashort phenomena readily available to academic and industrial research organizations. Using such versatile ultrashort sources we report on the novel generation of ultrashort (<300fs) mid-IR (3um - 6um) pulses. We report for the first time to our knowledge an ultrafast mode-locked Erbium fiber laser directly pumping a CdSiP2 (CSP) optical parametric generator at ~1.550 um to generate ultrashort mid-IR mW-level average power. We also investigate using a raman shifted fiber source to create a spectrally tunable mid-IR source without the need for mechanical adjustment of crystal angle in the parametric generator. Further optical parametric amplification of mid-IR light in both CSP and ZGP is also investigated.

8240-26, Session 6

Few cycle high energy pulse compression at MHz repetition rate

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We demonstrate a simple method for broadening and compression of laser pulses at megahertz repetition rates by self-phase modulation in a large mode area (LMA) fiber. [Ganz]. In order to avoid the currently limiting factor of damage by self-focusing, we positively chirp the input pulses, which allows coupling of significantly more energy into the fiber, while maintaining the same spectral bandwidth and compression as compared to the Fourier-limited case at lower energy. Using a commercial chirped pulse Ti:sapphire oscillator (Femtolasers, Femtosource XL) with 55fs, 400nJ pulses at 5MHz and a LMA with 25µm core diameter, we generate 16fs, 350nJ pulses which is a factor of 4 more energy than possible with unchirped input pulses. Good stability has been measured over at least 12 hours for the chirped case and Fourier-limited case. Pulse measurements using SPIDER revealed a very good compressed pulse with nearly no higher order dispersion left. Furthermore, with a 5 µm core diameter LMA we achieved compressed pulses with 6fs and 20nJ output energy. This would allow to CEP stabilize the laser system by the new shown external cavity stabilization scheme [Steinmeyer].

A variety of application would benefit of such a laser system due the increase signal-to-noise ratio and reduced measurement time, like ultrafast pump probe spectroscopy, nonlinear optics, material processing, high harmonic generation or resonant plasmonic field enhancement.

8240-27, Session 6

A highly efficient broadband picosecond pump high gain OPCPA system demonstrating 50% conversion to signal for Ti-sapphire seed pulses: an ideal seed for high-contrast, large-energy CPA laser systems

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The seed pulse is achieved by taking a Ti-sapphire pulse that is also used for the regenerative amplifier. For efficient energy extraction from the OPA, this pulse is stretched in a compact CPA scheme using a 4 reflection single grating stretcher to 3ps. Each BBO crystal is 15mm long and the pump pulse is suitably image relayed before being amplified in the OPA scheme. The second amplification stage uses the residual pump light from the first stage and with a separate telescope to match the diameter of the expanded signal beam from the first stage. For synchronisation of the seed and pump, mechanical delay lines are used on the collimated Ti-sapphire seed for the first OPA - the signal from here is then re-collimated for input into the second OPA. Careful control of these delays is used to optimise the spectral width at the final output.

This compact high energy seed sources will have a dramatic effect on the intensity contrast achievable on large scale Petawatt systems - We have measured a nanosecond intensity contrast better than 10-10 when seeded by this picosecond OPCPA system. These systems have traditionally required gains of 108 before being energetic enough for larger aperture rod and disc amplifer systems. This demonstrated high efficiency picosecond seed source will reduce the gain required from mixed glass laser systems which are required to provide the bandwidth for CPA Petawatt sytems where intensities that can be achieved are limited by energy densities on diffraction gratings at the end Laser.

8240-28, Session 6

Broadband OPCPA pumped by ultra-narrowband gaseous iodine laser

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Amplification of femtosecond pulses using an ultra-narrowband gaseous pulse laser was demonstrated for the first time. A single-shot sub-nanosecond iodine photodissociation laser with a bandwidth of 20 pm was used as a driver in an all-stage OPCPA. To ensure temporal overlap of pulses in parametric amplifiers an externally triggerable OPO tuned to laser line of 1315.24 nm was used in the front end of the iodine laser. Frequency tripled beam at 438 nm was used to pump parametric amplifiers, LBO and KDP crystals at intensities of 3.5 GW/cm2 and 0.9 GW/cm2, respectively. The signal pulses from a Ti:sapphire laser at the central wavelength of 800 nm with a bandwidth of 70 nm (FWHM) and the energy of 7 nJ were stretched from 12.5 fs to 250 ps and amplified by a factor of 2×10^8. The amplified pulses of typical bandwidth of 50 nm were compressed down to 27 fs. The output power of 0.5 TW and pulse energy of 15 mJ was achieved. An optimized amplifier chain and addition of a third nonlinear crystal would enable to generate pulses of several terawatts. The broadband pulses at 800 nm central wavelength were amplified in the KDP crystal for the first time, due to the suitable wavelength of the pump pulses. A kilojoule iodine laser could generate pulses of petawatt peak power, namely because the KDP crystals can be grown in large apertures. The results show that the bandwidth of high-energy lasers is not critical for intense femtosecond pulses production.

8240-29, Session 7

Microresonator-based optical frequency comb generation

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Optical frequency comb generation has attracted significant interest, particularly for applications in spectroscopy, precision frequency metrology, astronomy, high-speed communications, and optical clocks. Recently, high-qualityfactor optical microcavities have shown enormous potential as a platform for efficient nonlinear optical processes.

Here we describe recent results results on the use of the silicon-based platform for generating high-precision frequency combs via the process of cascaded parametric four-wave mixing. We demonstrate comb generation that can span more than an octave which represents a significant step towards a stabilized, integrated frequency comb source.

8240-30, Session 7

Mid-infrared frequency combs based on microresonators

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The mid-infrared spectral range (λ ~ 2 μm to 20 μm) is known as the "molecular fingerprint" region as many molecules have their highly characteristic, fundamental ro-vibrational bands in this part of the electromagnetic spectrum. Mid-infrared frequency combs are therefore highly desirable for molecular spectroscopy which has application in biochemistry, pharmaceutical monitoring and material science. Here we report on a promising alternative to mid-infrared frequency comb generation with a continuous-wave pumped microresonator. The ultra-high Q (Q~109, corresponding to an optical cavity finesse of F=105-106) whispering-gallery mode microresonator is made of crystalline magnesium fluoride. Its distinguishing features are compactness, efficient conversion, large mode spacing and high power per comb line. A spectrum with about 100 comb lines centered at λ=2.5 μm and spanning more than 200 nm (≈10 THz) is generated via four-wave-mixing due to the material's Kerr nonlinearity. The mode spacing of the comb, which is determined by the free-spectral range of the resonator, can be adjusted by changing the resonator diameter. Beat note measurement of the comb lines with a diode laser shows no linewidth broadening of the comb modes relative to the pump laser with current resolution. This work therefore opens the path to a versatile mid-infrared spectrometer, and holds promise to facilitate dual-comb spectroscopy. Combining the broad transparency window (up to ~7 μm) of crystalline microresonators with high power quantum cascade lasers, a compact frequency comb source that extends deep into the mid-infrared can be envisioned.

8240-31, Session 7

Remote molecular spectroscopy with a broadband mid-IR frequency comb

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We demonstrate stand-off spectroscopy using a broadband mid-infrared frequency comb produced by degenerate optical parametric oscillation. Our generation technique efficiently transfers the desirable properties of shorter wavelength mode-locked sources to the mid-IR, where they are especially useful for high performance spectroscopy. In particular, the high spatial and spectral brightness of this source permits fast measurement of fundamental molecular absorption spectra over long distances. Our OPO resonator is a 3m ring cavity composed of one pair of concave mirrors with R=50mm and four flat mirrors, all but one of which are gold coated with > 99% reflection. A single dielectric mirror admits the 1550nm pump while maintaining high reflectance in the 2.5 - 4 micron range. Broadband parametric gain around 3.1-micron subharmonic is provided by short (0.2-0.5mm) periodically poled lithium niobate (MgO:PPLN) at Brewster angle. Oscillation occurs when signal/idler are brought into degenerate resonance by fine-tuning the cavity length with a mirror on a piezo stage. Spectroscopic measurements are made by passing the OPO output through a Michelson interferometer and projecting it to a remote sample. Efficient, broadband conversion delivers up to 30mW with intensity distributed from 2 to 3.8 micron. After interaction with the sample, scattered and reflected light is collected by a telescope on a high dynamic range detector. Transformation of the resulting interferogram provides the absorption spectrum of the sample and any intervening materials. Narrow comb lines make it easy to separate the sample spectrum from that of water vapor, CO_2 and other intervening gasses in long-distance measurements.

8240-32, Session 7

Second-order coherence properties of supercontinuum: from modal representation to experiments

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Supercontinuum (SC) light generated in highly nonlinear fibers possess unique spectral, temporal and spatial coherence which impacts directly the intended application. It is therefore important to be able to evaluate the coherence properties of SC light in a systematic way.

In this paper, we reconsider the shot-to-shot fluctuations of SC by using standard two-time and two-frequency correlation functions of second-order coherence theory of non-stationary light. This allows us to explicitly define measures of temporal and spectral coherence and show that, in general, the correlation functions of SC pulses include quasi-coherent and quasi-stationary contributions whose relative magnitudes depend on the input pulse parameters. Our approach has the advantage that it allows to define measures of both coherence time and coherence bandwidth, as well as an effective degree of coherence, for SC pulses. These results further allow for decomposing SC pulses into the linear superposition of a finite number of coherent modes and thus reducing significantly the dimensionality of SC light coherence characteristics, which is particularly useful for evaluating SC performance in linear optical systems.

We also address experimental arrangement for the measurement of the two-time and two-frequency correlation functions and report on experimental characterization of second-order coherence of SC generated in the anomalous dispersion regime of a photonic crystal fiber. Our results and analysis provide new insight into the fluctuations and coherence properties of SC sources and open the route for universal definitions of the coherence degree for broadband sources and optimization of frequency combs.

8240-33, Session 7

High-quality 3.6-fs pulses by compression of an octave-spanning supercontinuum

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Few-cycle pulses offer a wide range of interesting applications, for example in time-resolved studies of ultra-fast phenomena in physics, chemistry and biology. Nonlinear spectral broadening in photonic crystal fibers (PCFs) followed by dispersive compression allows for the generation of extremely short optical pulses. Pulse durations of 5.5 fs (2.4 optical cycles) have been demonstrated, by employing a PCF with a single zero dispersion wavelength (ZDW) near the pump wavelength However, this technique suffers from noise-sensitive soliton dynamics, which limit pulse compression. Alternatively, soliton self-compression in PCF has been exploited resulting in 4.6 fs (1.6 optical cycles), but poor pulse quality.

In this contribution we take advantage of SC generation in all-normal dispersion PCF (ANDi PCF), which features no ZDW across the spectral region of interest. Spectral broadening therefore is dominated by self phase modulation and optical wave breaking, leading to smooth and highly coherent SC spectra. We show generation of SC spectra covering more than one optical octave around 810 nm central wavelength. Active phase control and spectral shaping were employed to compress the pulses to 3.64 fs (1.3 optical cycles). This is the shortest pulse duration achieved via SC generation in PCF and subsequent temporal recompression to date. In contrast to other approaches, the presented concept delivers pulses with an excellent temporal pulse quality resulting from the smooth spectral intensity and phase achieved during SC generation. In principle, our technique can be extended to even larger bandwidths to reach the sub-cycle regime, provided an adequate compressor is employed.

8240-34, Session 8

Applications of extremely nondegenerate two-photon absorption in semiconductors

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We have experimentally verified 2 to 3 orders of magnitude enhancement of two-photon absorption (2PA) in direct bandgap semiconductors when using photon pairs of very different energies (photon energy ratio of ~10). We have utilized this large enhancement to allow for detection of sub-bandgap radiation. For example, a GaN photodiode of bandgap energy ~3.2 eV allows detection of 5.6 micron light using 390 nm gating pulses. We compare this gated detection to direct detection of the 5.6 micron pulses using a liquid nitrogen cooled HgCdTe detector and find comparable results. Significant optimization of the detection should be possible by going to thicker detector elements or waveguide detectors. In addition, all-optical switching should be possible using various geometries including ring resonators. For example, the Q of a resonating beam operating just below the bandgap could be rapidly switched from high to low by the large nondegenerate 2PA from an IR switching beam. Additionally, the complementary process of two-photon gain should also be enhanced by orders of magnitude by going to extreme nondegeneracy.

8240-35, Session 8

Twofold enhancement of two photon absorption by tailored photon statistics

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Following the treatments of Mollow [1], there is a linear relation between simultaneous two-photon absorption (TPA) rate and the second-order field correlation function at zero time delay g(2)(τ=0). The later one is a figure of merit for the light intensity correlation, respectively for the photon statistics of light sources. Mollow distinguished between chaotic and coherent light and showed that the time-averaged TPA rate generated by coherent light is only half as large as generated by chaotic light. This is of general interest for TPA applications as e.g. microscopy. To verify these predictions, we measured the two-photon excited fluorescence (TPEF) signal of common fluorophores illuminated by two light sources of different photon statistics. As coherent light source we choose a distributed feedback (DFB) diode laser. This laser showed a Poissonian photon number distribution and therefore g(2)(0)≈1 [2]. As chaotic light source we took a super luminescence diode (SLD). The light of SLDs is non-laser like and characterized by so called amplified spontaneous emission (ASE). Boitier has shown that for ASE sources g(2)(0)≈2 [2]. Both light sources emitted cw-light around the center wavelength of 976 nm and were designed to have the same transversal mode. To detect the TPEF signal in a large dynamic range, we constructed a highly-sensitive setup, allowing pump powers below 1 mW. Our results confirmed a 2 times more efficient excitation for chaotic light compared to the laser for all measured fluorophores.

[1] Mollow, Phys. Rev. 175, 1555 (1968).

[2]Boitier et. al, Nature Physics 5, 267 (2009).

8240-36, Session 8

Two-photon pumped amplified spontaneous emission in seeded CdSe/CdS nanorods

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Seeded CdSe/CdS nanorod heterostructures are excellent nanomaterials for multi-photon applications. The size of the CdSe dot determines it emissive properties while the CdS shell functions like an antenna for light harvesting. Recently, it has been demonstrated that these two unique features allows the independent tuning of the emission wavelengths and the absorption cross-sections which is non-trivial problem in spherical quantum dots. These nanorods are also highly luminescent, with quantum yields approaching 70%. In this work we leverage on the enlarged two-photon absorption (2PA) cross-sections to achieve ultralow threshold two photon pump amplified spontaneous emission (2ASE). The attractiveness of the two-photon excitation (or upconversion) technique over other nonlinear frequency conversion techniques (e.g. optical harmonic generation) in the generation and wavelength tuning of coherent light lies in the absence of a phase matching requirement for the former. This permits its application to a wide range of gain medium and resonator designs. an ultralow threshold fluence of ~ 1.5uJ/cm^2 for nanorods of length 39 nm is required to achieve 2ASE. Importantly, by exploiting this unique property of the seeded nanorods to exhibit strong quantum confinement even at relatively large rod sizes, a near inverse proportional dependence of the 2ASE threshold on the 2PA action cross-section (σ_2η), where η is the quantum yield, was found and validated over a wide volume range for II-VI semiconductor nanostructures. Transient photoluminescence and transient absorption spectroscopy were also used to investigate the carrier dynamics in these seeded nanorods.

8240-37, Session 8

Optical characterization of colloidal gold nanoparticles prepared by sputtering deposition

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The nonlinear and thermo-optical responses of gold nanoparticles dispersed in castor oil were investigated, using the thermally managed Z-scan technique. The colloids were prepared by sputtering deposition, which produced particles with an average diameter about 3.8 nm directly in castor oil, without the use of chemical processes and with the absence of impurities. Four samples with different concentrations of gold nanoparticles were investigated. The thermal and electronic contributions to nonlinear refractive index of the colloids were measured separately. The experimental setup was composed by a mode-locked Ti:Sapphire laser tuned at 793 nm with 76 MHz repetition rate. We observed that the refractive nonlinearities responses of thermal and electronic origins were increased as the particles filling factors were raised. The real part of third-order nonlinear susceptibility from nanoparticles was obtained using Maxwell-Garnett formalism. A figure of merit, M, which quantifies the influence of the thermal lens effect on the optical responses of the colloidal systems, was also defined and evaluated for the investigated colloids. We observed that particles investigated in this work present a large value of third-order nonlinear susceptibility and a small value of M in comparison with other gold nanoparticles reported in the literature. These results show that the colloidal nanoparticles prepared by sputtering deposition have a good potential for the development of photonic devices exploiting optical nonlinearities.

8240-38, Session 9

Chi(3) third harmonic generation and triple photon generation

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Nonlinear optical interactions governed by the third-order electric susceptibility have received huge interest in the past decay, mostly in the case of Raman scattering and parametric four-wave mixing (FWM) for the generation of supercontinuum light sources when achieved in optical fibers. During these two processes two pump photons at ω_0 and ω_1 disappear leading to the creation of two new photons at ω_2 and ω_3 such as $\omega_0 + \omega_1 = \omega_2 + \omega_3$ according to energy conservation. The present talk will be focused on two other classes of third order processes fulfilling $\omega_0 = \omega_1 + \omega_2 + \omega_3$ as generic energy conservation equation and recently considered for their interest in quantum optics, i.e. : Third Harmonic Generation (THG) where a photon at 3ω is generated from the collapsing of three incident photons at ω, and Triple Photon Generation (TPG) that is the reverse interaction where the splitting of a photon at 3ω gives birth to three lower energy photons at ω. THG and TPG are interesting from the three-photon correlations point of view, TPG being particularly relevant since it enables to generate a pure Greenberger-Horne-Zeilinger (GHZ) state of light. Nonlinear aspects as well as materials considerations are of prime importance in this context, the goal being to achieve efficient and pure THG or TPG. Different strategies and the main classical and quantum results will be described using birefringence phase-matching in crystals such as BBO, BiBO, KTP and TiO2 rutile or modal phase-matching in silica glass micro-fibers.

8240-39, Session 9

Growth of single-crystal cesium germanium chloride from the melt

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The cesium germanium halides, $CsGeCl_3$ and $CsGeBr_3$, are a highly promising class of nonlinear optical frequency conversion materials. They have demonstrated high nonlinear coefficients, transparency ranges that extend from the visible through the long-wave infrared, and sufficient birefringence to allow for phasematching. They are also ferroelectric, opening up the possibility of periodic poling in a manner analogous to lithium niobate. A key difficulty with the development of these materials, though, has been crystal growth. Previous methods have relied on aqueous synthesis followed by growth from aqueous solution; the resulting crystals are no more than millimeter-scale, and the use of aqueous solution opens up the possibility of water contamination, which would severely limit their utility for conversion into the infrared. We report here the first growth of single-crystal cesium germanium chloride from the melt, producing centimeter-scale crystals. A primary difficultly in melt growth of cesium germanium chloride is decomposition, which we were able to mitigate through the use of appropriate cover gases. To combat water contamination, we are also developing a novel, completely dry synthesis method that produces $CsGeCl_3$ directly from $GeCl_2$, generated in situ, and CsCl. Combined, we expect these techniques to generate the first cesium germanium halide crystals that are suitable for practical nonlinear frequency conversion systems.

8240-40, Session 9

Investigation and characterization of optical homogeneity of mid-IR nonlinear optical crystals for product yield improvement activities

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An investigation and characterization of the optical homogeneity and spatial birefringence uniformity of mid-IR non-linear optical crystals has been conducted in an effort to improve quality screening procedures, in an operations environment, at the crystal sample and full boule level of production. The spatial birefringence imaging diagnostic (SBID) and associated post processing correctly compares non-linear optical performance of a mid-IR optical crystal to a specified performance requirement. Our SBID has been implemented on >200 crystals spanning several boules of material, and thus far correctly screens >60% of the passing crystals. The figure of merit generated from imaging post processing is mathematically normalized to spectroscopic properties of the crystal to increase predicted yield to >70%. The normalization also allows for performance requirement scaling and adjustment of the screening criteria for a particular application. This test diagnostic has been proven at the sample level and is implemented at the full boule level with preliminary results demonstrating high level product screening capabilities. We aim to develop a low level product screening capabilities that discern product quality within a single boule by early 2012. Long term implementation of the SBID presents an opportunity for large increases in full boule yield in the near future.

8240-41, Session 9

Simultaneous multiphoton absorption in rutile (TiO2) across the half-bandgap

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Future optical systems require compact, ultra-fast devices capable of switching and logic across a wide range of wavelengths. To realize this goal, ultrafast nonlinearities must be exploited while maintaining manageable linear losses and nonlinear absorption. We present TiO2 as a nonlinear material to meet these needs. TiO2 is highly transparent for wavelengths > 400 nm and possesses both high linear and nonlinear refractive indices. We measurements the nonlinear index and multiphoton absorption in bulk TiO2 (rutile) using the z-scan technique near the half bandgap (800 nm). Using broadband femtosecond pulses, we observe behavior consistent with simultaneous two- and three-photon absorption. We present a theoretical model used to fit our data which includes the effects of simultaneous multiphoton absorption. By tuning our wavelength above and below the half-bandgap energy, we observe the onset of two-photon absorption. By combining our nonlinear refraction and two-photon absorption measurements, we will discuss the merits of TiO2 for all-optical processing.

Conference 8241: High-Power Diode Laser Technology and Applications X

Sunday-Tuesday 22-24 January 2012

Part of Proceedings of SPIE Vol. 8241 High-Power Diode Laser Technology and Applications X

8241-01, Session 1

kW-class direct diode lasers with comparable brightness to fiber, disk, and carbon dioxide lasers

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Direct diode lasers have traditionally had poor beam quality, preventing them from being used in demanding applications including industrial cutting and welding of thick sheet metal, and high performance military applications. TeraDiode, Inc. has developed direct diode lasers with the same brightness level as industrial fiber lasers, bulk solid state lasers (thin disk and rod), and carbon dioxide lasers. Using wavelength beam combination, TeraDiode has demonstrated a fiber-coupled direct diode laser with a power level of 940 W from a 50 µm core diameter, 0.14 numerical aperture (NA) output fiber. This kW-class laser, with a Beam Parameter Product (BPP) of 3.5 mm-mrad, has demonstrated substantially higher brightness than other previously demonstrated fiber coupled, direct diode lasers. Extension of this direct-diode laser technology to higher performance will also be discussed. In addition, the direct diode technology is inherently wavelength selectable and can be applied to brightness scaling of diode lasers of any wavelength of interest for defense applications. Currently we are scaling the system to higher power and brightness levels.

8241-02, Session 1

A 13-kW fiber-coupled diode laser for pumping applications

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New laser architectures require higher and higher pump powers. In this paper we report about the development of a new fiber-coupled diode laser capable of generating 13 kW from a fiber with 2 mm diameter and 0.22 NA (220 mm mrad). While this is a standard brightness for wavelength combined diode lasers used in material processing, a special beam transformation technique had to be developed to achieve these specifications at a single wavelength to serve as disk or fiber laser pumps.

Previous beam transformation techniques have been described that improve the efficiency of coupling a diode stack into a fiber. In the present work this beam transformation technique has been enhanced. After fast axis collimation and a beam reformatting a beam with a beam parameter product of 200 and 40 mm.mrad in the slow and fast-axis respectively is generated.

To obtain 13kW at 938 nm the output of four modules were polarization multiplexed to form two vertically and horizontally offset beams. After the slow-axis collimator, SAC, a fast-axis compressor reduced the fast-axis dimension by a factor of two. The two spatially offset beams were stacked by 45° mirrors and focused to the fiber coupling point.

The system was based on a turn-key industrial platform, allowing straight-forward integration into any laboratory pump application. The complete system has a footprint of less than 1 m2 and a height of less than 1.8 m. The diodes are actively cooled, have a wall-plug efficiency of up to 43%, and have proven lifetimes of typically >30,000 hours.

8241-03, Session 1

High brightness fibre coupled diode lasers of up to 4-kW output power for material processing

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Recent developments of high brightness laser diodes combined with diffraction limited beam shaping by refractive micro lenses lead to a new class of fibre coupled diode lasers whose beam parameters are more and more competitive to other lasers conventionally used in material processing, in the majority of cases in cutting or welding processes.

Direct diode lasers have the potential to be most efficient in comparison to other laser approaches since it works without a brightness converter as a key component.

To demonstrate the benefits of diode lasers in the kW power range, concepts, data of laser characterization as well as application results are presented for a system of 2000W out of a 200µm fibre with NA 0.2. The resulting power density of 6.4 MW/cm² and the excellent beam parameter product of 20mm·mrad allow high quality edges for cutting sheets of metal of up to 10mm thickness. Cutting samples of various materials from steel to aluminium alloys were fabricated with high cutting velocity.

As a subsequent step, concepts with further increased brightness and power in the multi-kW range are evaluated, e.g. for 4kW in 200µm NA 0.2. With high electro-optical efficiency of up to 40%, direct diode lasers are going to clear the way to multiple cutting and welding processes and beat the operating costs of conventional lasers.

8241-04, Session 1

kW-class line sources for direct applications

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A new series of high power diode laser line sources is reported on. The modules are designed for the industrial materials processing market and include both fiber coupled and direct beam configurations. Typical applications include welding, hardening and semiconductor processing. The biggest challenge in delivering line sources lies in the variety of application specific requirements. This problem is approached with modular concepts that allow for power scaling and custom beam shaping. All modules are available either as an OEM laser head or as a turn-key solution including power supply and chiller.

Fiber coupled diode laser modules are available at power levels ranging from 600W to 4kW at various wavelengths. New developments include a 1kW module with a single wavelength and 400um / 0.22NA fiber and a 2kW module based on two wavelengths. Up to 4kW has been achieved from a 1mm / 0.22NA fiber with a single wavelength. At 200um fiber diameter, power levels of 700W are available.

While fiber coupled modules allow for easy power scaling, free space systems are capable of even higher overall electro optical efficiencies and lower cost. Based on modular building blocks Dilas provides customized solutions that are optimized for individual applications. Two modules will be described in detail. The first module is a 600W line source with line dimensions of 10.5mm x 150um at a working distance of 160mm. The second module operates at 3kW output power and creates a homogenized line with dimensions of 9mm x 1.5mm at a working distance of 200mm.

Optical design trade-offs will be discussed and concepts for the modules described above will be shown. Experimental results will be presented.

8241-05, Session 1

3000-W CW diode laser cladding system

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Based on polarization multiplexing, the beam shaping method and optical design for kilowatts class diode laser system were introduced in this paper. A 3000W laser cladding system is designed and two 976nm diode laser stacks with 20 diode laser bars are used in this system, of which the total power is 4000W with 100W / bar at 80A. According to the design, the theoretical beam size of 90% maximun is approximately 2mm*9mm and the intensity distribution is a symmetrical rectangle at the work face. The actual laser head was made, and it has a small volume of 340mm*180mm*138mm and a light weight below 15kg. The performances of the laser system were tested at 25°C. When the current and voltage were set to 70A, the power on the working face was 3580W with optical transform efficient 96%. And the actual beam size on work plane agrees well with the theoretical value.

The collimated beam pointing error is the main problem to achieve satisfying beam quality on output facet. There are two types of collimation beam point error proposed. Two reasons for the pointing error have been found and the solved methods have been also proposed. The detail will be presented in full manuscript, and the beam pointing error is successfully corrected, and the value of parameter δ is below 0.1 degree, ΔD and b can be almost ignored.

The laser cladding system is composed of laser processing platform, power system and cooler device. The simple laser processing platform, which includes laser source and auto moving platform, is built. The cladding application tests showed that nickel powder was cladded onto steel plate uniformly.

8241-06, Session 2

Emission properties of diode laser bars during pulsed high-power operation

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Many applications require pulsed operation with pulse durations in the µs-ms range. Furthermore, in this regime, there should be a chance to pump at elevated output powers compared to the values specified for safe continuous wave operation. This again should lead to more economic system designs, e.g., by reducing the number of required pump diodes in a given system. Therefore, the emission characteristics of bars (such as the nearfields) as well as the thermal behavior in this operation mode are of particular interest.

We analyze a set of 808 nm emitting high power diode laser bars. They are based on a standard commercial Al-free active area 808 nm emitting InGaP/AlGaAs-based quantum well structure. The bars are subjected to single pulse step tests carried out up to and beyond their ultimate operation power limits. Emission and thermal behavior is monitored by streak- (time resolution ~20 ns) and thermo-cameras (time resolution ~10 µs), respectively.

The final phase of the step test allows the in-situ observation of the catastrophic optical damage (COD) effect. During such experiments, we never identify any typical location at the bars to be preferential for COD appearance. Furthermore, we find absolute perfect agreement between the location of COD signatures observed by transient emission and thermocamera measurements on the one side, and optical inspection of the degraded bars on the other side. COD thresholds are determined and the observed dependence on the pulse length is qualitatively explained.

This approach allows for testing the hardness of facet coatings on a cm-bar level with or without consideration of accidental single pre-damaged emitter failure effects and thermal crosstalk between the emitters. This knowledge allows for optimization of pulsed operation parameters, helps embanking sudden degradation, and provides insight into the mechanisms governing the emission behavior at ultimate output powers.

8241-08, Session 2

High performance diode lasers emitting at 780-820 nm

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High Power 780-820nm Diode Lasers have been developed for pumping and material processing systems. This paper presents recent progress in the development of 780-820nm high power laser diodes for reliable use in high performance applications. A newly released laser design in this wavelength range demonstrates thermally limited 25W CW power without catastrophic optical mirror damage (COMD), with peak wallplug efficiency >65%, at 10°C heatsink temperature. Ongoing accelerated lifetesting supports 100W reliable operation, with improved efficiency.

8241-09, Session 2

High power single emitters for fiber coupled diode packages

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The increasing demand for higher brightness sources has driven the development of new class of diode packages. These packages are based on coupling the output power of one or several single emitters into a single 105 micron core fiber. Today these are the preferable pumping sources for fiber lasers. In this paper we report the recent advances in the reliability and output power from 90 µm single emitters in the 9xx nm spectral range. By the use of longer cavities and low loss gain material for single emitter fabrication, we have achieved output power as high as 20 W. Reliability data of these emitters at optical power ~14 W will be presented. The advances in single emitter output power, beam properties and packaging combining methods are used for multi emitter packages to achieve more than 50 W ex-fiber optical power from 105 micron/0.15 NA. These fiber coupled packages will improve the brightness by a factor larger than 10 in the nearest future.

8241-47, Session 2

Scalable high-power and high-brightness fiber coupled diode laser devices

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The demand for high-power and high-brightness fiber coupled diode laser devices is mainly driven by applications for solid-state laser pumping and materials processing. The ongoing power scaling of fiber lasers requires scalable fiber-coupled diode laser devices with increased power and brightness. For applications in materials processing multi-kW output power with beam quality of about 30 mm x mrad is needed.

We have developed a modular diode laser concept combining high power, high brightness, wavelength stabilization and optionally low weight, which becomes more and more important for a multitude of applications. In particular the defense technology requires robust but lightweight high-power diode laser sources with high brightness.

Heart of the concept is a specially tailored diode laser bar, which epitaxial and lateral structure is designed such that only standard fast- and slow-axis collimator lenses are required to couple the beam into a 200 µm fiber with numerical aperture (NA) of 0.22. The spectral quality which is an important issue especially for fiber laser pump soruces is ensured by means of volume holographic gratings for wavelength stabilization.

In this paper we present a detailed characterization of different diode laser sources based on the scalable modular concept. The optical output power is scaled from 175 W coupled into a 100 µm, NA 0.22 fiber up to 2 kW coupled into a 200 µm NA 0.22 fiber.

8241-10, Session 3

Modular VCSEL solution for uniform line illumination in the kW range

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High power VCSEL arrays can be used as a versatile illumination and heating source. They are widely scalable in power and offer a robust and economic solution for many new applications with moderate brightness requirements. The use of VCSEL arrays for high power laser diode applications enables multiple benefits: Full wafer level production of VCSELs including the combination with micro-optics; assembly technologies allowing large synergy with LED assembly thus profiting from the fast development in solid state lighting; an outstanding reliability and a modular approach on all levels. A high power VCSEL array module for a very uniform line illumination will be described in detail which offers 150W/cm optical output and enables less than 1% non-uniformities per mm along the line. The applied optical principle of near field imaging and massive superpositioning of many thousand VCSELs by arrays of micro-lenses gives perfect control over the intensity distribution and is inherently robust. A specific array of parallelogram shaped VCSELs has been developed in combination with an appropriate micro-lens design and an alignment strategy. The concept uses parallel and serial connection of VCSEL arrays on submounts on water coolers in order to realise a good compromise between moderate operating currents and reliability. Lines of any desired length can be built from modules of 1cm length because this optical concept allows large mounting tolerances between individual modules. Therefore the concept is scalable for a wide range of applications.

8241-11, Session 3

High reliability 20-KW QCW area array diode laser

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With the increased applications of high power semiconductor lasers in industrial, advanced manufacturing, aerospace, medical systems etc, higher power, higher reliability and higher brightness semiconductor lasers are required. For specific applications such as pumping high power solid state laser, higher power semiconductor lasers with peak output power of tens kilowatts (KW) level operating at quasi-continuous wave (QCW) mode are demanded. Scale-up of the output power from kW to tens kW, it is common to assemble the several stacks which are assembled by multiple laser bars together and form an area array laser. Laser stacks with power of KW level were common packaged using conduction cooled G-stack technology and water cooled copper micro-channel cooler (MCC) technology. For G-Stack laser, although the higher output peak power can be obtained, it only operates at lower duty cycle (commonly less than 2%) due to its heat dissipation limitation. For QCW laser, the output peak power is higher, but average power is low. Therefore, the transient thermal density is very high. For commercially-available water cooled copper micro-channel coolers (MCC), the heat dissipation capability is more than that of G-stack, however, due to the coefficient of thermal expansion (CTE) mismatching between copper and laser chip, hard-solder cannot be directly used. Most of MCC-based laser were packaged using the conventional indium soldering technology. For indium soldering, it has the problem of electro-thermal migration when the temperature grades were high in QCW mode. Furthermore, copper is susceptible to erosion and corrosion. To overcome these drawbacks and reach higher peak output power at high duty cycle without reliability decrease, a novel macro channel cooler (MaCC) for area array laser which has both good heat dissipation and high reliability was presented in this work.

In this paper, a novel macro channel cooler (MaCC) was designed and optimized, and a high power 20KW QCW Indium-free area array laser was fabricated. The basic unit of the area array laser with peak power of multi-tens of kilowatts is MaCC. The MaCC has advantages of low thermal resistance, and it is not easily corroded and maintenance easy. A series of transient thermal behaviors of high power MaCC-packaged semiconductor laser array at QCW mode were simulated using finite element analysis (FEA). Based on the water cooled MaCC-packaged laser stack, a 2*40 bars area array laser was fabricated. The high output power over 20kW and slope efficiency of 98.61 W/A at 240 amps were obtained at 5% duty cycle (100Hz, 500μs).

The major challenges in area array laser packaging are the spectrum control and beam control. In this work, we used advanced packaging process to maintain temperature distribution uniform, which can control the spectrum broadening effectively. The full width at half maximum (FWHM) spectrum width is only 3.94nm, and 90% energy width is 5.45 nm.

Beam control includes beam size, light spot uniformity and directivity control. During the packaging process, advanced real-time monitoring equipment and advanced beam shaping process were used to ensure accurate positioning of each bar. It was found that the output light spot of each bar was very uniform and the directivity was excellent.

The lifetime test curve in Figure 7 exhibits that the power of the MaCC-packaged area array laser is still stable after working 7.2×E8 shots, which indicates a good reliability. The lifetime test is still ongoing for these devices.

8241-12, Session 3

Automated alignment of optical components for high-power diode lasers

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The assembly of beam shaping optics such as fast axis collimators (FAC) for high-power diode lasers (HPDL) and the assembly of resonator mirrors in diode-pumped solid state lasers (DPSS) require high resolution movements in up to six degrees-of-freedom. This publication presents an approach towards flexible automation of such alignment processes. The presented solution is based on a flexure-based micromanipulator attached to a Cartesian manipulator with large workspace.

For automated FAC alignment the measuring equipment consists of two CCD cameras used either for passive image-based pre-alignment or for an active beam profiling.

The beam profiling of the diode bar requires a special combination of lenses to achieve a correct visualization of all the emitters at the CCD, the resulting image allows to indirectly evaluate the magnitude of the misalignment of the FAC. At the end of the alignment relevant information related to the quality of the FAC lens itself and to the quality of the alignment is obtained, such as the shape of "the smile" and the collimation achieved at each emitter of the diode bar.

The active algorithm and the assembly process itself are parametrizable allowing to adapt them to a number of diode laser bars and FAC configurations. The assembly process was extensively tested and optimized for alignment times of less than one minute.

Concluding, it will be shown that the use of the ultra-precise micromanipulator attached to a large workspace unit allows to easily reconfigure the system for other assembly tasks, e.g. the resonator alignment in DPSS.

8241-13, Session 3

Operating condition limitations of high density QCW arrays

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Northrop Grumman Cutting Edge Optronics has developed a laser diode array package with minimal bar-to-bar spacing. These High Density Stack (HDS) packages allow for a power density increase on the order of ~ 2.5x when compared to industry-standard arrays. Power densities as high as 15 kW/cm2 can be achieved when operated at 200 W/bar.

This work provides a detailed description of the duty factor, pulse width and power limitations of high density arrays. Previously, the absence of the interposing heatsinks meant that all of the heat generated by the interior bars must travel through the adjacent bars to the electrical contacts. This results in limitations to the allowable operating envelope of the HDS arrays. Thermal effects such as wavelength shifts across large HDS arrays are discussed.

An overview of recent HDS design and manufacturing improvements is also presented. These improvements result in reliable operation at higher power densities and increased duty factors. A comparison of the effect of bar geometry (including fill factor and cavity length) and T0 (characteristic temperature for the variation in threshold current) on HDS performance is provided. Test data from arrays featuring these improvements based on both full 1-cm long diode bars as well as 3cm x 3cm arrays based on mini-bars is also presented.

8241-14, Session 3

Long pulse compact and high brightness near 1-kW QCW diode laser stack

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Next generation novel solid state laser systems require both high brightness, high duty cycle (>10%) as well as pulse widths that are both longer (~msec) and variable for the generation of sequential wavelength switching operation from a single solid state crystal material. Implementation into user friendly systems require that they be compact for ease of integration, especially for hand held type systems. Compact diode-pumped Er-doped laser systems are of particular interest for medical applications because they can deliver powerful laser radiation directly from a handheld device used by the physician without the need or the cost implied by using of still less robust IR-fibers.

A custom designed compact, high brightness diode laser array stack was internally manufactured using proprietary methods that are robust and suitable for low cost manufacturing. The diode laser stack consisted of four 10mm-wide diode laser bars having lasing wavelength of 970nm mounted onto high performance submounts separated by approximately 1mm. Each diode laser bar had a 50% fill factor. The cooling methodology employed used a combined passive and active scheme and not the traditional more expensive and more complicated standard micro-channel coolers used for high duty cycle applications. The diode was operated under long current pulses (>1mS) and high duty cycle (>10%). The total combined optical power attained from the diode array stack was close to 1kW for current levels up to 220A, limited only by the capability of the power supply.

In this paper, we provide a brief review of the design and then summarize the performance results for this diode laser array and analyze the maximum expected optical performance as a function of operating current and pulse width.

8241-15, Session 3

Record-brightness laser-diode bars for fiber coupling

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High-power laser diode (LD) bars are used to optically pump solid-state lasers. In the absence of optical requirements, the highest optical power and reliability are achieved with the highest fill factor bars. In addition to high-power, high brightness is required in direct-diode applications and for pumping fiber lasers where the optical power is coupled into a fiber. Attempts to couple high fill-factor LD-bars into a small-core fiber will generally result in inefficient coupling and damage to the fiber, therefore low fill-factor laser-diode bars, e.g. 20%, are required for efficient coupling into small-core optical-fiber.

We achieved record brightness using 20% fill-factor, 980nm, 1cm-wide, 4mm cavity-length bars with 20°C coolant temperature. The bars fail by catastrophic optical damage at ~350W. No failure was observed in a single bar operated at 200W during a 1000hr life test. Life testing of 3-bar stacks indicates similar power/lifetime results. The slope efficiency of the bars is 1.17 W/A and the peak power conversion efficiency (PCE) is 65% at 100A. The PCE decreases to 61% at 200A. Using these single bars and 3-bar stacks, more than 75% coupling efficiency is expected into a 200µm core, 0.22NA fiber.

The remarkable performance of the single bar and 3-bar stack was in part the result of a novel EPIC (Enhanced Performance Impingement Cooler) heat-sink which has the lowest reported thermal resistance (60mK/W), ~2X better than the state-of-the-art micro-channel coolers, and a heat removal capacity exceeding 2kW/cm2.

8241-16, Session 3

High power semiconductor laser array packaged on micro-channel cooler using gold-tin soldering technology

J. Wang, Xi'an Focuslight Technologies Co., Ltd. (China)

High power semiconductor laser arrays have been widely used in many fields, such as industry, scientific research, medical therapy etc. As the improvement of device technology and the increase of optical output power, laser diode bars packaged on microchannel cooler (MCC) with hundreds of watts of CW output power have been commercially available.To avoid the drawbacks of copper MCC-packaged high power diode bar and meet the high output power and to enhance the reliability, developing hard soldering technology based on MCC actively cooled laser diode bar becomes a trend.

In this work, a hard soldering MCC (HSMCC) technology was developed for packaging high power diode laser bars. Numerical simulations on the effects of different submount materials on the thermal behavior and thermal stress of Hard soldering MCC (HSMCC) packaged diode laser array were conducted and analyzed.

Based on the simulation results, the device structure and submount materials of HSMCC packaged diode laser array were optimized.

A series of high power HSMCC packaged diode laser array were fabricated and characterized. For a typical 80W 976nm laser bar with 2-mm cavity length and 50% fill factor, using HSMCC packaging technology, the output power of 185W at CW mode and 331W at QCW mode was obtained, respectively. The measurement results indicated that the HSMCC packaged laser bar has lower smile and narrow spectrum in comparison with the conventional copper MCC packaged laser bar using indium soldering technology. More importantly, reliability of high power diode laser arrays is improved significantly.

8241-17, Session 3

Newly developed high power laser diode bars

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High power laser diodes have recently gained considerable interest for a number of industrial applications, particularly materials processing. To achieve such high power laser output, we would have mostly two options; single-emitter arrays or laser diode bars. Different from individually aligned single-emitters, the laser diode bars could provide significant cost and size advantages for laser systems.

In this paper, we report on recently developed high power laser diodes based on 1-cm bars. The laser diodes feature an optimal structure design for efficient operation at the high power output. The inner structure of water-cooled heat sink has been designed for excellent thermal performance as well as stable water flow. A low smile, which is defined as a slight bend of the horizontal line connecting the emitters in laser array, is also important characteristic to realize the efficient laser systems. So we have developed a thermal-expansion-controlled assembly technology to improve the smile. We will present a detailed characterization of the 940 nm laser diode bars CW-operated at a high power of 200 W with a low smile of ~1 µm.

8241-18, Session 3

10-W CW blue-violet laser diode array on the micro-channel cooler

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There is increasing interest in the realization of high optical power blue-violet laser source for material processing (e.g. crystallization of amorphous silicon), optical displays, solid state laser pumping and other applications. Multi-emitter laser diode (LD) array is promising solution to obtain high optical output power. To overcome the limitation of heat dissipation of conventional packaging, we tried to mount multi-emitter 405 nm LD array on micro-channel coolers (MCCs). After consideration on heat dissipation and mounting handiness, the LD arrays were directly mounted on the CTE (coefficient of thermal expansion) controlled MCCs using AuSn hard solder. Under continuous wave (CW) operation, we achieved over 10 W output with 10 emitter LD array, representing the highest reported output power for a blue-violet laser source. Moreover, from steady thermal analysis using finite element method, we found the direct-mounted LD array basically has a flat-shaped transverse temperature distribution across the array. In contrast, the convex-shaped distribution was obtained in the case of using highly thermal conductive sub-mounts, such as diamond-composite, between the array and MCCs. The local temperature rise in the center emitter of the direct-mounted laser array was suppressed due to their relatively shorter heat transfer paths. The flat-shaped temperature distribution has contributed to high optical output power.

8241-19, Session 4

Wavelength-stabilized fiber-coupled diode laser module with >500-W output and 20-mm x mrad beam quality

D. M. Grasso, N. Shou, H. Chen, R. Pathak, P. Liang, Coherent, Inc. (United States); S. Roh, LG Innotek (Korea, Republic of); D. Lee, Coherent, Inc. (United States)

We report the development of a fiber-coupled diode laser module with high spatial and spectral brightness. Four arrays of diode laser bars are multiplexed using polarization and narrow-band wavelength combination. The module achieves > 500 W of output power from a 200 micrometer, 0.2 NA fiber. The output spectrum, composed of contributions from more than 150 emitters, is narrowed using VBGs and has nearly 100% content within +/- 1 nm of 975 nm at full power. We will also discuss ongoing work to pump an active Yb-doped fiber.

8241-20, Session 4

Very high brightness diode laser

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Single emitter based diode laser modules allow highest brightness with 75 W from a 100 µm fiber 0.15 NA are now available. Single emitter modules eliminate the loss of brightness associated with smile of a mounted diode bar and optical elements required for symmetrizing the beam divergence of bars. Spectral combining of laser modules with offset wavelengths can be deployed for further brightness scaling. External surface gratings, typically in Littrow design, allow narrow band emission at specific wavelengths and dense spectral combining, but result in bulky and alignment sensitive devices.

We present single emitter modules stabilized to very narrow linewidth using Volume Bragg Gratings (VBG) and subsequent spectral combining via VBGs and dichroic multilayer dielectric mirrors. Compact set-ups are realized combining three modules with offset wavelengths within the 5 nm wide absorption peak of fiber lasers at 976 nm. Power exceeding 250 W is obtained from a 100 µm fiber 0.15NA.

VBG's reflectivity that determines feedback in the diode laser is optimized for low power losses and for wide temperature range of spectral locking and narrowing. A compact single emitter module with external VBG cavity was designed and cost effective methods for module manufacturing were developed. Spectral beam combining was performed using reflecting VBGs and steep edge dichroic mirrors for 1 and 2.5 nm channel spacing, respectively. Performance characteristics and designs for both approaches are reported and the scalability to kilowatt power levels is discussed.

8241-21, Session 4

VBG controlled narrow bandwidth diode laser arrays

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Northrop Grumman Cutting Edge Optronics has developed large kilowatt class lensed laser diode arrays with sub-nanometer spectral width using volume Bragg grating (VBG) reflectors. Using these CW arrays with 100W bars at 885nm, excellent absorption in Nd:YAG is achieved, with lower thermal aberration than can be attained with 808nm pumps. The additional cost of the VBG reflectors and their alignment is partially offset by the much broader wavelength tolerance that is allowed in the unlocked array enhancing bar yield. Furthermore, the center wavelength of the arrays exhibit lower temperature sensitivity allowing the arrays to be operated over a wider current or temperature range than arrays without wavelength control. While there is an efficiency penalty associated with the addition of VBGs of 5-8%, it is more than compensated for by enhanced absorption, especially when used with narrowband absorption lines, such as 885nm in Nd:YAG. An overview of the design and manufacturing issues for arrays that are wavelength locked with VBGs is also presented.

New results promise that even tighter wavelength control may be possible. After the array is built, additional processing to the VBG glass can tune the center wavelength a few tenths of a nanometer without affecting power. Such extraordinary control could open up the use of VBGs for pumping alkali lasers and other applications were 0.1 nm control of the center wavelength is needed.

8241-22, Session 4

10-W Reliable 100-µm wide broad area lasers with internal grating stabilization

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Broad area (BA) diode lasers with narrow, temperature-stable spectral lines are required for pumping narrow spectral lines in solid state lasers and for dense spectral multiplexing in direct applications. Two device technologies in particular have reached a high performance level, based on development work at the Ferdinand-Braun-Institute. Firstly, etched surface gratings can be used to form the rear facet reflector, in distributed Bragg-reflector (DBR) format. Secondly, gratings can be buried within the semiconductor using etch and overgrowth technology, to form distributed feedback (DFB) lasers. In this case, the rear facet has a high reflectivity coating, and the DFB operates effectively as the low reflectivity out-coupler. For both technologies, BA diode lasers with 90-100µm stripes operating at 975nm deliver peak continuous wave (CW) powers of over 12W within a spectral width of < 1nm (with 95% power content). Recently, reliable operation has been confirmed for CW powers of 10W, and power conversion efficiency of 63% has been demonstrated. However, the two technologies have different strengths. For example, DBR-BA lasers have low sensitivity to external feedback and are insensitive to the onset of spectral side-modes. In contrast, DFB-BA lasers achieve the highest reported power conversion efficiencies. A comparison of the relative merits of the two technologies for different high power laser applications will be presented, and options for further performance improvement will be discussed.

The German Federal Ministry of Education and Research (BMBF) funded this work as part of the SpektraLAS and HemiLas programs (FKZ: 13N9730 and 13N9578).

8241-23, Session 4

High brightness 975-nm pumps with ultra-stable wavelength stabilization

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We report on high-brightness wavelength stabilized CW devices optimized for air-cooled applications. Performance of pumps rated for 100W and 50W is discussed. Optimized pumps launch over 95% output power into spectral window of 975±0.5nm with current increase from 2A to 12A and the heatsink temperature variation from 25°C to 55°C. Such performance qualifies these wavelength-stabilized pumps for use in many air-cooled applications.

8241-24, Session 4

High-peak-power and high-brightness pulsed single and array diode laser sources

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Surface-emitting distributed feedback (SE-DFB) diode lasers possess many advantages compared to edge-emitting high power Fabry-Perot diode lasers. Some of these attributes include higher output power per device, higher spectral and spatial brightness, higher facet damage threshold, and lower thermal drift with temperature[1]. Since the output power is extracted from the surface rather than the facet, optical power density at the output is three orders of magnitude lower compared to edge-emitting diode lasers. As a result, much higher peak power can be extracted from SE-DFB lasers.

We have demonstrated 300 W of peak power (1µs, 100Hz) from a single 97x nm SE-DFB diode laser with an electrically-pumped stripe area of 3.75 mm^2 corresponding to 80 W mm^-2 of power density. This result is limited by the available current supply. The laser beam is nearly collimated in one direction with a 4 mrad full-width divergence and has a 10° at full-width in the orthogonal direction. On a smaller device with a stripe area of 0.18 mm^2, peak power of 68 W has been achieved corresponding to power density of 377 W mm^-2 and with slope efficiency of 1.1 W/A. Power scaling is achievable with one or two dimensional arrays of SE-DFB lasers and we will report on both the high peak power SE-DFB lasers and fiber-coupled arrays.

References:

[1] M. Kanskar and F. Brunet, “Novel grating boosts brightness,” Compound Semiconductor, June 2009.

8241-25, Session 5

High-power diode laser pumps for alkali lasers (DPALs)

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Diode pumped alkali vapor lasers (DPALs) have the potential to achieve high power at near-infrared wavelengths: cesium 895 nm, rubidium 795 nm, and potassium 770nm. They combine the advantages of semiconductor laser diodes such as high power and efficient operation with those of gas lasers as for example high beam quality or the absence of stress birefringence. Furthermore, the aperture (transverse dimension) of gas lasers can be scaled readily. These systems create a laser that is compact and efficient, while working well at high temperatures and high powers.

We present performance data of recent high-power laser diodes emitting at typical pump wavelengths for DPALs: 766 nm for potassium, 780 nm for rubidium, and 852 nm for cesium atoms. Due to different approaches in alkali laser systems, we report on usual pumps at these non-standard wavelengths with typical line widths of a few nm used for collisional and pressure broadened gas absorption lines as well as on wavelength stabilized laser diodes using volume Bragg gratings (VBGs) for systems with narrow gas absorption lines. The detailed characterization of laser diodes available at DILAS includes power, efficiency, spectral data, and life time results.

While bars at 7xx nm are limited in optical output power due to the strong in-built strain, especially the bars at 852 nm with a small in-built strain have the biggest potential in terms of pump power. The power conversion efficiency in cw operation is as high as 60% at 100W. Higher power and operation at increased heat sink temperatures up to 50°C are possible depending on lifetime requirements.

8241-26, Session 5

High efficiency high brightness diode lasers at 1470 nm/1550 nm for medical and defense applications

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We report on significant advancements of the state of the art for InP diode lasers in the 1400 to 1550nm range. We demonstrate new record-breaking performance from both narrow stripe single emitters and high brightness fiber-coupled modules.

Specifically, we will present a compact, conduction-cooled fiber-coupled module producing 200W CW from a Medical-grade 550µm/0.22NA fiber at 1470nm, which represents twice the power available only two years ago in the same package. We will also discuss the performance of a high brightness fiber-coupled module at 1532nm, reaching 25W from a 100um/0.15NA fiber with on-chip wavelength stabilized laser diodes to enable kW-class 1550nm fiber laser.

Significant performance improvement of single emitters from 1440nm to 1550nm is also demonstrated. We will discuss a modified epitaxial design of our InP structure producing CW power in excess of 4W CW at 8A and 40ºC from a single 100µm wide stripe emitter. A similar structure is employed at 1550nm to achieve peak power greater than 20W from 100µm wide stripe, over twice the highest brightness reported so far from a similar stripe width.

Finally, we report on ongoing efforts funded by US government agencies to improve performance at elevated temperature, demonstrating 20% E/O efficiency of single emitters at extreme temperature up to 80ºC.

Optical and electrical performance of the new generation devices will be discussed in details as well as existing and emerging applications in consumer healthcare, fiber laser pumping, surgery, rangefinder, and low speckle SWIR illumination.

8241-27, Session 5

Slab-coupled optical waveguide lasers and amplifiers

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Slab-coupled optical waveguide lasers (SCOWLs) and amplifiers (SCOWAs) are inherently low-confinement structures with large nearly-circular modes that are easily coupled to optical fibers or collimated for free-space applications. We have previously reported 2 W of CW power from single-mode SCOWLs emitting at 1060 nm. Recently we have increased this power to 3 W by increasing the cavity length to 1 cm and improving the heat removal with junction-down bonding to a micro-impingement cooler. At the maximum output power the devices fail catastrophically but the majority of the devices do not show signs of facet failure, indicating a bulk effect is the dominant failure mechanism. At high powers the laser efficiency is limited by the series resistance which also heats the junction. Work is ongoing to lower the series resistance to improve the laser efficiency at high powers and thereby increase the output power further. SCOWAs configured in a master-oscillator-power-amplifier (MOPA) are coherently combined to achieve a very high-brightness source. SCOWAs can be phase modulated by simply using the amplifier current to modulate the phase of each element, with typical two-pi phase currents of 150 mA. Our previous laser-diode coherent-beam combination demonstration of nearly 40 W with 218 amplifiers utilized double-pass SCOWAs that limited the output power per element due to instabilities related to facet feedback. To overcome this limitation, the coherent combining system has been redesigned for single-pass amplifiers using angled-facet SCOWAs that suppress feedback. Single-pass, 5-mm long, SCOWAs have now been demonstrated with 1.5 W CW output with only 50 mW seed power.

8241-28, Session 5

High power broad-area diode lasers optimized for fiber laser pumping

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In diode laser applications for fibre laser pumping high brightness becomes important in the last years. So fibre coupled modules benefit from continuous improvement of broad-area (BA) lasers on chip level regarding output power, efficiency and beam

characteristics resulting in high-brightness.

To achieve high brightness not only output power must be increased, but also far field angles have to be below a certain value for higher power levels because brightness is proportional to output power divided by beam quality.

Typically fast axis far fields show a current independent behaviour, whereas for broad-area lasers far-fields in the slow axis suffer from a strong current and temperature dependence, limiting the brightness. These limitations can be overcome by carefully optimizing epitaxial design and processing and also thermal management of the mounted device. The easiest way to achieve a good thermal management of BA-Lasers is to increase resonator length while simultaneously decreasing internal losses of the epitaxy structure.

We have realized MBE grown InGaAs/AlGaAs broad-area lasers with resonator lengths of 4-6mm emitting at 976nm. For a 4mm long BA-laser with 90µm stripe width a beam parameter product of less than 5.9mm x mrad has been achieved at 10W with a slope efficiency of 1.1W/A and a maximum wall-plug efficiency of 67%. With a 6mm long resonator with adapted epitaxial design an increase of more than 30% in brightness could be demonstrated in comparison to 4mm long devices at same operation current. From these designs also mini-bars consisting of 5 emitters have been realized.

8241-29, Session 6

Progress in increasing the maximum achievable output power of broad area diode lasers

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High power broad area diode lasers provide the optical energy for all high performance laser systems, either directly or as pump sources for solid-state lasers. Continuous improvement is required in the peak achievable output power of these diode laser devices in order to enable performance improvements in full laser systems. In recent years, device technology has advanced to the point where the main limit to optical power is no longer device failure, but is instead power saturation due to various physical effects within the semiconductor device itself. For example, the combination of large optical cavity designs with advanced facet passivation means that facet failure is no longer the dominant limiting factor. Increases in the optical power therefore require firstly a clear identification of the limiting mechanisms, followed by design changes and material improvements to address these. Recent theoretical and experimental diagnostic studies at the Ferdinand-Braun-Institute have helped trace the saturation effects to three main effects: gain saturation, longitudinal hole burning and current driven carrier leakage. Design changes based on these studies have enabled increases in the achievable emitted power density from broad area lasers. Recent experimental examples include 100W from 100µm stripes under short-pulsed conditions, > 30W from 100µm stripes under quasi-continuous wave conditions and > 10W from 30µm stripes under continuous wave conditions. An overview of the results of the diagnostic studies performed at the FBH will be presented, and the necessary design changes to address the observed power saturation will be discussed.

8241-30, Session 6

Compact sources for the generation of high-peak power wavelength-stabilized laser pulses in the picoseconds and nanoseconds ranges

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Diode lasers are ideally suited for the generation of optical pulses in the nanoseconds and picoseconds ranges by gain-switching, Q-switching or mode-locking. We have developed diode-laser based light sources where the pulses are spectrally stabilized and nearly-diffraction limited required by many applications. Diffraction limited emission is achieved by a several microns wide ridge waveguide (RW), so that only the fundamental lateral mode should lase. Spectral stabilization is realized with a Bragg grating integrated into the semiconductor chip, resulting in distributed feedback (DFB) or distributed Bragg reflector (DBR) lasers. We obtained a peak power of 2.6W for 4ns long pulses using a gain-switched DFB laser and a peak power of more than 4W for 65ps long pulses using a three-section DBR laser. Higher peak powers of several tens of Watts can be reached by an amplification of the pulses with semiconductor optical amplifiers, which can be either monolithically or hybrid integrated with the master oscillators. We developed compact modules with a footprint of 4x5cm2 combining master oscillator, tapered power amplifier, beam-shaping optical elements and high-frequency electronics. In order to diminish the generation of amplified spontaneous emission between the pulses, the amplifier is modulated with short-pulses of high amplitude, too. Beyond the amplifier, we obtained a peak power of more than 10W for 4ns long pulses, a peak power of about 40W for 80ps long pulses and a peak power of 70W for 10ps long pulses at emission wavelengths around 1064nm.

8241-31, Session 6

High efficiency kW-class semiconductor laser bars with passive cooling

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We present our recent efforts to improve power rating, efficiency, reliability and cost of semiconductor laser bars in the 8xx nm wavelength band. KW-class laser bars are grown by metal-organic chemical vapor deposition (MOCVD), and are cleaved, passivated, coated, and die bonded onto either standard copper CS-style heat sinks using indium solder, or onto expansion matched CuW CS heat sinks using hard solder. In an effort to realize the high power operation, nLIGHT's current high efficiency 880-nm epitaxial designs have been adjusted and optimized. Bars of varying fill factors, cavity lengths, and facet coating reflectivities are explored to improve the rated electrical to optical (E-O) efficiency up to approximately 70% under low duty cycle QCW operations. The enhanced E-O efficiency makes possible not only the passive cooling of the devices, but also the reliable operation in the kW power range. We demonstrate that the semiconductor laser bars can survive over 100 million laser shots working in the QCW mode. It is expected that the development of these passively cooled, highly efficient and highly reliable kW-class semiconductor laser bars will enable commercial applications, especially in the area of defense as well as the consumer markets which need convenient high-power laser energy.

8241-32, Session 6

Extremely low losses 14xx single mode laser diode leading to 550-mW output power module with 0-75°C case temperature and 10-W consumption

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High power 14xx laser pumps are more and more required for eye safe industrial, medical, safety and defense applications as well as for increased telecom network capability (e.g. for 100 Gb Ethernet). However, this need of high power requires to control the overall power consumption in a range in line with systems requirements. In this respect, 3S PHOTONICS has developed a 14xx nm single mode laser diode with record internal losses of 1.5 cm-1 compared to the 2.7 cm-1 reported up to now. These lasers are based on p/nBH technology and use the asymmetric cladding concept to reduce internal losses. The record loss value, coupled to an internal efficiency higher than 0.8, allow realization lasers of 3.0 mm length with external efficiency higher than 0.5 W.A-1 at 25°C in AR/HR coating configuration. Modules using direct coupling technology were realized. High coupling efficiency is obtained thanks to the 8° x 14° far field pattern of the diode. Output power of 550 mW at 1.8 A is thus obtained, with or without FBG stabilization, with maximum output power above 700mW. Thanks to the lasers length, voltage at this current level is below 1.9 V, which gives a reduced thermal load. Thus, the overall modules electrical consumption remains lower than 10 W at case temperatures ranging from 0°C to 75°C. The 3.0 mm length also guaranties high reliability of these laser diodes.

8241-33, Session 6

Improvement of wall plug efficiency in near infrared lateral single-mode LDs at high temperature

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There is a long history of wall plug efficiency (WPE) improvement of near infrared LDs. The endeavors have been done mainly for broad area LD and LD arrays, not lateral single mode LDs. They are used at cooled condition, thus only the WPE at room temperature was focused. Recently a lateral single mode high power LD lased at 830 nm has been gathered attentions for a 3D motion sensor light source. Some of the sensors will be droved connecting a USB port. Thus low power consumption, in other words, high WPE at temperature higher than room temperature is strongly required. Conventional 830 nm LDs consist of AlGaAs material, which has relatively small energy gap in conduction band between an active layer and a p-cladding layer. This results that WPE at high temperature is not so good. One of promising methods to obtain superior WPE is using AlGaInP material instead of AlGaAs. The material has larger gap and is effective to improve the temperature characteristics dramatically. A lateral single mode high power 830 nmLD was newly designed based on AlInGaP material. The LD chip has 1.5 mm cavity length, and the chip is assembled in junction down configuration on conventional TO-56. Window mirror structure is adopted to prevent catastrophic optical degradation at high power operation. The LDs show excellent temperature characteristics as To of 154 K in wide range of 15 to 75 C, and its WPE is around 40% at 400mW, CW output, 60 C case temperature. They also show very stable operation at the condition up to 1000 hours.

8241-34, Session 7

Industrial high power diode lasers: reliability, power, and brightness

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Industrial High Power Diode Lasers: Reliability, Power and Brightness

High-power semiconductor lasers, single emitters and bars are developing fast.

During the last decade key parameters of diode lasers, such as beam quality, power, spacial and spectral brightness, efficiency as well as reliability have been greatly improved. However, often only individual parameters have been improved, accepting an adverse effect in the other key parameters.

For demanding industrial applications it is in most cases not sufficient to achieve a record value in one of the parameters, on the contrary it is necessary to optimize all the mentioned parameters simultaneously.

To be able to achieve this objective it is highly advantageous to have insight in the whole process chain, from epitaxial device structure design and growth, wafer processing, mounting, heat sink design, product development and finally the customer needs your final product has to fulfill.

In this publication an overview of recent advances in industrial diode lasers at TRUMPF will be highlighted enabling advanced applications for both high end pump sources as well as highest brightness direct diode.

8241-36, Session 7

Advances in performance and beam quality of 9xx-nm laser diodes tailored for efficient fiber coupling

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The impact of new direct-diode and fiber laser systems on industrial manufacturing drives the demand for high-brightness diode laser pump sources suitable for simple fiber coupling with high efficiency. For this purpose, laser mini-bars with different bar geometries, small fill factors, and tailored beam parameter products were investigated within the German funded project HEMILAS. We present results on 9xx nm bars designed for coupling to fibers with core diameters of 200µm and 300µm with a numerical aperture of 0.22 and compare slow axis divergence, brilliance, maximum conversion efficiency, maximum output power, and thermal performance of different bar designs. The optimized epitaxy structure yields maximum conversion efficiencies above 66%. Combined with an improved chip structure featuring 4mm resonator length and mounted on actively cooled submounts using hard solder, each of the 100µm wide emitters on the mini-bars with lateral fill factor 10% reached over 9W at a full slow axis divergence angle of 7°. This corresponds to a total power of 45W from a 5mm wide mini-bar with 5 emitters, featuring a beam parameter product of 15.3mmmrad. At the same slow axis divergence angle the output power of the 100µm emitters on the 20% fill factor bars reached over 8W, corresponding to a total output power of 58W from the 7 emitters of a 3.5mm wide bar with a beam parameter product of 21.4mmmrad.

No COMD failures were observed up to currents exceeding the thermal rollover. The maximum output power is about 95W for both 10% and 20% fill factor bars.

8241-37, Session 7

Comparative study of the performance of semiconductor laser based coherent Doppler lidars

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In the wind-energy industry, Coherent Doppler Lidar (CDL) is becoming a popular alternative to conventional anemometry instruments (i.e. fixed sensors like wind cups, wind vanes and sonic-anemometers). Furthermore, new studies have shown that a wind turbine with a control system relying on remote wind velocity measurements of a forward-looking, nacelle-mounted CDL produces 20% higher power-production than a conventionally controlled turbine. To scale-up this substantial improvement in wind harvest, low-cost, compact mass-producible CDLs need to be developed. One potential approach is to employ semiconductor laser (SL) sources in CDL systems. In 2000, researchers who initially considered SL-based CDLs identified several problems associated with the use of SL sources (e.g. low output power, phase-induced intensity noise). Due to these challenges, Lidar developers redirected their attention to embodiments based on expensive fiber-laser and fiber-amplifier (FLFA) tandem. In 2006, we started a reinvestigation of SL-based CDL systems to tackle the abovementioned problems. Our efforts focused on two novel SL sources as potential emitters for developing an “all-semiconductor-laser” wind Lidar for field operation. In this work, we demonstrate that two SL-based CDLs using (1) a 1550-nm monolithic master-oscillator-power-amplifier (MOPA) SL and (2) a 1480-nm external-cavity tapered diode laser (ECTDL) can compete in reliability and performance against expensive commercial FLFA-based counterparts. Our preliminary outdoor/field tests demonstrate excellent agreement of the two SL-based CDLs with a mast-mounted sonic-anemometer. Furthermore, we compare the two SL-based systems by considering performance parameters such as CDL probing range (coherence length), signal-to-noise (e.g. relative intensity noise), stability, form-factor and cost.

8241-38, Session 7

1540-nm surface-emitting distributed feedback (SE-DFB) laser for range finding application

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Diode lasers used in range finders for consumer, industrial and military applications require a wide operating temperature range and eye-safety is of paramount importance. 1540 nm surface-emitting distributed feedback (SE-DFB) diode lasers can provide an efficient and cost-effective solution as transmitters for range finding application. We report on the design and fabrication progress of a 1540 nm SE-DFB laser comprising curved second-order grating. There are several key advantages of using 1540 nm SE-DFB laser as a transmitter for range finding application. The curved second-order grating design provides a much brighter source compared to multi-junction edge-emitters. Furthermore, several times higher peak power can be extracted from SE-DFB laser since there is no limitation of catastrophic optical mirror damage (COMD). Spectral output is an order of magnitude narrower and the spectral shift due to temperature is several times smaller. As a result factor of five narrower optical filter can be used for detectors cutting down on background solar noise. Due to these factors, a factor of four higher signal-to-noise ratio can be achieved at the system level compared to an edge-emitting diode laser at the same peak power and wavelength.

8241-39, Session 7

External-cavity high-power dual-wavelength tapered amplifier with tunable THz frequency difference

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A tunable high-power dual-wavelength diode laser system with double-Littrow external-cavity feedback is demonstrated around 800 nm. To our knowledge, this is the first tunable dual-wavelength diode laser system based on a tapered diode amplifier. The tapered diode amplifier was chosen as gain medium in the dual-wavelength laser system based on the fact that it can produce relatively high output power and has good beam quality.

When single-Littrow external-cavity feedback is applied, an output power of 2.15 W is obtained at a wavelength of 801.43 nm, and the laser system is tunable from 786 to 813 nm with output power higher than 1.02 W and the amplified spontaneous emission is more than 35 dB suppressed. When double-Littrow external-cavity feedback is applied, the two wavelengths can be tuned individually, and the frequency difference of the two wavelengths is tunable from 0.5 to 5.0 THz. A maximum output power of 1.54 W is achieved with a frequency difference of 0.86 THz, the output power is higher than 1.3 W in the 5.0 THz range of frequency difference, and the amplified spontaneous emission intensity is more than 20 dB suppressed in the range of frequency difference. To our knowledge, this is the highest output power from a dual-wavelength diode laser system operating with tunable THz frequency difference. The beam quality factor M2 is 1.22±0.15 at an output power of 1.35 W. The simultaneous oscillation of the two wavelengths is verified by the sum-frequency generation experiment in a BIBO nonlinear crystal.

8241-45, Session 7

High-power single emitters and laser bars with improved performance developed at JENOPTIK

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High-power single emitters and laser bars have established as widely-used light sources in many industrial applications such as materials processing or as pump source for solid state or fiber lasers. A steady increase in optical and cost efficiency is needed to find the way into new markets. Therefore laser structures and devices have to be designed according to new requirements.

The epitaxial structures as well as the design of the laser bars and single emitters are optimized to enhance the laser performance. Important parameters include the efficiency, the maximum output power, the wavelength stability and finally the reproducibility of the whole manufacturing process. This includes for example the development of a wavelength stabilization for 976 nm laser devices applicable under production conditions.

The latest developments in the field of high-quality laser bars and single emitters at JENOPTIK will be presented within the whole wavelength range of the product portfolio.

8241-40, Poster Session

Experimental studies for improvement of thermal effects in a high power fiber-coupled diode laser module operating at 808 nm

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High power diode laser module operating at 808 nm is required for different applications, such as developing an efficient high power Nd3+-doped solid state laser and Tm3+ -doped silica fiber laser, industrial, medical and military applications. Optical and thermal images characterization for a fiber-coupled high power diode laser module is presented experimentally for 6.6 Watt output optical power.An external temperature controller system was designed, which stabilizes the central wavelength at 808 nm at 25°C over a wide range of diode laser driving current from 1A to 6 A. without this cooling system, the wavelength changes by 0.35nm/°C for temperature changes from 20°C to 40°C at the same range of the driving current. In this paper we have present a methodology for temperature reduction of a 808 nm high power diode laser module, based on dynamically thermal control, which is known as dynamic thermal management. Stabilization of the output wavelength has been done by using proportional speed control (PSC) of a CPU cooling fan with certain scheme of straight fins heat sink. Two electronic circuits based on pulse width modulation (PWM) in microcontroller and comparators IC have been used. This technique can be considered as an effective mechanism for reducing temperature and power dissipation to make stabilization of the diode laser output wavelength by preventing heat accumulation from the thermo electric cooling (TEC) inside the diode laser module confirmed by thermal images.

8241-41, Poster Session

Physics of failure investigation in high power broad-area InGaAs-AlGaAs strained quantum well lasers

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Continued improvements in broad-area InGaAs-AlGaAs strained-quantum-well (QW) lasers have led to unprecedented performance characteristics in these lasers including optical output powers of over 20 W and power conversion efficiencies of over 70% under CW operation. Catastrophic optical mirror damage (COMD) is responsible for failures in (Al)GaAs QW lasers, but InGaAs-AlGaAs strained-QW lasers with optimized facet passivation predominantly fail by catastrophic optical bulk damage (COBD). Since COBD is relatively a new failure type, it requires physics of failure investigation to understand its root causes and then develop COBD-free lasers for high reliability applications including potential satellite systems. We recently proposed a model for degradation mechanism responsible the COBD process and this paper further investigates the root causes of COBD in the lasers using various failure mode analysis techniques. We investigated reliability and degradation mechanism in MOCVD-grown broad-area InGaAs-AlGaAs strained-QW single emitters. Accelerated lifetesting was performed on these lasers. During entire accelerated life-tests time-resolved electroluminescence (TR-EL) and thermal imaging techniques were employed to observe formation of a hot spot and subsequent formation and progression of dark spots and dark lines through windowed n-contacts. Deep-level-transient-spectroscopy (DLTS) and time-resolved photoluminescence (TR-PL) techniques were employed to study trap characteristics and carrier dynamics in pre- and post-stressed lasers to study the role that non-radiative recombination centers play in COBD. Lastly, we employed electron-beam-induced-current (EBIC), focused ion beam, and high resolution TEM to study dark line defects and crystal defects in post-stressed lasers at different stages of degradation. We will present our physics of failure investigation results.

8241-42, Poster Session

The optical system designing for the laser array with high power

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Based on the technology of beam shaping with aspherical surface, a more suitable type of aspherical surface to shape and focus the beam of high power laser diode array was studied by analyzing and calculating. By analyzing the characteristics of fiber and GRIN lens and conditions of coupling, a kind of beam shaping technique which combined fiber with GRIN lens will be presented to improve the beam quality of high power laser diode array. The study uses a laser diode arrays sources, firstly, using several aspherical surface lenses to collimate and compress laser beam at the slow axis and the fast one respectively. And then, using a focusing lens to focus the pre-collimated beam into fiber and obtain a bunch of coupling beam. Furthermore, using the GRIN lens to collimate the beam again and get a bunch of more uniform beam. At last, let the uniform beam pass an aspherical surface lens and gain a smaller spot with high density.

8241-44, Poster Session

Testing of a compact and self-contained active heat sink for advanced high-power laser diodes

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We have previously introduced a novel active heat sink (AHS) for high-power laser diodes offering unparalleled capacity in high-heat flux handling and temperature control [1, 2]. The AHS employs convective heat transfer by a liquid metal coolant flowing at high speed inside a miniature sealed flow loop. The liquid metal receives waste heat at a high flux, transports it by forced convection, and rejects it at a much lower heat flux. Liquid metal flow in the loop is maintained electromagnetically without any moving parts. AHS can handle a heat load of several hundred watts at a heat flux over 1,000 W/cm2 with a thermal resistance as low as 0.1 °C/W. AHS thermal conductance can be electronically adjusted, allowing for precise control of diode temperature and the diode light wavelength. In particular, diode temperature can be maintained even when rejecting heat to a medium (e.g., water or air) at varying temperature.

This paper presents a new compact and self-contained configuration of the active heat sink intended as a drop-in replacement for standard products, and data from testing this unit at high heat flux and high heat loads. This work was in-part funded by the US Air Force contract number FA9453-10-C-0061.

1. J. Vetrovec, "Progress in the Development of Active Heat Sink for High-Power Laser Diodes," SPIE vol. 7583-19

2. J. Vetrovec et al., "Testing of an Active Heat Sink for Advanced High-Power Laser Diodes, SPIE vol. 7918-15 (2011)

8241-46, Poster Session

Application of room temperature pulsed Fabry-Perot quantum cascade laser in situ monitor concentration of methane

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In this paper, the concentration of methane is detected with room temperature (RT) pulsed fabry-perot quantum cascade lasers (FP-QCLs) using the v4 basic absorption line at 7.71μm (1332.72 cm−1) and the sensitivities are down to 250ppm. We design an instrument with lasers, circuits and lens which are developed by the authors of this paper. The whole instrument is compact, functional and convenient can be applied to many in situ monitoring environments. The instrument's response time is very short, only 5 second, so it can constantly show the monitoring concentration of methane on time. Nowadays, mid-infrared QCLs optical detection systems have attracted more and more attention for gas monitoring applications due to their potential features of (i)intrinsically safe, (ii) ability to detect a specific gas by selection of appropriate wavelengths, and (iii) able to operate in zero-oxygen environment. In 2000, Kosterev et al. have presented a new pulsed distribute feedback quantum cascade laser (DFB-QCL) system to measure CH4 with a three stages thermoelectric-cooled units, astigmatic mirror multipass cell (100-m pathlength) based spectrometer. This system successfully detected the limit of concentration of CH4 about 2.03ppm. This result is much lower than that of this paper, but in that system, all drivers and digital processers are commercial instruments which are totally different with this paper. However, with the development of integrate circuits all these instrument can be integrated one circuit board. Here we report on the further development of techniques for high-sensitivity laser absorption spectroscopy with thermoelectrically cooled FP-QCLs. The utility of these techniques is demonstrated by CH4 concentration measurements in ambient air.

Conference 8242: Vertical External Cavity Surface Emitting Lasers (VECSELs) II

Monday-Tuesday 23-24 January 2012

Part of Proceedings of SPIE Vol. 8242 Vertical External Cavity Surface Emitting Lasers (VECSELs) II

8242-01, Session 1

MIXSELs for frequency combs

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Stable frequency combs from femtosecond lasers have been a major breakthrough in optical science and metrology. Typical frequency combs are either based on complex green-pumped Ti:sapphire lasers or amplified fiber lasers. Optically-pumped VECSELs and diode-pumped solid-state lasers (DPSSLs) modelocked by SESAMs are promising for cost-efficient, reliable, and compact frequency combs. Similar to Ti:sapphire lasers, they operate with high-Q cavities and moderate intracavity nonlinearities, resulting in low fundamental quantum noise limit and free-running CEO-beating signal with narrow linewidth. Recently, we presented the first CEO detection of a gigahertz DPSSL, which generated 2.2 W average power in 290-fs pulses at 1042 nm, and evaluated the influence of pulse duration on the CEO beating signal.

These results indicate a large potential of ultrafast VECSELs for frequency comb applications. A recent timing jitter measurement confirmed low noise operation comparable to DPSSLs. We already obtained average power levels >1 W in the sub-picosecond regime. The highest average power of any modelocked semiconductor laser are obtained from MIXSELs (modelocked integrated external-cavity surface emitting lasers), in which VECSEL and SESAM are integrated into a single semiconductor structure. So far, we obtained 6.4 W average power in 28 ps pulses at a repetition rate of 2.5 GHz, and 2.2 W at 10 GHz. The simple straight cavity contains only two intracavity elements, the MIXSEL chip and the external output coupler. While the average power levels of the MIXSEL appear suitable for frequency comb applications, the pulse duration has to be reduced into the femtosecond regime. In this presentation, we present the current status of MIXSEL research and present several concepts for further pulse shortening and future frequency comb applications.

8242-02, Session 1

Picosecond to sub-picosecond pulse generation from mode-locked 1.55-µm VECSELs

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Mode-locked vertical-extended-cavity-surface emitting lasers (ML-VECSEL) are promising candidates for the generation of stable short pulses, owing to the small thickness of the active semiconductor medium and the high finesse of the cavity. Unfortunately, a high intra-cavity power is generally required to achieve an efficient saturation of the fast SESAM, and the poor thermal behavior of quaternary InP-based semiconductor compounds often limits the performance of ML-VECSELs operating at 1.55 µm. Very efficient heat dissipation can be achieved with a top-mounted intra-cavity diamond heat spreader. In another approach optimizing downward heat sinking, we have developed a ½-VCSEL chip with a low thermal resistance using a hybrid metal-metamorphic GaAs/AlAs mirror and bonded onto a highly thermally conductive host substrate. The ½-VCSEL chip assembled in a 4-mirror cavity with a 1.55µm fast InGaAs(Sb)N/GaAsN SESAM. Nearly Fourier transform-limited mode-locked pulses (repetition frequency of ~ 2 GHz) are generated at an operation temperature of 25 °C, and the RF linewidth of the free running laser is measured to be less than 1000 Hz. When the resonance and group delay dispersion of the SESAM microcavity is modified by selective etching of specific phase layers, the pulsewidth can be reduced from several picoseconds to less than 1 ps.

A practical advantage of the downward heat sinking approach is to be compatible with surface post-processing of the ½-VCSEL structure and therefore compatible with optical and electrical pumping.

8242-03, Session 1

Passively mode-locked GaSb-based VECSELs emitting sub-400-fs pulses at 2 µm

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We report on the development of GaSb-based passively mode-locked VECSEL generating sub-picosecond pulses at 2 µm wavelength range. The general goal for this development was to leverage the unique features of the mode-locked VECSELs (i.e. high-average power, sub-ps operation, high repetition rate) to the 2-3 µm wavelengths. High-power ultrashort pulses at this wavelength range are required for the development of numerous applications, such as time-resolved molecular spectroscopy, as pump sources for synchronously-pumped OPOs operating in the mid-IR, or as seeders for mid-IR supercontinuum sources.

The demonstration of ultrashort pulse GaSb VECSELs based on passive mode-locking has remained elusive until recently, partially due to a lack of technological developments for the key components such as semiconductor saturable absorber mirrors (SESAMs). Using a gain mirror and a SESAM incorporating InGaSb/GaSb quantum wells, we have been able to demonstrate a VECSEL producing near transform-limited 384 fs pulses at a wavelength of 1950 nm. Important part of this development has been focused on understanding the ultrafast absorption recovery dynamics of the SESAM. An intersting observation is that the absorption recovery time of as-grown InGaSb SESAMs is within ps range and is not much affected by a change of the growth temperature.

8242-04, Session 1

Harmonically and fundamentally mode-locked InGaAs-AlGaAs disk laser generating pulse repetition rates in the 100 GHz or pulse durations in the 100-fs range

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Optically pumped semiconductor disk lasers (SDLs) have gained much attention in the last years combining high output power, wide wavelength coverage, and high beam quality. In combination with a semiconductor saturable absorber mirrors (SESAM), mode-locked pulses can be achieved at very high repetition rates and on the sub-ps time scale. Here we report on the generation of femtosecond pulses with passively mode-locked SDLs based on different operation regimes.

We investigated SDLs containing a SESAM in the cavity, in the bunch-mode, the harmonically and the fundamentally mode-locked regime. Optimum parameters were derived for almost chirp-free femtosecond pulses. The pulse durations strongly depended on the relaxation behavior and the effective modulation depth of the SESAM. We used semiconductor media with minimized group delay dispersion. Wavelength matching of gain chip and SESAM was essential for ultrashort-pulse generation. Spectral-hole burning of both gain chip and absorber affected the stability of single-pulse operation. For fundamental mode-locking, avoiding of too strong saturation of the semiconductor elements was required.

Pulses as short as 107 fs and 198 fs were generated in the fundamentally and harmonically mode-locked laser, respectively. The corresponding spectral widths (FWHM) were 10.2 nm at 1030 nm and 6.5 nm at 1021 nm, which is close to the transform-limit for both operation regimes. At an output power in the 10-mW range the pulse repetition rates were 5 GHz and 92 GHz corresponding to fundamental and harmonic mode-locking, respectively. The 92-GHz result should fuel interest in using SDLs for communications or frequency comb generation.

8242-05, Session 2

20-watt CW TEM00 intracavity doubled optically pumped semiconductor laser at 532 nm

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Optically-pumped semiconductor (OPS) lasers are power-scalable, wavelength-flexible, infrared brightness converters. Adding intra-cavity frequency doubling turns them into efficient, low noise, high power visible laser sources. We report on a laser combining an InGaAs gain medium with an LBO nonlinear crystal to produce more than 20 Watt CW in single transverse mode at 532 nm. Efficient cooling of the single gain chip using advanced mounting techniques is the key to making the laser reliable at high CW powers. A rugged and compact package achieves the thermal and opto-mechanical stability required for the resonator to withstand significant environmental excursions. The laser's low noise makes it suitable for the most demanding Ti:Sapphire pumping applications. The wavelength flexible platform supports high power visible single transverse mode lasers ranging from 460 nm to 577 nm, and single frequency operation with the addition of an intra-cavity etalon.

8242-06, Session 2

High-power quantum dot semiconductor disk lasers

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Quantum-dot materials allow extending further the spectral range of semiconductor disk lasers (SDLs). Moreover, the localization of the charge carriers in three dimensions has been shown to lead to large gain bandwidth and to temperature insensitive operation.

In this work, several quantum dot semiconductor disk lasers operating at 1040 nm - 1260 nm emission wavelength were studied. All the structures were grown with molecular beam epitaxy on GaAs substrates. The quarter wave thick layers of GaAs/AlAs formed the distributed Bragg reflectors (DBRs). The gain was provided by a multilayer stack of Stranski-Krastanov quantum dots. Different number of quantum dot layers were used and operated either in ground or in excited state transition. Both resonant and antiresonant structures have been investigated for high power and broad band tuneability purposes.

Frequency doubling of the quantum dot SDLs is also demonstrated. The dual-gain approach was found to be practical approach to adopt the losses induced by the frequency doubling element. This technique is particularly relevant with quantum dot lasers with low single pass gain. In addition to the intracavity heat spreader configuration, thinned device structure has been developed. In this method, the structure is grown in reverse order, i.e. the DBR is located on top of the active region of the as-grown structure. The structure was bonded to a diamond heat spreader and the substrate chemically etched. The two heat spreader techniques are compared and discussed.

8242-07, Session 2

Recent advances in the development of yellow-orange GaInNAs-based semiconductor disk lasers

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Dilute nitride (GaInNAs/GaAs) quantum wells are a viable option for extending the emission wavelength of frequency-doubled semiconductor disk lasers (SDLs) to yellow-orange part of the visible spectrum. Such lasers are required for a number of high impact applications including dermatology, photodynamic therapy, microscopy, and surgery. Furthermore, lasers operating close to the absorption line of sodium (589 nm) can be used for industrial process control or as guide star lasers in telescopes equipped with adaptive optics. The addition of a small amount of nitrogen into GaInAs quantum wells enables reduction of lattice strain and band-gap. Thus, using dilute nitrides one can achieve lasing at wavelengths around and above 1200 nm, while alleviating the appearance of misfit dislocations in the crystal lattice that are generated when using standard GaInAs/GaAs quantum wells with a high indium content.

Infrared emission of over 10 W has been demonstrated at ~1.2 µm by using a dilute-nitride gain mirror incorporating a small amount on N. Furthermore, with intracavity nonlinear frequency conversion, dilute-nitride SDLs emitting frequency-doubled yellow-orange light have been realized. These lasers have reached output power in excess of 7 W in free-running mode or more than 2 W in narrow-linewidth single-frequency operation. These results show it is possible to generate high-quality, high-power light at this spectral range.

8242-08, Session 2

Strategies for power scaling VECSELs

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Power scaling of CW VECSELs requires a combination of accurate epitaxy quantum design, accurate wafer growth and good thermal management. Internal heat generated in the VECSEL chip is typically exploited to align a low wavelength offset PL/gain peak with an initially detuned micro-cavity resonance. Strategies for optimizing power extraction may include recycling the excess pump via reflection from a metalized reflector at the back of a transparent DBR, AR-coating at the pump wavelength while preserving the signal micro-cavity resonance, minimizing the thermal impedance of the DBR itself or increasing the PL/micro-cavity detuning that increases the threshold but also increases the slope and optical efficiency.

In this study, low thermal impedance VECSEL devices consisting of a high thermal conductivity heat spreader and a semiconductor material with its substrate removed are investigated. Three devices with absorbing and nonabsorbing DBRs plus devices with a large detuning are fabricated and tested. Characteristics of the VECSEL devices are investigated from their temperature-dependent reflectivity and surface photoluminescence spectrum. Output performance, lasing threshold, slope efficiency, optical efficiency and roll-over temperature of the VECSEL devices are studied experimentally. Improvement was observed in efficiency of VECSEL devices with a transparent DBR by recycling the pump light. Despite the low efficiency in devices with an absorbing DBR, over 60 W of output power was observed at 0°C when thermal impedance is low. VECSEL devices with large detuning lase at higher threshold power but both improved slope efficiency and optical efficiency.

8242-09, Session 3

Monolithic approaches to VECSEL devices

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VECSELs demonstrated to date mostly utilise an air-spaced external cavity a few mm's to several 10's cm in length, in which the feedback is provided by bulk optics. This is a convenient configuration for e.g. mode matching, bandwidth control, tuning and intra-cavity nonlinear conversion. However, the semiconductor active structure of VECSELs also lends itself to a range of monolithic formats, which can be ultra-compact (cavity length as small as 10's - 100's of microns) and 'alignment free'. These monolithic VECSELs, which we review here, are most readily facilitated either by utilising the (polished and suitably coated) epitaxial substrate of the VECSEL itself as the external cavity or by bonding/depositing a coated platelet of some other material to the epitaxial surface of the VECSEL gain chip. In the former case, for example, as has been shown particularly in electrical injection VECSELs, a coated GaAs substrate can help provide wavelength stabilisation and linewidth control whilst also facilitating current spreading over a large mode area. In the latter case, mirror-coated platelets of optical materials including polymers, glass, sapphire, SiC and diamond can be used to define the cavity and provide external feedback. In most cases, it is possible in principle to shape or microstructure the external surface of the platelet where this is beneficial. Attractions of these monolithic devices include; suitability for array operation; mode selection and linewidth control; thermal and mechanical stabilisation; ultra-high repetition rate mode-locked lasers (e.g. MIXSELs); intracavity microfluidics for sensing.

8242-10, Session 3

Wavelength tuning of VECSELs by cavity geometry

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Optically pumped VECSELs employing semiconductor quantum wells have been shown to be wavelength agile laser sources capable of producing high power near-diffraction limited beams from the UV to the IR. The characteristics of the VECSEL wafer are predominantly determined by the precise design and growth of the multi-layered varying index structures of the quantum wells and the DBR. Typically VECSEL wafers can be fabricated with great precision, but growth and design errors do occur resulting in decreased performance and spectral shifts from the desired wavelength. In addition, optically pumped VECSELs are known to deviate from the design wavelength for a variety of reasons including the pumping level and device temperature. In this paper, we demonstrate that by building a v-shaped cavity around a VECSEL chip, we can change the lasing wavelength and broaden the tuning range of the VECSEL by increasing the fold angle of the laser cavity. Specifically we show numerically and experimentally that we are able to introduce a spectral blue shift that is angle dependent. In addition, the introduction of the angled cavity alters the resonant periodic gain (RPG) structure such that the antinodes of the standing wave are not necessarily in precise alignment with the quantum wells resulting in increased spectral tuning at the expense of maximum output power. Thus, a v-shaped cavity can be beneficial for correcting small growth errors, or in applications such as mode locking which require a broader spectral gain.

8242-11, Session 3

Development of EP-VECSELs for mode locking applications

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Optically pumped vertical external cavity surface emitting lasers (VECSELs) offer the ultimate in flexibility for the realization of semiconductor laser devices. Band-gap engineering provides precision wavelength selectivity while the external cavity allows the insertion of saturable absorbers for mode-locked devices, or periodically poled crystals for frequency doubling. High quality (low M2) TEM00 Gaussian beams profiles can be obtained, coupling this with the ability to power scale with pump spot size gives rise to a very attractive type of device. However, in order to achieve the ultimate in compactness and reduced cost, electrically driven devices are preferred. Electrical injection results in a number of competing design trade offs and compromises. The p-n junction required for electrical injection introduces free carrier losses, introduces a source for Joule heating and impacts critically upon device geometry.

To date, much of the development work for EP-VECSELs has been carried out commercially for devices for display applications, but in some cases these design developments are at odds with those required for achieving mode locked operation. In this paper we present a study of the design trade-offs for achieving room temperature CW operation from EP-VECSELs, with the goal of maximising output power and beam quality for mode-locking applications. Key areas of design for achieving high power and beam quality are highlighted and discussed. We describe the effects of device geometry (substrate current spreading versus epitaxially grown spreader), the effect of intermediate DBRs, doping schemes, and describe our mode-locking of these devices.

8242-12, Session 4

GaSb-based semiconductor disk lasers: recent advances in power scaling and narrow linewidth operation

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The (AlGaIn)(AsSb) materials system has been shown to be ideally suited to realize optically-pumped semiconductor disk lasers (OPSDLs) for the 2-3 µm wavelength range [1,2]. Using barrier pumping with standard commercial 980 nm diode lasers, cw output powers of 4.2 W @ 20°C heatsink temperature (6 W @ 0°C) have been achieved for 2.0 µm emitting GaSb-based OPSDL with ternary GaInSb quantum well active region. Corresponding quantum efficiency and optical power conversion efficiency are 53% and 26% @ 20°C, respectively, the latter adversely affected by the large quantum deficit between pump and lasing photon energy.

In this presentation recent advances in this laser technology will be reviewed with special emphasis on factors potentially limiting further power scaling, such as lateral lasing, and single-mode narrow linewidth operation, exploiting the resonator versatility offered by the OPSDL external cavity configuration.

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8242-14, Session 4

Evaluation of the single-frequency operation of a short vertical external-cavity semiconductor laser at 852 nm

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Stable single-frequency laser emission at 852 nm with narrow linewidth (<500 kHz), fine tunability over a few GHz and output power in the 0.1 W range is required for laser cooling, optical pumping and detection of Cs atoms in atomic interferometry experiments. We have developed a short external-cavity semiconductor laser based on a AlGaAs/GaAs structure emitting at 852 nm. The pump source is a fiber-coupled diode laser emitting at 690 nm. The thermal lens of the semiconductor chip has been measured using a wavefront sensor for various laser parameters (pump waist, temperature) under lasing and non-lasing condition. These measurements give a more precise understanding of the thermal effects in a semiconductor active structure. Taking benefit of the strong thermal lensing, a simple short cavity (L = 3 mm) consisting of a plane output coupler and the active semiconductor structure has been implemented. We achieve an output power of 106 mW for an incident pump power of 600 mW. The laser emission is purely single-frequency thanks to the large free-spectral range (150 GHz) of the laser cavity, with a side-mode suppression ratio about 35 dB. The stability of the laser line is better than 6 pm over an hour, and is significantly improved with output couplers of high transmission.

8242-15, Session 4

GaSb-based semiconductor disk laser above 2-µm wavelength with <100-kHz linewidth and 1000-mW output power

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In recent years, optically pumped semiconductor disk lasers (SDLs) have attracted considerable interest due to their capability of delivering simultaneously a high output-power and an outstanding beam quality [1]. The modular design of SDLs allows a straightforward insertion of wavelength-selective elements in the laser cavity in order to achieve narrow-linewidth single-frequency emission and wavelength tunability [2]. These narrow-linewidth laser sources are of special interest for a range of applications such as remote spectroscopic sensing and optical free-space communications, in particular when heterodyne detection schemes are employed [3]. To-date demonstrated single-frequency kHz-linewidths SDLs above 2 µm have output powers clearly below 1 W (e.g. 5 mW [4]).

Contrary to that, we demonstrate a SDL with a linewidth of 90 kHz and an output power above 1 W at 2.05 µm emission wavelength, thus surpassing established mid-infrared kHz-linewidth lasers (even solid state lasers [5]) by more than a factor of 15 with respect to output power.

In order to reduce technical frequency noise, we have realized the SDL in a rugged, hermetically sealed module housing. By inserting a birefringent filter, single-frequency emission and coarse tuning in a 120-nm wavelength range was achieved. Designing the cavity length for an optimized pump-spot cavity-mode overlap, we extracted 1000 mW output power in a single cavity mode at 2.05 µm. The 90-kHz linewidth was determined in a heterodyne scheme [6] by generating the beat note of two identical SDLs.

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8242-16, Session 4

IV-VI mid-infrared VECSEL on Si-substrate

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Lasers in the mid - infrared (MIR) are essential for countless spectroscopic applications, since many gases have absorption lines in this spectral region. We review Vertical External Cavity Surface Emitting Lasers (VECSEL) emitting above 3 µm wavelength. Our VECSEL are based on IV-VI semiconductors (lead-salts) grown on Si-substrates. The lasers are optically pumped.

VECSELs have many favorable properties like power scalability and excellent beam quality, i.e. a narrow circular output cone. By using IV-VI semiconductors we were able to develop the first VECSELs emitting above 3 µm wavelength. These lasers operate up to >10 µm wavelength. This is due to the narrow band gap of the IV-VI materials, which is tuned by temperature and by alloying. The lead-salts are therefore very well suited for optical applications in the whole MIR. Maximum operation temperatures of our VECSELs are well above room temperature with output powers >1 Wp.

With our new developed modular design the VECSEL consists of three separate parts. This setup allows an easy comparison between different structures, since a new active layer is combined with already existing mirrors.

By reducing the cavity length to 100 µm or less only one longitudinal mode develops. This single emission line is shifted mode-hop free by displacing the external mirror. With this compact design a continuously tunable VECSEL emitting around 3.3 µm near room temperature has been developed. The laser may be used to detect various hydrocarbons and hydroxides.

8242-20, Session 4

589-nm single-frequency VECSEL for sodium guidestar applications

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High power single frequency laser sources are of great interest in the bands covering the 570-590 nm range for applications in sodium guidestar lasers, quantum computing, and medical uses. Despite the many applications, the lack of suitable gain materials has limited the advances of lasers in the yellow-orange range. Here we report on the development and demonstration of a tunable high power single frequency VECSEL operating at 589nm. We show that a highly strained InGaAs/GaAs VECSEL designed to operate at ~ 1178nm when used in conjunction with an intracavity Birefringent Filter (BF) and Fabry-Perot (FP) etalon is able to achieve high power single frequency operation. When an intracavity non-linear optical element is included in the cavity, we are then able to obtain the single frequency output at the desired wavelength of 589nm for sodium guidestar applications. We also demonstrate that by passing the yellow output through a sodium reference cell, we are able tune across and measure the sodium D2 and D1 lines thus confirming the narrow linewidth operation. Our results show that outputs in excess of 4W at 589nm with a FWHM linewidth of less than 15MHz have been achieved.

8242-13, Session 5

2.7-µm single-frequency TEM00 operation of Sb-based diode-pumped external-cavity VCSEL

A. Garnache, Univ. Montpellier 2 (France)

We present the design, technology and performances of a single-frequency tunable Sb-based diode-pumped type-I quantum well vertical-external-cavity surface-emitting lasers emitting at 2.7 µm. The 2-3 µm Mid-IR window is especially well adapted for laser spectroscopy applications as many molecules of interest exhibit strong absorption lines : CH_4, NH_3, CO, HF near 2.3 µm for gas analysis/detection applications and H_2O, CO_2 near 2.7 µm for isotopic ratio spectroscopy applications. A compact powerfull laser design can be thus achieved using a short cavity Quantum-Well VECSEL without any intracavity filter, as it exhibits an ideal homogeneous gain behavior. The half VCSEL structure was grown by MBE with quantum-well growth temperature of 440°C. The sample was thermally annealed to adjust the QW gain peak wavelength. We report on room-temperature continuous-wave laser with 0.15mW output power and low threshold incident pump intensity of 0.7 kW/cm2 while pumping at 830 nm with a commercial diode laser. The external cavity provides a circular TEM00 beam with a low divergence of 3.6°. The short mm-long optical cavity laser exhibits single frequency operation, with a side mode suppression ratio >>16 dB, a linewidth <<4GHz and a linear light polarization. These devices were studied in terms of output power, beam quality, polarization, spectral and thermal properties. Laser power performances, limited by the high thermal impedance, could be greatly enhanced thanks to a membrane technology bonded on high thermal conductivity host substrate. Work is in progress in this direction.

8242-17, Session 5

VECSELs: non-equilibrium effects and THz emission

S. W. Koch, Philipps-Univ. Marburg (Germany)

In this invited talk, I will present an overview of nonequilibrium effects in VECSELs and discuss how these phenomena help to stabilize two-color operation. Inserting a nonlinear crystal into the VECSEL cavity allows for cw room temperature THz generation.

8242-18, Session 5

Advances in narrow-linewidth continuous wave semiconductor disk laser pumped optical parametric oscillators

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The paper reports on M Squared Lasers' recent work in the field of narrow-linewidth, continuous wave (CW) optical parametric oscillators (OPO) that utilise the semiconductor disk laser (SDL) format for intra- and extracavity pumping schemes. For the experimental investigation, InGaAs quantum well gain structures were employed to produce compact SDLs which were subsequently used to pump OPOs based on periodically poled lithium niobate (PPLN).

Using the intracavity architecture, a compact, CW, narrow-linewidth OPO was developed, capable of delivering up to 250mW of idler output power (at ~3.3µm). The SDL maintained stable single longitudinal mode operation and the spectral bandwidth of the OPO output was measured to be 15W), single frequency SDLs were developed using single- and multichip configurations. The extracavity OPO pumped by these sources delivered up to 950mW of idler output power, with a minimum threshold of 2.4W and tuning range from 2.8 to 3.6µm. Further details of the high power, single frequency SDLs as well as the extracavity OPO will be discussed, with specific focus on the advantages and disadvantages of multichip and singlechip arrangements for single frequency SDLs.

8242-19, Session 5

CW Raman lasers intracavity pumped by VECSELs

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The relatively recent development of CW crystalline Raman lasers has been motivated by the opportunity to exploit the red-shift imparted by stimulated Raman scattering to extend the spectral coverage of compact solid-state lasers to the 1.1-1.5 µm region. Typically the domain of high power pulsed lasers, the threshold for single pass Raman conversion is on the order of GW/cm2; however, reduction of the threshold to a level more appropriate for compact lasers is achieved by placing the Raman gain medium in a cavity that resonates the Stokes wavelength, and even better, within the cavity of the pump laser.

We believe that VECSELs are an attractive intracavity pump source for CW Raman lasers. The typical threshold intracavity power required for crystalline Raman gain media, on the order of 100 W, is well within the capabilities of these high finesse laser cavities. In addition, as the Raman shift is fixed, tuning the VECSEL tunes the Raman laser. We will present tunable, CW Raman lasers, intracavity pumped by InGaAs-based VECSELs. These lasers utilise KGW and diamond as Raman gain media to reach wavelengths around 1150 and 1230 nm respectively with Watt level output power and competitive optical efficiency. Although VECSELs have been demonstrated to operate around these wavelengths without nonlinear conversion, this method provides an alternative to the highly strained gain structures or less robust materials required for direct emission and makes use of InGaAs-based VECSELs around their peak performance wavelength.

8242-21, Session 5

UV laser emission around 330 nm via intracavity frequency doubling of a tunable red AlGaInP-VECSEL

H. Kahle, T. Schwarzbäck, M. Eichfelder, R. K. Roßbach, M. Jetter, P. Michler, Univ. Stuttgart (Germany)

The wide range of applications in biophotonics, television or projectors, spectroscopy and lithography made the vertical external cavity surface-emitting lasers (VECSELs) an important category of power scalable lasers. The possibility of bandgap engeneering, inserting frequency selective and converting elements into the open laser cavity and laser emission in the fundamental Gaussian mode leads to ongoing growth of the area of applications for tuneable laser sources.

We present an intra cavity frequency doubled VECSEL with emission wavelength around 330 nm and a maximum tuning range of more than 7 nm with output powers up to 100 mW. Frequency doubling is realized with an anti-reflection coated beta barium borate crystal, while a birefringent filter, placed inside the laser cavity under Brewster's angle, is used for frequency tuning. The fundamental laser, pumped by a 532 nm Nd:YAG laser under an angle of 50° normal to the surface, is realized by a multi quantum well structure consisting of 20 compressively strained GaInP quantum wells in an Al(x)Ga(1-x)InP separate confinement heterostructure and it emits around 660 nm. The VECSEL-chip with its n-λ-cavity is completed by a 55 λ/4 pairs Al(0.50)Ga(0.50)As/AlAs distributed Bragg reflector. Next to the optical properties of the device, we show results of different arrangements of the quantum wells, namely five times four and ten times two packages, and investigate further innovative approaches for the active region.

8242-22, Session 6

High-average power modelocked VECSELs and MIXSELs

U. Keller, ETH Zurich (Switzerland)

High-power ultrafast lasers are important for numerous industrial and scientific applications. Current multi-watt systems, however, are based on relatively complex laser concepts. Moving towards a higher level of integration would reduce complexity, packaging, and manufacturing cost, which are important requirements for mass production. Semiconductor lasers are well established for such applications, and optically-pumped vertical external cavity surface emitting lasers (VECSELs) are most promising for higher power applications, generating the highest power in fundamental transverse mode (>20 W) to date. Ultrashort pulses have been demonstrated using passive modelocking with a semiconductor saturable absorber mirror (SESAM), achieving for example >6-W average power, <100 fs pulse duration, and <50-GHz pulse repetition rate. In 2007, the integration of both the gain and absorber elements into a single wafer was demonstrated with the MIXSEL (modelocked integrated external-cavity surface-emitting laser).

This talk will give a tutorial about the power scaling and modelocking of VECSELs and MIXSELs.

8242-23, Session 6

Multiphoton imaging with compact semiconductor disk lasers

P. Loza-Alvarez, R. Aviles-Espinosa, ICFO - Institut de Ciències Fotòniques (Spain); D. Artigas-García, ICFO - Institut de Ciències Fotòniques (Spain) and Univ. Politècnica de Catalunya (Spain)

Ti:sapphire-based ultrashort pulsed laser systems have been widely used in nonlinear microscopy applications (such as two-photon excited fluorescence (TPEF) or Second-harmonic generation (SHG)) as they provide the adequate peak powers and tunability across a large spectral range. However, these are normally over-specified for certain imaging applications. In addition, they are bulky, maintenance-intensive and expensive. These limitations have prevented their wide-spread use for multiphoton imaging in biomedical applications.

In this work we present the performance of a compact, non expensive and easy to use ultrafast semiconductor disk laser (SDL) (modelocked by a quantum-dot semiconductor saturable absorber mirror (SESAM)) for multiphoton microscopy applications. This laser delivers average output powers up to 1W with 1.5 ps pulses at 500 MHz and operating in the 970 nm region. Importantly, this corresponds to the peak of the two-photon action cross section of the Green Fluorescent Protein (GFP), one of the most widely used fluorescent markers in biomedical applications. This property greatly relaxes the required peak powers for efficient TPEF imaging. This is demonstrated in GFP labeled neurons in living C. elegans nematodes. We also assess the suitability of this laser for: i) TPEF imaging with other dyes in different samples, ii) imaging at different penetration depths, iii) time-lapse studies and iv) SHG imaging of the pharynx and body wall muscles in living C. elegans. Finally, we assess the performance of the laser for its use in fully commercial microscope systems and in comparison with the conventional Ti:sapphire lasers.

8242-24, Session 6

Frequency-tuneable ultrashort pulse VECSEL sources

K. G. Wilcox, Univ. of Southampton (United Kingdom)

Femtosecond pulse VECSELs are ideally suited to repetition frequency tuneable operation through cavity length variation. I will describe a system suitable for optical sampling by cavity tuning (OSCAT) type pump-probe systems, requiring no external variable delay line. I will also discuss a VECSEL with repetition rate tuned continuously between 2.8 and 7.8 GHz, showing a variation of pulse duration with repetition frequency, and hence fluence. This provides an insight into the modelocking mechanisms that produce ultrashort pulses in VECSELs.

Generation of high repetition rate high average power pulse trains using VECSEL seed YDFA power amplifier technology and its potential for high repetition rate high average power supercontinuum will be discussed.

8242-25, Session 7

Quantum dot gain structures for VECSELs

U. W. Pohl, Technische Univ. Berlin (Germany)

Surface emitting lasers with a vertical cavity experienced a rapid development during the last decade. Most of this work focused on gain media based on quantum wells. Quantum dots (QDs) provide an enhanced concentration of electron and hole levels at the band edges, promising an increased material gain and a decreased lasing threshold. Early applications of QDs in gain media of edge-emitting lasers confirmed characteristics originating from the full quantization of confined charge carriers, such as a very low lasing threshold with close to zero temperature sensivity. The success stimulated the use of QDs in surface-emitting lasers. The tutorial review introduces into the characteristics of different kind of quantum dots and their implementation into gain media. The impact on applications for injection lasers with a vertical cavity (VCSELs) and optically pumped lasers with a vertical external cavity (VECSELs) is discussed, and advancements as well as challenges in the field are presented.

8242-26, Session 7

Recent progress in near-infrared VECSEL grown by metal organic vapour phase epitaxy

W. Stolz, Philipps-Univ. Marburg (Germany)

The application of a specific metal organic vapour phase epitaxy (MOVPE) process for (GaIn)As-based VECSEL using thermally more efficiently decomposing MO-group-V-sources results in an extended emission wavelength range and facilitates the necessary strain compensation of the highly compressive-strained (GaIn)As-quantum well layers by specific tensile-strained Ga(PAs) barrier layers. Applying a closed-loop-design concept of detailed microscopic modelling and experimental realization as well as laser characterization allows for an efficient optimization of these complex laser devices. Recent developments for the realization of high-power VECSEL will be presented and discussed.

8242-27, Session 7

Influence of non-radiative carrier losses on pulsed and CW VECSEL performance

A. Laurain, J. Hader, T. Wang, J. M. Yarborough, Y. Lai, College of Optical Sciences, The Univ. of Arizona (United States); G. Balakrishnan, T. J. Rotter, P. Ahirwar, The Univ. of New Mexico (United States); J. V. Moloney, College of Optical Sciences, The Univ. of Arizona (United States)

Vertical external cavity surface emitting lasers (VECSELs) have found applications in various industrial and scientific laser applications due to their high-power, high-brightness outputs together with an excellent beam quality. Here we investigate experimentally and theoretically the influence of non-radiative carrier losses on the performance of VECSELs under pulsed and CW pumping conditions. These losses are detrimental to the VECSEL performance not only because they reduce the pump-power to output-power conversion efficiency and lead to increased thresholds, but also because they are strong sources of heat. This heating reduces the achievable output power and eventually leads to shut-off due to thermal roll-over. We investigate the two main sources of non-radiative losses, defect recombination and Auger losses in InGaAs-based VECSELs for the 1010nm-1040nm range as well as for InGaSb-based devices for operation around 2μm. While defect related losses are found to be rather unsignificant in InGaAs-based devices, they can be severe enough to prevent CW operation for the InGaSb-based structures. Auger losses are shown to be very significant for both wavelengths regimes and it is discussed how structural modifications can suppress them. For pulsed operation record output powers are demonstrated and the influence of the pulse duration and shape is studied.

8242-28, Session 8

Non-diffracting beams from surface-emitting lasers

G. S. Sokolovskii, Univ. of Dundee (United Kingdom) and Ioffe Physico-Technical Institute (Russian Federation); S. N. Losev, V. I. Kuchinskii, Ioffe Physico-Technical Institute (Russian Federation); W. Sibbett, Univ. of St. Andrews (United Kingdom); E. U. Rafailov, Univ. of Dundee (United Kingdom)

Non-diffracting light fields such as Bessel beams are of high demand for a number of applications such as optical trapping and tweezing or manipulation of micromachines. To date, Bessel beams have generally been produced by reconfiguring the output beams from the gas and solid-state lasers, but many practical applications require sources to be compact and efficient. For long time, it was believed that the main condition for generation of non-diffracting light fields is the coherence of light but recently we have shown that non-diffracting beams can be formed from low-coherent light sources, including surface and edge-emitting semiconductor lasers and light-emitting diodes. In our experiments, it was shown that spatial rather than the temporal coherence plays the leading role in generation of Bessel beams. We have also demonstrated that in the case of poor laser beam quality generation of Bessel beam can be limited by the divergence of the constituting quasi-Gaussian beam. In this sense, utilization of the surface-emitting lasers, such as electrically and optically pumped VECSELs, offering watt power levels with excellent beam quality could be the best opportunity for generation of high-power non-diffracting beams from the semiconductor light sources. In our experiments, we demonstrate VECSEL-generated Bessel beams with output powers of sub-watt level and central lobe diameters of a few to tens micrometers that suggests these lasers to be the best candidates for replacement of gas and solid-state counterparts for power-demanding applications in optical manipulation.

8242-29, Session 8

Dual-frequency operation of a vertical external-cavity semiconductor laser at 852 nm

F. A. Camargo, J. Barrientos, Lab. Charles Fabry (France) and Ctr. National de la Recherche Scientifique (France) and Univ. Paris-Sud (France); G. Baili, L. Morvan, D. Dolfi, Thales Research & Technology (France); I. Sagnes, Ctr. National de la Recherche Scientifique (France); A. Garnache, Univ. Montpellier 2 (France); F. Bretenaker, Lab. Aimé Cotton (France) and Ctr. National de la Recherche Scientifique (France); P. Georges, Lab. Charles Fabry (France); G. Lucas-Leclin, Lab. Charles Fabry (France) and Ctr. National de la Recherche Scientifique (France) and Univ. Paris-Sud (France)

We describe the dual-frequency emission of a vertical external-cavity semiconductor laser operating at 852 nm. Two coherent laser lines distant from a few GHz are obtained by inserting a birefringent component inside the laser cavity. The different lengths for the ordinary and extraordinary polarizations result in two laser frequencies. The superimposed cross-polarized beams are strongly correlated, as they share the same laser cavity. Additionally, we benefit from the inherently low phase noise of VECSEL thanks to their relaxation-oscillations-free dynamics behavior.

The GaAs/AlGaAs semiconductor structure is designed for emission at λ = 852 nm. The laser cavity consists of a R = 25 mm output coupler, a 25-µm thick Fabry-Perot etalon and a YVO4 birefringent plate. The pump source is a 670 nm fiber-coupled laser diode. Without intracavity component, the laser power reaches 92 mW, limited by the strong thermal roll-over of the structure. With the addition of both the etalon and the birefringent plate, the output power reaches 20 mW on each linearly-polarized single-frequency beam. The frequency difference is imposed by the phase anisotropy of the YVO4 plate, and was in the GHz range in this experiment, below the free spectral range of the laser cavity. The coherence of the two laser beams is assessed through the measurement of their beatnote spectrum, which linewidth is $\leq$ 130 kHz limited by residual mechanical fluctuations of the birefringent plate. This laser source provides an optically-carried microwave signal in a simple architecture, which will be used for the coherent population trapping of cesium atoms in frequency standards.

8242-30, Session 8

Organic VECSELs: towards low-cost UV-visible lasers

S. Chénais, Univ. Paris 13 (France) and Ctr. National de la Recherche Scientifique (France); H. Rabbani-Haghighi, Univ. Paris 13 (France); A. Siove, S. Forget, Univ. Paris 13 (France) and Ctr. National de la Recherche Scientifique (France)

Vertical External Cavity Surface Emitting Organic Lasers (VECSOLs) are the counterparts of VECSELs with organic solid-state gain materials, i.e. dye-doped polymer thin films or organic semiconductors. They gather the well-known properties of VECSELs (high conversion efficiency, excellent beam quality, power scaling capability, high versatility offered by the open cavity) to the key properties offered by organic thin films : low cost, ease of fabrication (by high-throughput processes such as spin coating, potentially ink-jet printing on large areas), broad emission spectra (typ. 100-nm wide) offering a high potential for wavelength tunability, easy chemical tuning (from near-UV to near-IR), and high gain. With a simple structure consisting of a plane highly-reflective mirror onto which a thin film of Rhodamine-640-doped PMMA layer was spun cast, a concave output coupler closing the cavity, pumped by the second harmonic of a Nd:YAG laser (532 nm, 7 ns, 10 Hz), we achieved a record conversion efficiency for a thin-film organic laser of 57% with a diffraction-limited output at 620 nm. Extension to the UV through intracavity frequency doubling enables continuously tunable laser action from 309 to 322 nm, with 2% efficiency, in a very compact setup (1-cm long). Experimental results are shown to be well described by a simple model based on Statz-DeMars equations; they both show a large dependence of device performance versus cavity length and pump pulse duration. Photobleaching issues, which are common to all organic solid-state lasers, will be discussed in detail.

8242-31, Session 8

VECSEL development in AFRL

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Vertical external cavity surface emitting lasers (VECSELs) have proven themselves to be a versatile semiconductor answer to many solid-state lasers. Their design simplicity makes them a very versatile platform for accessing wavelengths from the UV through the THz through direct and frequency-converted emission. Moreover, unlike most semiconductor lasers, the transverse gain profile is almost completely uncoupled from the mode-defining optical cavity. The combination of these two elements allows for very high output power in a stable, Gaussian mode. This wavelength flexibility, combined with an optical cavity that may accommodate additional tuning or nonlinear elements, make the VECSEL a uniquely suited solution to a variety of applications. We will present recent AFRL progress in VECSELs, novel cavities, and potential applications for these lasers.

8242-32, Poster Session

Characterization of gain parameters in quantum-dot and quantum-well based VECSEL structures

M. Mangold, V. J. Wittwer, O. D. Sieber, M. Hoffmann, M. C. Golling, T. Südmeyer, U. Keller, ETH Zurich (Switzerland)

We present gain characterization measurements for different VECSEL structures with active regions based on quantum wells (QW) and quantum dots (QD). To explore the power scaling potential in the femtosecond regime for SESAM modelocked VECSELs, a quantitative understanding of the pulse formation processes is required. In semiconductor gain materials we have to deal with strong saturation effects within an incoming pulse, and therefore the interplay between gain and absorber saturation dynamics is essential for pulse generation. To date typical simulations of modelocked VECSELs relied on an estimated saturation fluence of ≈ 500 µJ/cm2 for QW-based structures, while the value for QD-based structures was unclear.

Using optically-pumped (OP) VECSELs with an emission wavelength around 960 nm, we obtain a saturation fluence in the range of 30-70 µJ/cm2 for both QW and QD active regions, which is substantially lower than previously assumed. We used a high-precision reflectivity measurement setup to determine the change in reflectivity of the OP-VECSEL gain chip as function of incident pulse fluences, pump intensity, and heat-sink temperature. The gain structure is optically pumped up to 10^4 W/cm2 under an angle of 45 degrees with a 808-nm diode laser. We measured the gain saturation behavior and the small-signal gain for several VECSEL samples with QD and QW active regions and different heat-spreader materials (diamond and copper). The characterization was performed at two different pulse durations (130-fs and 1.4-ps pulses) from an 80-MHz Ti:Sapphire laser. A small-signal gain up to 5% for different gain chips was measured, strongly depending on the pump power and the heat-sink temperature.

8242-33, Poster Session

Wetting-layer-pumped continuous-wave quantum dot VECSEL

H. J. Kbashi, A. H. Quarterman, O. J. Morris, Univ. of Southampton (United Kingdom); M. Henini, The Univ. of Nottingham (United Kingdom); A. C. Tropper, K. G. Wilcox, Univ. of Southampton (United Kingdom)

We report a continuous wave quantum dot VECSEL which is wetting-layer-pumped using a 915 nm diode laser. The performance was characterised and compared to standard barrier pumped operation using an 830 nm diode laser. With an unprocessed sample the slope efficiency relative to absorbed pump power was measured as 56 % in the wetting layer pumped case, 1.75 times higher than that of the barrier pumped case. Wetting layer pumping decreases the total pump absorption relative to barrier pumping due to the shorter length of absorbing material, but the quantum defect is smaller, reducing the heat deposited in the active region.

When a 50 µm thick intracavity diamond heatspreader was used, a ten-fold increase in output power, up to 2.25W, was obtained in the barrier pumped case. A much smaller two-fold increase in power, to a maximum of 0.3 W, was seen for the wetting layer pumped case. This significantly smaller increase in power for the thermally managed wetting layer pumped sample is due to the absorption of the majority of the pump light in the 500 micron thick GaAs substrate, where the diamond has little effect in removing the heat. A tailored sample with a double periodic DBR would allow the full potential of wetting layer pumping to be evaluated as this would both increase the pump absorption due to the double pass through the active region and localise the heat generation to the active region.

8242-34, Poster Session

Sub-80-fs timing jitter of a stabilized SESAM modelocked VECSEL

V. J. Wittwer, R. van der Linden, ETH Zurich (Switzerland); B. Resan, K. J. Weingarten, Time-Bandwidth Products AG (Switzerland); T. Südmeyer, U. Keller, ETH Zurich (Switzerland)

We present timing jitter measurements of an actively stabilized VECSEL passively modelocked with a quantum dot (QD) SESAM. For VECSELs we can expect much lower noise compared to edge-emitting semiconductor lasers because the interaction length with the quantum well gain is very short, and the cavity losses are very low, which results in a high-Q cavity with low noise. We demonstrate a noise performance that is comparable to ion-doped solid-state lasers which typically show excellent stability.

The laser generates 4-ps pulses with 2-GHz repetition rate and 20-mW average output power at a wavelength of 956 nm. The VECSEL is optically pumped perpendicular to the surface using an 808 nm fiber coupled multimode diode laser. All optical elements including the pump diode are mounted inside a metallic housing to shield against air currents and vibrations. The repetition rate was stabilized with a piezo actuator controlling the SESAM position. The laser was phase-locked to a low noise reference oscillator with a feedback loop of 10 kHz bandwidth. The timing phase noise power spectral density was measured with an Agilent E5052B Signal Source Analyzer. Integration over an offset frequency range of 1 Hz to 1 MHz resulted in an RMS timing jitter of less than 80 fs, which is several times lower than previously demonstrated modelocked VECSELs. Below 1 kHz we are limited by the reference source and above 1 MHz by the system noise floor. Above 30 kHz the timing phase noise is lower than the reference source.

8242-35, Poster Session

High-average power femtosecond VECSELs with tunable repetition rates up to 10 GHz

O. D. Sieber, V. J. Wittwer, M. Hoffmann, M. C. Golling, T. Südmeyer, U. Keller, ETH Zurich (Switzerland)

Compact multi-GHz optical sources operating in the femtosecond regime are of high interest for many applications, such as optical clocking, photonic switching, optical sampling and frequency metrology. quantum well (QW) VECSELs (Vertical External Cavity Surface Emitting Lasers) passively modelocked by quantum dot (QD) SESAMs (semiconductor saturable absorber mirror) achieved repetition rates up to 50 GHz in the picosecond regime. The low saturation fluence and the large gain cross-section of the semiconductor gain suppresses the Q-switching instabilities. The low saturation fluence of QD-SESAMs enables modelocking with the same mode area on SESAM and VECSEL, which allows for a simple cavity design. In this submission, we discuss the performance of femtosecond multi-GHz VECSELs based on QW and QD gain and modelocked by QD-SESAMs.

We achieved 1.05 W in 784-fs pulses from a QD-VECSEL with extremely low dispersion modelocked by a QD-SESAM with fast recovery dynamics. A similar QW-gain structure modelocked with the same SESAM enabled stable 480-fs with an average output power of 300 mW at a repetition rate of 7 GHz. Furthermore, we investigated repetition rate scaling by change of the cavity length. Using a cavity configuration for which the laser mode on the VECSEL chip remains nearly constant for a change in cavity length, we demonstrated fundamentally modelocked pulses with 150 mW average power over a tuning range from 6.5 GHz up to 10 GHz.

8242-36, Poster Session

Strain compensation of InGaAs/GaAs SDL gain mirrors grown by molecular beam epitaxy

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Efficiency and lifetime of semiconductor disk lasers (SDL) are strongly dependent on the crystalline quality of their gain mirrors. The lifetime is usually limited by the propagation of dark line and dark spot defects that originate from the lattice strain accumulated in the gain mirrors. The net strain associated with the high number of quantum wells required for adequate gain in SDLs makes them particularly vulnerable to the ap-pearance of the defects. This problem is severe for GaInAs/GaAs quantum wells emitting at wavelengths longer than 1100 nm due to the high In/Gallium ratio required. A common way to alleviate the net lattice strain is to introduce strain compensation layers to cancel the net strain.

Despite the fact that remarkable SDLs results using strain compensation have been published before, the details of the structures and growth have been scarcely reported. In this presentation we discuss the design and growth condition aiming at alleviating the the dark lines in GaInAs/GaAs quantum well gain mirrors emitting at 1120-1170 nm. The effect of the strain compensation has been assessed by measuring the curvature of the wafers and by mapping the photoluminescence to identify the dark areas. We demonstrate that ~90 % strain compensation is sufficient for removing the dark lines. Rapid thermal annealing studies revealed that the strain compensation prevents appearance of dark line even for samples that have been annealed at temperatures as high as 700 °C for a considerable time. Using the strain compensation approach, we demonstrate multi-watt SDL operation.

8242-37, Poster Session

A wavelength-tuneable picosecond-pulse passively mode-locked VECSEL

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It has been shown that an intra-cavity etalon can be used as a tuning element, allowing the selection of an optimal operating wavelength for a passively mode-locked VECSEL [1]. We demonstrate that an intra-cavity etalon can also be used to create a wavelength tuneable, passively mode-locked, VECSEL. Using a 25 micron thick, fused-silica intra-cavity etalon we were able to demonstrate a tuning range of 14 nm around a centre wavelength of 1034 nm. The tuning range was limited by the 14 nm free spectral range of the etalon.

The tuning range was demonstrated using a Z-cavity configuration VECSEL. A 6 quantum-well, anti-resonant gain chip with a design wavelength of 1025 nm was used in combination with a 0.3% transmission output coupler. The VECSEL was passively mode-locked using a single quantum-well, surface recombination SESAM. The radius of the mode area was approximately 60 microns on the gain chip and 15 microns on the SESAM. With the intra-cavity etalon inserted at Brewster's angle between the gain chip and output coupler, a lasing threshold increase of 57% was recorded. Over the 14 nm tuning range, the VECSEL produced near-transform-limited 3.1 ps sech2 pulses at a fundamental repetition rate of 1 GHz and with a minimum output power of 8 mW.

The centre wavelength of the VECSEL falls within the bandwidth of an ytterbium doped fibre-amplifier. An amplified, wavelength-tuneable, picosecond-pulse, passively mode-locked VECSEL would be highly suitable for the generation of heralded single photons in photonic crystal fibre at GHz bit-rates [2].

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[2] Wadsworth, W.J., Joly, N., Knight, J.C., Birks, T.A., Biancalana, F., Russell, P. St.J. (2004) Supercontinuum and four-wave mixing with Q-switched pulses in endlessly single-mode photonic crystal fibres. Optics Express, 12, 299

8242-38, Poster Session

MBE growth of electrically pumped VECSELs

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Vertical external cavity surface emitting lasers (VECSELs) are excellent high power semiconductor lasers with diffraction-limited circular output beams and outstanding modelocking performance even at a repetition rate of tens of GHz. Passively modelocked optically-pumped VECSELs, using a semiconductor saturable absorber mirror (SESAM), have generated shorter pulses and higher average powers than any other modelocked semiconductor laser. Electrical pumping (EP) of modelocked VECSELs is the obvious next step towards compact high-power ultrafast laser sources.

Epitaxy of VECSELs is a critical process. It contains many layers with a total thickness around 10 µm for 960 nm emission wavelength. For these thick epitaxial structures, thickness and material composition have to be grown very precisely. Thickness variations have to be smaller than 1.5 % for working devices. For optically pumped VECSELs no intentional doping of the layers is necessary. This results in low optical absorption of the lasers.

Electrical pumping needs doped layers and also requires changes in the epitaxial design. Additional growth steps like a current spreading layer are necessary. Crucial for high power operation is a low electrical resistance, because the electrical losses heat up the device which lowers the performance. Looking at the different sections of the device, the p-type doped mirror gives the largest contribution to the electrical resistance. High doping levels might solve the problem, but also increase the optical absorption. There are certain possibilities to both reduce the resistance and keep the optical losses low. Among these techniques are graded interfaces and improved doping schemes.

Conference 8243: Laser Applications in Microelectronic and Optoelectronic Manufacturing (LAMOM) XVII

Monday-Thursday 23-26 January 2012

Part of Proceedings of SPIE Vol. 8243 Laser Applications in Microelectronic and Optoelectronic Manufacturing (LAMOM) XVII

8243-01, Session 1

Near-field nanopatterning on rough surfaces using optically trapped microspheres

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The ability to pattern surfaces at the nanometer scale is of critical importance in a great number of emerging commercial technologies. Where most existing nanopatterning technologies are able to produce uniform sub-100 nm structures on flat surfaces through both parallel and serial methods, few techniques are able to provide similar pattern fidelity on rough or textured surfaces. Here we demonstrate the use of optical trap assisted nanopatterning (OTAN) to produce nanoscale features on complex surfaces including polyimide and silicon substrates. In this technique, a micron-scale dielectric sphere is positioned in close proximity to a substrate using an optical trap and is subsequently used as a near-field focusing objective. By using a Bessel beam optical trap, the microsphere is able to position itself above the surface due to the force balance between the surface interactions and the optical scattering force. This effect allows the bead to track surface features without falling out of the trap or losing positioning capabilities in the x-y direction. We experimentally show the use of OTAN for creating continuous and isolated nanoscale features and characterize the patterning accuracy on these surfaces. Moreover, we explore the effects of a step height, elevation angle, and trapping power on the ability of spheres transverse steps.

8243-02, Session 1

Picosecond fiber laser microfabrication of THz wire-grid polarizers on polymer membrane substrates

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Ultrafast picosecond lasers provide the gentle cold ablation required to selectively remove a 400 nm metal film from an unsupported ultra-thin polymer membrane without damaging the membrane substrate. Selected areas of the metal film are completely removed in an ablative lift-off process enabled by a single laser pulse. No damage to the polymer membrane is observed even for samples with the metal completely removed over a 50x50 mm area of the membrane. The 400 nm thick metal films can be patterned into arbitrary forms with feature sizes as small as 10 micrometers, and even submicron features are realistically possible with a modification to the processing system. The skin depth of aluminium in the THz regime is significantly shorter than the 400 nm metal thickness, so thicker metal films that are significantly more difficult to machine are not beneficial. As an example, thin-film wire grid polarizers for the THz regime are demonstrated. The thin-film polarizers are much easier and faster to fabricate than polarizers made by winding free-standing wires around a frame and their performance is very comparable. The thin-film polarizers also have the added benefit of a significantly higher potential for functionality deeper in to the THz spectrum due to their capacity for smaller feature sizes. More intricate patterns, such as meshes, can also be made to create THz bandpass filters. This method can be extended to cold ablation processing of multilayer films fabricated on thin polymer substrates for applications such as plastic electronics, displays and solar cells.

8243-03, Session 1

Laser direct writing of high refractive index polymer/TiO2 nanocomposites

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Laser Direct Polymerization has been proven as one of the promising approaches to the manufacturing of 3D polymer MOEMS. However, the 3D polymer structures often lack important functional properties, e.g. optical, electrical, mechanical and magnetic properties. Therefore, their use in MOEMS is limited. To overcome this limitation, functional nanocomposites can be prepared by incorporating inorganic nanoparticles into the polymer matrices. The properties can be tuned by varying the composition, size and concentration of inorganic nanoparticles. In this work, we present a novel laser direct writing method to fabricate structures on the basis of high refractive index photosensitive composites. The structures will be used e.g. in optical tweezers, as the acting forces depend on the refractive index of the materials. For this, we pursue two different steps. The first step is to develop a homogeneous dispersion of nanocomposites by directly mixing the polymer and high refractive index TiO2 nanoparticles with different concentrations, subsequently optimize the suitable nanocomposite concentration, i.e. realization of high refractive index nanocomposites and investigating the polymerization process at specific laser wavelengths. The second step is using the two-photon polymerization (2PP) effect induced by femtosecond laser pulses to write novel 2D and 3D micro- and nanostructures containing functional nanoparticles. This technology opens new prospects for the realization of functional MEMS and MOEMS with increased integration and higher level of miniaturization.

8243-04, Session 1

Bimetallic grayscale photomasks written using flat-top beam vs. Gaussian beam

R. Qarehbaghi, G. H. Chapman, W. Boonyasiriwat, Simon Fraser Univ. (Canada)

Grayscale photomasks are bi-layer metallic films consist of two thin layers of Bi-on-Indium or Tin-on-Indium. These films become controllably transparent by accurately varying laser power such that the optical density changes almost linearly from ~3 OD (unexposed) to <0.22OD (fully exposed). Previously, a direct-write raster-scan photomask system with a multiline CW Argon-ion laser was used with feedback-controlled Gaussian beam to achieve 256-level grayscale masks. With the Gaussian laser spot, the feedback system was effective such that the average gray-level error reduced from ±4.2 gray-levels in an open-loop approach to ±0.3 gray-levels in a closed-loop approach. As most of the gray-level errors are due to the Gaussian beam profile making variations on the mask, a beam shaper was used to change the laser spot to a flat-top beam. Raster-scanning the mask using the flat-top beam helps further reduce the gray-level errors. Preliminary results show that the flat-top beam reduces gray-level fluctuations, and lines can be written with less overlapped area helping to have higher resolution masks. Having lines closer with smaller overlap suggests that accurately controlled laser power results in an accurate OD profile on the mask even with an open-loop approach. The accuracy of the laser power is controlled by a beam stabilizer that maintains the intensity within 0.03%. Some test patterns are written on the mask using open-loop and closed-loop approaches to demonstrate how accurate the gray-levels of the bimetallic thin-films are using a flat-top laser beam.

8243-05, Session 2

Multiple interactions between an excimer laser beam and a ZnO single crystal target

E. Khan, S. Langford, J. T. Dickinson, 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 several PLD related applications involving the emitted atomic and molecular species. In this talk we examine these phenomena and surface/near-surface modifications in oriented single crystals of the transparent semiconductor ZnO (band-gap ~3.4 eV). This material is of high interest for potential production of transparent conductors and transistors, solar cells, lasers, sensors, and in catalysis (including possible use in the photo-dissociation of water). We show that there are laser fluences where the latter interacts strongly with the laser light via two photon absorption within the ~25 ns pulse width. This leads to very interesting modification of the detected particle emission including very easily detected excited Zn atoms in long lived Rydberg states. In addition, slow positive Zn ions are also generated via the same 2 photon excitation. Models that depend on the survival of excitations near surfaces as a function of particle velocity are shown to nicely predict the energy distributions of the detected Zn Rydberg and slow Zn ions. Implications of these studies on PLD of ZnO will be discussed.

8243-06, Session 2

Optimization of the volume ablation rate for metals at different laser pulse-durations from ps to fs

B. Neuenschwander, B. Jaeggi, M. Schmid, U. Hunziker, Berner Fachhochschule Technik und Informatik (Switzerland)

Ultra short laser pulses in the ps or fs regime are used, when high requirements concerning accuracy, surface roughness, heat affected zone etc. are demanded. The interest for applications has significantly increased with the reported promising results and new developed processes. However, beside the machining quality also the process efficiency (defined as ablated volume per time) denotes a key factor for the successful transfer of this technology into real industrial applications. Based on the logarithmic ablation law, which holds for ultrashort pulses, it has been shown that a maximum volume ablation rate per average power can be achieved with an optimum setting of the laser parameters including the pulse duration. This maximum volume ablation rate depends on the threshold fluence and the energy penetration depth. For pulses shorter than about 10 ps the threshold fluence is found to be almost constant due to the thermalization time which is in the same order for metals. In contrast, the results of an analysis of the energy penetration depth for pulse durations between 10 ps and 100 ps implies that this measure could still increase for shorter pulses resulting in a higher volume ablation rate compared to the pulse duration of 10 ps. A systematic study of the maximum volume ablation rate for typical metals like copper, iron, stainless steel and aluminum is presented and the possibility of improvement of the volume ablation for pulses shorter than 10 ps is discussed.

8243-07, Session 2

Time-and space resolved microscopy of induced ablation with ultrashort laser pulses

M. Domke, S. Rapp, G. Heise, H. P. Huber, Hochschule München (Germany)

Laser lift-off processes have been observed during structuring CIGS thin film solar cells with ultra-short laser pulses, if a Mo film on glass is irradiated from the glass side or ZnO is ablated from the CIGS layer. To investigate the underlying physical effects, a pump-probe setup is used for time- and space resolved microscopy. The setup consists of a 650 fs-laser pulse at a wavelength of 1053 nm that is split up into a pump and a probe beam. The pump beam ablates the thin film, while the frequency doubled probe beam illuminates the ablation area after an optically defined delay of up to 4 ns. For longer time delays, a second electronically triggered probe laser is used with a pulse duration of 600 ps. A CCD Camera behind a microscope objective captures an image of the ultra-short exposed region. Hence, a series of pictures is taken with time delays between femto- and microseconds, showing the complete temporal evolution of induced laser ablation (lift-off). First results show that mechanical deformation is initiated several hundred picoseconds after the impact of the laser pulse, whereas about 100 ns elapse until the actual Mo or ZnO film lift-off. Furthermore, the temporal evolution of the reflectivity and the bulging height can be investigated.

8243-08, Session 2

Ultrafast coherent phonon excitation and non-thermal melting: a molecular dynamics study

Y. Wang, X. Xu, Purdue Univ. (United States)

Non-thermal melting upon ultrafast laser excitation has been observed in semiconductors, metals, and semi-metals with Peierls distortion, such as bismuth. Non-thermal melting is distinguished from thermal melting in the following three aspects: 1) the liquid phase is detected at a sub-picosecond time scale, 3) the lattice might remain cold when phase transition occurs, and 3) it may occur at laser fluences much higher than the thermal melting threshold. In semiconductors, with a large percentage of excited carriers (above 5~6%), the potential energy surface is strongly modified and the anti-bonding character of the conduction band accelerates the lattice disordering.1 In bismuth, the excited electron gas displaces the equilibrium position of atoms, and these atoms start to oscillate around the new equilibrium position along the direction of the Peierls distortion2, through which longitudinal optical A1g phonon mode is generated. However, how the initially well-oriented displacement can induce such an ultrafast collapse of the lattice structure is still not clear. This study attempts to reveal the mechanism behind this coherent-phonon triggered ultrafast phase transition. Molecular dynamics simulation is employed to investigate the melting process with and without coherent phonon excitation in bismuth telluride, which also has Peierls distortion in the lattice structure. Our results show that the structural distortion caused by coherent phonons appears as early as 80 fs, while it takes about 2 picoseconds for the whole phonon-excited area to evolve into liquid. The co-existence of solid and liquid phase can explain the phase-transition times observed experimentally. It was also found that the temperature in the phonon-excited area rises up thousands of degress within tens of femtoseconds, while the rest of the lattice remains at the initial temperature even after several picoseconds. This phenomenon is analogous to the heat transfer across a solid-liquid interface but is not completely the same, since in this case there is no abrupt solid-liquid interface between the cold lattice and liquid.

1. Rousse, A. et al. Non-thermal melting in semiconductors measured at femtosecond resolution. Nature 410, 65-68 (2001).

2. Cheng, T.K. et al. Impulsive Excitation of Coherent Phonons Observed in Reflection in Bismuth and Antimony. Applied Physics Letters 57, 1004-1006 (1990).

8243-10, Session 2

Laser ablation plasmas for diagnostics of structured electronic and optical materials during or after laser processing

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Laser induced plasmas can be used for real-time optical diagnostics during laser processing of electronic, optical, and electro-optical structures. An overview of the latest results in fundamental studies of laser ablation mechanisms will be presented, including behavior of acoustic and supersonic shockwaves, an approach to nanoscale chemical analysis in the optical near-field, a comparison between nanosecond and femtosecond laser ablation processes and crater formation.

Plasma monitoring and diagnostics can be realized during laser processing in real time by means of measuring optical emission that originates from the pulsed laser-material interaction. The technique is particularly beneficial in fabrication of thin-film structures, such as electronic, photovoltaic and electro-optical devices or circuits of devices. Post-process applications (e.g., quality assurance and control) include rapid micro-localized chemical analysis with high spatial resolution in lateral and depth profiling, without a need for sample preparation or evacuation of samples. Spectrum acquisition from a single laser shot provides detection limits for metal traces of ~10 mg/kg, which can be improved by accumulating signal from multiple laser pulses. Three to four orders of magnitude lower detection limits can be obtained with a femtosecond laser ablation - inductively coupled plasma mass spectrometer (LA-ICP-MS).

8243-11, Session 3

Novel semiconductors and nanoscale patterning using pulsed lasers

M. J. Aziz, Harvard Univ. (United States)

The discovery of semiconductor materials whose properties depend dramatically on the introduction of a dopant or alloying species at levels below a few atomic percent has opened opportunities for the synthesis of quantum structures and hitherto unexplored device structures. Examples of these dilute alloys are GaNxAs1 x, which is characterized by a giant bandgap bowing that makes it ideal for quantum confinement; Ga1 xMnxAs, which displays ferromagnetic behavior that makes it a prime candidate for spintronics applications; and Si1 xSx, which displays an insulator-to-metal transition that could lead to sub-bandgap photodetection and intermediate-band photovoltaic applications. In all of these alloys, the very low value of x opens new routes to their synthesis and integration. Additionally, the discovery of sub-bandgap electroluminescence from silicon controllably injected with native point defects creates the opportunity for the development of an electrically pumped silicon laser operating at important communications wavelengths.

I will report on the explorations of my collaborators and my group on the synthesis and patterning of these materials using Pulsed Laser Melting (PLM) induced rapid solidification following ion implantation or ultra-thin film deposition. PLM has unique advantages for hyperdoping, metastable alloy formation, and point defect manipulation. It also enables an entirely new approach to the realization of novel 1D and 0D quantum structures in an arbitrarily programmable direct writing process creating concentration changes with lateral resolution that could approach 10 nm.

8243-12, Session 3

Annealing of sol-gel derived metal-oxide thin films by a UV laser pulse train

J. Zhang, Panasonic Boston Lab. (United States)

Annealing of Sol-Gel material has been proved to be an eco-friendly and low-cost method of depositing inorganic thin film. This method is, in particular, useful in large-area processing for printable electronic devices. Traditionally, furnace is used as heating source to anneal the Sol-Gel material at the temperature >400oC. Use of laser makes (i) low temperature processing and (ii) direct patterning possible by confining the heat to a localized area. Taking advantage of these two effects, one can perform laser annealing to simultaneously deposit and pattern the desired thin film without causing significant collateral damages.

Annealing of high-k metal-oxide (TiO2, PZT, and BaTiO3) Sol-Gel by a 266nm laser pulse train on ink-coated films was investigated. The organic TiO2, PZT and BaTiO3 Sol-Gel ink from Chemat Technology Inc. were used as precursors. A high repetition rate DPSS laser (up to 300 kHz, 25ns, 266nm, Coherent AVIA series), which produces a ns pulse train with 3.3 µs -33.3 µs interval of pulse-to-pulse, was used as the heating source. The pulse train heating combines the advantages of single laser pulse and continuous wave laser heating.

Uniform and crystalline metal-oxide films on silicon substrate were successfully obtained with this laser pulse train annealing process. In this paper, in addition to the annealing procedure and recipe, characterizations of the annealed films with transmission electric microscopy, atomic force microscopy, scanning electric microscopy as well as Raman spectroscopy will be reported. The mechanism of laser pulse train induced annealing was also discussed.

8243-13, Session 3

F2 laser modification of silicone-coated polycarbonate for lightweight automobile window

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Transparent, hard silica glass (SiO2) layer was formed on a conventional protective coat made of silicone ([SiO(CH3)2]n) on polycarbonate plate by the 157 nm F2 laser-induced photochemical modification of silicone into SiO2. An optimum laser irradiation time of the F2 laser was found to form crack-free SiO2 layer. High optical transparency of the samples in visible light region remained unchanged after the F2 laser irradiation. In the Taber abrasion test, the SiO2 layer remarkably reduced the number of the scratches, showing a low haze value. The haze values of the samples also depend on the thickness of the silicone-protective coat underneath the SiO2 protective layer. As a result, the delta-Haze was successfully reduced to 3.6 %, compared with the cases in the nonirradiated sample and a bare polycarbonate of approximately 11.3 and 41.3 %, respectively, which is comparable to the case in a bare silica glass of approximately 1.6 %. In addition, the thickness of the SiO2 protective layer was estimated to be approximately 0.44 micron for the 30-s laser irradiation by immersing the samples in 1 wt.% hydrogen fluoride aqueous solution and measuring the depth by a surface profilometer.

8243-14, Session 3

Laser-induced transient stress distribution inside a single crystal by time-resolved birefringence imaging

T. Tochio, M. Sakakura, S. Kanehira, Y. Shimotsuma, K. Miura, K. Hirao, Kyoto Univ. (Japan)

When femtosecond laser pulses are focused inside a single crystal, anisotropic structural change occurs along several crystal orientations. For example, when femtosecond laser pulses are focused inside a rock salt crystal, such as MgO and LiF, a cross-shaped pattern with highly concentrated dislocations appears in the direction and cleavages occur in the direction from the photoexcited region. These anisotropic structural changes should be attributed to the transient stress change after the photoexcitation, because various researches have elucidated that a large thermal stress and a strong stress wave appears in the photoexcited region. Therefore, we have to elucidate the transient stress distribution change after the irradiation with a femtosecond laser pulse inside crystals to elucidate the mechanism of the anisotropic structural change. The mechanism is also important for realizing a novel laser fabrication technique to control the structural changes in crystals. In this research, we developed a novel time-resolved polarization imaging system, in which circularly polarized femtosecond laser pulse is used as the probe light. The system provides us with the transient birefringence distribution after the photoexcitation. Because the birefringence is the result of the laser-induced transient stress, we can elucidate the mechanism of the structural change based on the observation by the system. In addition, we observed and controlled the transient stress distribution by interference of stress waves generated from the multiple photoexcited regions. The system can contribute to elucidate relation between laser-induced transient stress distribution and anisotropic structural change and develop a novel micro-fabrication technique.

8243-13, Session 4

XPS study of InP/InGaAs/InGaAsP microstructure irradiated by KrF and ArF lasers in different environments

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Laser-induced formation of chemically and structurally modified surface of III-V quantum semiconductors has been investigated as a method leading to selected area bandgap nanoengineering achieved through the quantum well intermixing (QWI) process. In this study, we have investigated the effect of irradiating InP/InGaAs/InGaAsP quantum well (QW) microstructures with KrF and ArF excimer lasers on the modification of surface properties of the cap InP material. Typically, the irradiation was carried out with pulse fluence not exceeding 150 mJ/cm2, i.e., below the threshold for ablation, and with up to 100 laser pulses. Samples irradiated in air, water and liquids comprising different elements have been analysed with an X-ray photoelectron spectroscopy (XPS) technique. A significant increase of In and InP oxides has been observed following the irradiation in an air environment, which confirms some of the results reported earlier. In contrast, the samples irradiated in deionized water show a negligible change in chemical composition. Rapid thermal annealing (700°C in forming gas of N_2 : H_2 = 9 : 1 for 2 minutes) of laser irradiated QW microstructures leads to bandgap shifting that depends on both the chemical composition and the presence of nanoscopic defects induced by the laser. These findings have provided important arguments for the construction of a physical model concerning laser-induced defects mediating atomic intermixing in III-V semiconductors.

8243-14, Session 4

Designed near fields for parallel surface nanostructures

F. Hubenthal, S. Maag, A. Jamali, B. Witzigmann, F. Träger, Univ. Kassel (Germany)

Generation of highly ordered nanostructures with dimensions well below the diffraction limit is a great challenge in nanotechnology. To achieve this goal, irradiation of triangular gold nanoparticles with single laser pulses has been successfully applied [1,2]. However, with single pulses, only certain nanostructure shapes can be generated. To achieve a higher variability, time delayed double pulses or shaped laser pulses can be applied, which allow a better spatial control of the local fields.

In this contribution, we present experiments, where triangular gold nanoparticles supported on fused silica were irradiated with fs-pulsed laser light with a central wavelength of 790 nm. After irradiation, nanostructures with dimensions well below the diffraction limit were created on the fused silica surface by ablation. The shape of the nanostructures is explained by 3D simulations of the energy density of the local fields, using a finite integration technique in time domain. In addition, first studies will be presented, in which two time-delayed pulses with different polarisation directions are applied. This strategy allows the generation of more complex predetermined nanostructures and to monitor the ablation process of the triangular nanoparticles by investigating the nanostructure evolution as a function of time delay between the pulses.

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8243-15, Session 4

Surface plasmon-assisted nanolithography with nanometric accuracy

K. Ueno, Hokkaido Univ. (Japan)

Surface plasmons (SP) become increasingly important for implementation of optical lithography with sub-wavelength resolution. Typically, optical field of propagating or localized SP modes formed on nanoscale metallic features is used for contact exposure of photosensitive medium. Resolution of SP lithography generally depends on the size of metallic features. Here we demonstrate SP nanolithography in a commercial photoresist which exploits SP modes localized in a few nanometer-wide gaps between larger gold nanoparticles.

To facilitate the collective SP modes, arrays consisting of nanogap gold nanoblock pairs (one block: 80 nm x 80 nm x 35 nm) were fabricated on glass substrates by electron-beam lithography and lift-off techniques. This substrate works as a photomask. To achieve exposure by near-field, 70 nm thick film of positive photoresist spin-coated on a glass substrate was brought into direct optical contact with the top surface of nanoblocks. Light source was a beam of a femtosecond laser (f=82 MHz). The beam was polarized linearly along the diagonal of the blocks.

Films of positive resist attached to nanoparticle arrays were exposed to the laser beam with gradually decreasing total exposure dose, and size and shape of resulting pits in the developed photoresist surface was observed. As the result of the exposure, a pattern of pits with period of 400 nm, replicating arrangement of nanoblock pairs can be seen after the development. While typical lateral size of pits is 30-40 nm, at some locations one can see features with lateral size of about 5 nm.

8243-15, Session 4

Dynamics of TiO_2 nanoparticle formation and deposition for nanostructured thin films

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The dynamics of the nanoparticle-assisted pulsed laser deposition (NAPLD) process for the formation of high surface-area aligned nanostructured TiO_2 films are studied by time-resolved, in situ diagnostics in different background gas pressure regimes. TiO_2 is a workhorse wide-bandgap semiconductor for applications including photocatalytic water splitting and photoanodes for dye-sensitized solar cells. Laser vaporization and condensation in background gases offers opportunities for both doping, and deposition of high surface area nanoparticle films. Here we study the NAPLD process of high surface area, vertically aligned TiO_2 nanoparticle films not only in the typically-employed high-pressure regime (several Torr), but concentrating upon background oxygen pressure conditions of 30-200 mTorr more typically employed for PLD of many oxide thin films. The surface areas and film morphologies have been found to vary considerably as a function of target-substrate distance and the background pressure. In situ ICCD imaging of laser-induced incandescence and Rayleigh scattering from nanoparticles, and laser-induced fluorescence from atoms and molecules, are compared with in situ particle sizing analysis with a differential mobility analyzer in order to define the timescales for nanoparticle formation and transport in both high and low pressure regimes, including the effects of thermophoresis. Ex situ scanning and transmission electron microscopy, x-ray scattering, and optical analysis of materials collected at various positions are used to correlate the film morphology with the in situ studies. The low pressure nanoparticle deposition process is found to include dynamic multipulse interactions between cooling plasma plumes and nanoparticles condensed on previous laser shots.

Research supported by the U.S. Department of Energy, Basic Energy Sciences, Materials Science and Engineering Division, and performed in part at the Center for Nanophase Materials Sciences, which is sponsored at Oak Ridge National Laboratory by the Office of Basic Energy Sciences, U.S. Department of Energy.

8243-16, Session 4

Laser ablation and nano-material fabrication in supercritical fluids

K. Saitow, Hiroshima Univ. (Japan)

We developed a novel method of fabricating nanomaterials by conducting pulsed laser ablation (PLA) in a high-pressure supercritical fluid. This method has three distinct properties: (i) The plasma density is locally enhanced, because the plasma generated near the target is spatially confined by the high-pressure fluid, e.g. 20 MPa; (ii) cooling rate for the thermal relaxation processes is controlled during the generation of nanoparticles, because thermal conductivity and heat capacity of a supercritical fluid have infinite values at the vapour-liquid critical point, and vary easily by changing the pressure; and (iii) a variable density is achieved, from gas-like to liquid-like, by changing the fluid pressure in the absence of a phase transition. Here we show the nanosecond PLA of two systems, both of which fabricate the photofunctional nanomaterials. That is, red, green, and blue (RGB) light-emitting silicon nanocrysltals were generated. Note that changing the fluid pressure during the PLA varies the luminescence colours and increases the luminescence intensity by a factor of 100. As for gold nanoparticle, the morphology is changed significantly by the fluid pressure during the PLA, i.e. gold nanonecklace, nanosphere of the diameter ranging from 30 to 800 nm, and medusa-type gold particle. In particular, the medusa-type gold nanoparticle is a significant SERS (Surface Enhanced Raman Scattering) active material. Namely, the SERS enhancement factor becomes 109, whose value enables us to measure a single molecules detection of Raman spectrum.

8243-17, Session 4

Template-assisted metal nanoneedle/nanoprotrusion array fabrication at a sub-diffraction-limited scale

Y. Tanaka, Keio Univ. (Japan) and Harvard Univ. (United States); J. D. B. Bradley, E. Mazur, Harvard Univ. (United States); M. Obara, Keio Univ. (Japan)

We present a template-assisted sub-diffraction-limited method for patterning nanoneedles and nanoprotrusions on a metal film.

In recent years, methods for downsizing and fabricating arrays of such nanostructures have been widely studied. The diameter of apex of the nanostructures has been reduced to sub-diffraction-limited size using a tightly focused femtosecond laser pulse. Nanoprotrusion arrays fabrication has been achieved over a large area via interference of femtosecond laser beams (but with $\geq$ 1 um in period).

In this paper, we demonstrate fabrication of nano-spaced and nano-sized nanoprotrusion arrays by exposing a gold-film-coated nanohole template to 800 nm femtosecond laser pulses. We obtained the diameter and periodicity at the sub-diffraction-limited scale. Our method is based on exploiting near-field optical effects to overcome the diffraction limit imposed by conventional far-field optics.

FDTD simulations reveal that the electric field intensity is selectively enhanced in the holes due to the excitation of surface plasmons. We successfully fabricated nanoneedles/nanoprotrusions with diameters of approximately 100 nm and periodicity of 460 nm over a large area by a single femtosecond laser pulse with a spot diameter of 0.55 mm. In the applied template, diffraction-limited laser spot diameter is 642 nm. We observed spherical particle ejection from the top of the nanoprotrusions upon increasing the laser fluence. The fabricated structures could be useful for smart applications such as field emission devices, nanosurgery and surface enhanced Raman scattering. Our proposed method also has a significant potential as a repeatable and cost-effective fabrication technology for plasmonic devices and metamaterials.

8243-18, Session 5

Applications of picosecond laser and pulse-burst in precision manufacturing

R. Knappe, LUMERA LASER GmbH (Germany)

Picosecond lasers are established as powerful tools for micromachining. Industrial processes like micro drilling, surface structuring and thin film ablation benefit from a process, which provides highest precision and minimal thermal impact for all materials. Applications such as microelectronics, semiconductor, and photovoltaic industries use picosecond lasers for maximum quality, flexibility, and cost efficiency. The range of parts, manufactured with ps lasers spans from microscopic diamond tools over large printing cylinders with square feet of structured surface. Cutting glass for display and PV is a large application, as well.

With a smart distribution of energy into groups of ps-pulses at ns-scale separation (known as burst mode) ablation rates can be increased by one order of magnitude or more for some materials, also providing a better surface quality under certain conditions.

The talk will report on the latest results of the laser technology, scaling of ablation rates, and various applications in ps-laser micromachining.

8243-19, Session 5

High sensitive concentration analysis of biochemical liquids using a microfluidic chip fabricated by femtosecond laser

Y. Hanada, K. Sugioka, K. Midorikawa, RIKEN (Japan)

Protein carry out many biological, chemical functions, including, but not limited to, catalyzing reactions in living organism, decoding information in cells, regulating biochemical activities, storing and transporting small molecules, providing mechanical support, and serving many other specialized functions. The onset of various diseases usually involves altered protein expression and distribution. Therefore, detection technique for certain proteins at low level is useful for the diagnosis of specific diseases in health care although most of the conventional techniques are only capable of detecting abundant proteins.

In the meanwhile, we have proposed using microchips with three-dimensional (3D) microfluidic structures to detect concentration of liquid samples. In this case, we have developed a technique for fabricating 3D microfluidic structures with smooth internal surfaces inside a photostructurable glass. This method uses femtosecond (fs) laser direct writing followed by annealing and successive wet etching. It permits rapid prototyping of 3D microfluidics with different structures, which is highly desired by biochemical processes. Furthermore, microoptical elements such as optical waveguide can be easily integrated with the microfluidic structure, permitting more functional analysis. In this talk, we attempted fabricating a microfluidic chip integrated with waveguide in the glass for protein concentration assay. By covering the internal walls of microfluidics with low refractive index polymer, high-sensitive protein concentration assay is performed at low level.

8243-20, Session 5

Ultrahigh precision surface structuring by synchronizing a galvo scanner with an ultrashort pulsed laser system in MOPA arrangement

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Currently in industrial applications ultra short pulsed laser systems will be used, if high requirements concerning accuracy, defined surface roughness and small heat affected zone are demanded. For surface and 3D structuring these systems are usually used in combination with galvo scanners. Today, the available industrially suited ultra short pulsed systems are turnkey systems, set up in a MOPA arrangement with passively mode locked seed laser and rod or disk amplifier. The frequency of the amplified laser pulses is finally defined by the seed oscillator and can't be actively controlled. For high precise structuring applications this combination therefore suffers from certain inaccuracies due to the asynchronous motion of the scanner mirrors relative to the pulse train.

This work reports on the synchronization of the scanner mirror motion with the clock of the laser pulses, which is usually in the range of a 100 kHz and more, by a modification of the electronic scanner control. This synchronization facilitates the placement of the small ablation craters from single pulses with the precision of about 1 um relative to each other. The precise control of the crater positions offers the possibility to test and optimize new structuring strategies. Results of this optimization process with respect to minimum surface roughness, steepness of wall, accuracy to shape, moiré-effects and efficiency will be presented.

8243-35, Session 5

Three-dimensional silver nanostructure fabrication through multiphoton photoreduction

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Metal nanostructure fabrication techniques have become increasingly important for photonic applications with rapid developments in the fields of plasmonics, nanophotonics and metamaterials. While two-dimensional techniques to create high resolution metal patterns are readily available, it is more difficult to fabricate three-dimensional (3D) metal structures that are required for new applications in these fields. We present an ultrafast laser technique for 3D direct-writing of disconnected silver nanostructures embedded in a dielectric. We induce the photoreduction of silver ions through non-linear absorption in a solution doped with silver salts. Utilizing nonlinear optical interactions between the chemical precursors and femtosecond pulses, we limit silver-ion photoreduction processes to a focused volume smaller than that of the diffraction-limit. The focal volume is scanned rapidly in 3D by means of a computer-controlled translation stage to produce complex patterns. Our technique creates dielectric-supported silver structures, enabling the nanofabrication of silver patterns with disconnected features in 3D. We obtain sub-300 nm resolution and create 3D arrays of dots, grids and woodpile patterns. We show that the process is scalable and suitable for metamaterial applications.

8243-36, Session 5

Material specific effects and limitations during ps-laser generation of micro structures

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The generation of micro structures by high power ps-laser radiation is increasingly becoming a common application. However, during the ablation processes different objectionable side effects might occur. These effects depends et al. on material properties and geometry of the structure. One obvious example is the variation of the flank angle. Next to general laser parameter like fluency or polarisation orientation the emerging angle is linked with physical characteristics of the substrate. Without specific setup modification best achievable edge steepness can show a variance of 10 degree and more among different materials. Also known is the formation of trenches on the ablation ground next to the flanks. Partly this effect is due to technical reasons and depends on insufficient synchronization between laser and acceleration/deceleration of the scanner system. A further reason is based on reflection of laser radiation at vertical flank walls leading to increased irradiation and thereby enhanced ablation of the surrounding area. These and more side effects lead to imprecise geometric micro structures. Application specific parameters and adapted setups can help to overcome or reduce these problems.

For this study the used ps-laser (Trumpf TruMicro 5050 Compact, 50 Watt, optical scanner) was attached with an x/y/z-stage and confocal chromatic sensor to measure the generated structure subsequently. The 3D-scan allows to analyze directly the influence of the last modifications and to reduce the optimisation process. Experimental research on a variety of different substrates (metals just as dielectrics) should help to understand the cause and effect of influencing variables.

8243-22, Session 6

Laser processing with ultrashort vortex pulses

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We present the results of material modification using tightly focused femtosecond laser vortex pulses. Double-charge femtosecond vortices were synthesized with a vortex beam converter [1] by using polarization singularities associated with the beam propagation in birefringent crystals. A vortex beam was focused using moderate and high numerical aperture optics (viz., NA = 0.45 and 0.9) to ablate fused silica and soda-lime glass. By controlling the pulse energy we consistently machine micron-size ring-shaped structures with down to 70 nm uniform groove thickness with single-pulse irradiation [2].

By focussing the vortex beam in the bulk of transparent material to the intensity above the optical breakdown threshold we demonstrate the ability to form a toroidally shaped plasma confined inside the solid. Our preliminary experiments with powerful femtosecond vortex beam demonstrate that the central volume of the cylindrical focus with zero intensity in the axis is indeed heated in the centre of the beam above the ablation threshold.

Using the pulse energy below the ablation threshold and irradiating the same spot on the surface with many, up to 1000 pulses, we demonstrate formation of nanostructured patterns which accurately replicate the vectorial structure of laser field of tightly focused beams and provide insights into the directionality of radiation pressure in the nanoscale domain [3]. These complex polarisation-replicating nanostructures may find applications in the fabrication of polarization micro-optic components and beam shapers, and in the synthesis of chiral materials.

[1] V. G. Shvedov, C. Hnatovsky, W. Krolikowski, A. V. Rode, "Efficient Beam Converter for the Generation of Femtosecond Vortices," Opt. Lett. 35, 2660 (2010).

[2] C. Hnatovsky, V. G. Shvedov, W. Krolikowski, A. V. Rode, "Materials processing with a tightly focused femtosecond vortex laser pulse" Optics Letters, 35, 3417 (2010).

[3] C. Hnatovsky, V. Shvedov, W. Krolikowski and A. Rode "Revealing local field structure of focused ultra-short pulses", Phys. Rev. Lett. 106, 123901 (2011).

8243-23, Session 6

Machining of glass and quartz using nanosecond and picosecond laser pulses

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New laser processing strategies in micro processing of glass, quartz and other optically transparent materials are being developed with increasing effort. Utilizing diode-pumped solid-state laser generating nanosecond pulsed green (532 nm) laser light in conjunction with either scanners or special trepanning systems can provide for reliable glass machining at excellent efficiency. Micro ablation can be induced either from the front or rear side of the glass sample. Ablation rates of over 100 µm per pulse can be achieved in rear side processing. In comparison, picosecond laser processing of glass and quartz (at a wavelength of 1064 or 532 nm) yield smaller feed rates at however much better surface and bore wall quality. This is of great importance for small sized features, e.g. through-hole diameters smaller 50 µm in thin glass. Critical for applications with minimum micro cracks and maximum performance is an appropriate distribution of laser pulses over the work piece along with optimum laser parameters. The presentation discusses several laser machining examples: long aspect micro drilling, slanted through holes, internal contour cuts, micro pockets and more complex geometries. Materials involved are soda-lime glass, B33, B270, D236T, AF45 and BK7 glass, quartz, and Zerodur. The LMTB development of a new trepanning system as a key beam delivery tool for micro machining of brittle materials will be presented.

8243-24, Session 6

Fabrication of photo-induced microstructure embedded inside ZnO crystal

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Zinc oxide (ZnO) has wide range of applications from a transparent conducting electrode, surface acoustic wave devices, to gas sensor. Especially ZnO is expected to high efficiency ultraviolet emitting material or excitonic semiconductors due to its wide band gap (3.4 eV) and large exciton binding energy (~ 60 meV). Recently, various studies relating to nanostructuring on ZnO surface using ultrashort pulse laser have demonstrated that polarization-dependent ripple structures were self-assembled, however, until now, there has been no observation of structural modification inside ZnO crystal by femtosecond laser irradiation and the mechanisms has not been fully understood. Here we demonstrate the space-selective oxygen defects were successfully induced inside ZnO crystal by means of focused femtosecond laser irradiation. The threshold energy for oxygen defect formation was estimated by changing the pulse width of the irradiated femtosecond laser. The mechanisms of the pulse-width dependence of femtosecond laser damage inside ZnO crystal was interpreted in terms of the excitonic Mott transition to the electron-hole plasma depending on the electron plasma density induced by the laser irradiation. We have also discussed the interaction of infrared ultrashort laser pulses (l = 1.24 um) with silicon. These results could be useful to the micromachining inside semiconductor using femtosecond laser based on the intense laser-plasma interaction.

8243-37, Session 6

Water assisted microhole drilling in fused silica using burst-train femtosecond laser pulses

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In this paper, we present the investigation results on high aspect-ratio microhole drilling in fused silica glass by use of burst-train femtosecond laser pulses and water assistance. When the time interval between neighboring burst pulses is shorter than the thermal diffusion time of the material, residual heat remaining at the next burst laser pulse can be accumulated over multiple burst pulses to increase the temperature around laser interaction volume, which enables improved laser absorption and the realization of more efficient and ductile crack free femtosecond machining. A custom built burst resonator integrated with a commercial Ti:Sapphire laser system (800 nm, 50fs-5ps, 500 Hz) generates 38-MHz repetition rate burst-train pulses, which were focused on the rear face of fused silica glass (1 mm thick) either in contact with water or in the air. The microholes were drilled starting from the rear face by translating the sample along laser propagating axis during laser exposure. The dependency of microhole drilling on laser parameters including number of burst-train pulses, pulse energy, pulse duration, as well as sample scanning speed and background media (water or air) were investigated. The results have demonstrated both the benefit of the burst mode operation compared with single pulse mode, and water assisting on the depth of microholes: for example, the depth of ~780 µm by using 3-pulse burst trains and water contacting is approximately 2.6 times of that (~294 µm) by use of single pulse mode and water, while drilling in air with 3-pulse bursts resulted in ~2.6 times (~302 µm) shorter holes.

8243-25, Session 7

Comparison of picosecond and femtosecond laser ablation for surface engraving of metals and semiconductor

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Pico and femtosecond lasers present a growing interest for industrial applications such as surface structuring or thin film selective ablation. Indeed, they combine the unique capacity to process any type of material (dielectrics, semiconductors, metals) with an outstanding precision and a reduced affected zone. In this paper, we report on results about surface engraving of metals (Al, Cu, Mo, Ni), semiconductor (Si) and polymer (PC) using a picosecond thin disk Yb:YAG-amplifier, which could be used in the picosecond regime as well as in the femtosecond regime by simply changing the seed laser source. In the picosecond regime the oscillator pulses, ranging from 10 to 34ps, can be directly amplified which leads to a quite simple and efficient amplifier architecture. On the other hand, a broadband femtosecond oscillator and a CPA configuration can be used in order to obtain pulse duration down to 900fs. We compare these results to recently obtained achievements using commercial femtosecond lasers based on Yb-doped crystals and fibers and operating at comparable output power levels, up to 15Watt. Finally, we have considered etch rate and process efficiency for both ps- and fs-regimes as a function of average power, of fluence and of intensity

8243-26, Session 7

Correlating texturing, milling, and scribing of ceramics and metals using ns and fs pulsed fiber lasers

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The type of applications and the type of materials chosen for this discussion are meant address the middle-of-the-ground where neither laser dominates in performance. For example, processing of plastics, as well as stent cutting is avoided. On the other hand, texturing of ceramics or metals can be addressed by both systems, with certain advantages for both.

8243-38, Session 7

Sub-wavelength multi-period ripple phenomena on stainless steel irradiated with high repetition rate femtosecond laser pulses

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Femtosecond laser surface structuring is showing growing promise recently to transform highly reflective metal surfaces into grey-scale patterns for logo and parts labelling or into highly absorbing surfaces noted as “black metals”. Such enhanced absorption and colour rending arises from the ultrashort-pulsed laser formation of various nano- and micro-structures, including the widely observed phenomenon of laser-induced periodic surface structures (LIPSSs). Typically, the period of LIPSS structures is approximately similar with or slightly smaller than the wavelength of incident light. LIPSS is thought to arise from either the interference between the surface scattered wave and the incident wave or due to a non-uniform energy deposition. In this work, we expand on this LIPSS phenomena by controlling femtosecond laser exposure to create multi-colored metal surfaces. The colorful surfaces arise by optical interference from multi-periodic ripples generated simultaneously both on nano- and micro-scale periods and have a variety of potential applications, such as sensing, detection, embossing, and security or cosmetic marking. Polished stainless steel surfaces were irradiated with focused beams from two types of femtosecond lasers: a Ti:sapphire multi-pulse burst generator and a high-repetition rate fiber laser (IMRA America, FCPA µJewel D400-VR). A top-down approach of direct writing of grating lines was applied to generate large area colored metal surfaces with laser polarization oriented perpendicular to the scan direction for higher contrast surface grating formation. However, SEM and AFM images revealed the simultaneous formation of multiple periodic structures on wide ranging size scales: 2 to 20 µm periods that were operator controlled by the line-to-line laser scan separation; sub-wavelength LIPSSs with periods in the range of ~ 0.65 to 0.85 of the incident wavelength (□ = 800 nm) aligned perpendicular to the laser polarization direction; and nano-grating structures of ~70 to 100 nm that were aligned parallel to the laser polarization. The period of self-organized grating structures could be controlled from 340 to 720 nm by the pulse energy, laser wavelength, scan speed and focal positioning.

8243-39, Session 7

Structural changes of copper induced by high repetition rate femtosecond laser pulses

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High repetition rate micro machining of copper is performed with a 80-MHz femtosecond oscillator laser system and high focusing objective. Micro-grooves are machined at different fluences varying from 0.15 J/cm^2 to 0.36 J/cm^2. The number of scans necessary to perform the grooves is also studied, varying from 1 pass to 20 passes. Atomic Force Microscopy and Scanning Electronic Microscopy analyses show that structures obtained are above the surface and look like a continuous bump all along the machining. This overall of micro-machined copper is due to the experimental setup which allows to capture ablated copper. We put in evidence a relation between the laser parameters such as the number of pulses, the fluence used and the height of the structures obtained. High Resolution Transmission Electronic Microscopy puts in evidence microstructural changes occurred in copper between the grown matter and the bulk material. Depending on the analysed zones, high repetition rate femtosecond laser ablated copper exhibits nano-crystallisation and/or amorphization, to be compared with polycrystalline as-received sample. This confirms the thermal component of the femtosecond laser ablation in the case of a pure metallic sample and the highly severe quenching rate occurring in such a laser irradiation. Finally, SEM observations allow to make the hypothesis of an inter-granular propagation of the ablation intto the bulk material.

8243-40, Session 7

Femtosecond-laser-induced nanowires with very high aspect ratios at the surface fused silica

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Focused femtosecond pulses with energies of a few hundreds of nanojoules have become a key tool to modify the physical and chemical properties of materials in three dimensions. When exposed to a femtosecond pulse train focused inside the bulk, fused silica exhibits three different response regimes. At low fluence (type 1), the local refractive index (RI) change is isotropic. At intermediate fluences (type 2), the RI change is anisotropic due to the presence of "nanogratings". At high fluence (type 3), micro-cavities with a low RI core and a high RI shell are formed.

The formation of micro-cavities is due to different processes occurring at different time scales. Within the first picosecond, photo-ionization and electron-lattice energy transfer take place. After 1 ps, thermodynamic and hydrodynamic processes start. In the third regime, the temperature and pressure conditions are such that shock waves and micro-explosions occur. When the laser is focused inside the sample close to the surface, viscous micro-jets could exit the material and solidify, resulting in the formation of nanowires.

Here we report on the formation of high aspect ratio nanowires at the surface of fused silica when a high (MHz) repetition rate femtosecond laser is focused inside the sample close to the surface. The length of these wires can be as high as hundreds of μms, while the diameter remains smaller than 1 μm, resulting in aspect ratios higher than 100. Silica nanowires of 40 nm diameter can be obtained. Phenomenological modeling is given to explain this unexpected phenomenon.

8243-27, Session 8

Probing ultrafast laser-matter interactions with fs x-rays

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Upon intense excitation with ultrashort laser pulses materials are driven into highly non-equilibrium states and can undergo structural changes on very rapid time-scales. Due to the unique combination of atomic-scale spatial and temporal resolution, the recent progress in the development of ultrafast short wavelength sources has provided new opportunities for studying such processes. This talk will discuss some examples of our recent work using ultrafast time-resolved diffraction/scattering with laser-driven as well as accelerator-based femtosecond short wavelength (XUV- and X-ray) sources.

8243-28, Session 8

Raman spectroscopy as a diagnostic means of sapphire dicing using ultrashort pulsed lasers

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Sapphire wafers are widely used for substrate in manufacturing photonic and optoelectronic devices such as light emitting diode (LED) for its good optical property and chemical robustness. Dicing sapphire wafers without defect has been a challenge as chipping and edge cracks due to mechanical dicing cause serious reduction of the emitting efficiency of LEDs. Recently, lasers became an attractive means for sapphire dicing by providing higher edge quality than diamond saws with new benefits including zero-width and chip-free dicing. However laser-induced thermal distortion of the edge leads to another degradation of LED quality. Therefore, ultrashort pulsed lasers are considered as an alternative to minimize thermal damage in LED fabrication. In order to examine the effectiveness of ultrashort pulsed laser dicing, characterization of microscopic structural changes in sapphire is necessary. In this paper, we investigate laser diced surfaces of sapphire wafers using micro-Raman spectroscopy to characterize laser-induced response in molecular scale as Raman spectroscopy is useful for probing structural changes. Systematic investigation among different laser parameters in nanosecond and sub-nanosecond regimes is presented. Micro-Raman spectra are acquired across the irradiated region therefore the strength of thermal effect is visualized in the vicinity of the laser focus. Transmission electron microscopy will be complementarity used to investigate the phase change of crystal structures.

8243-29, Session 8

Direct investigation of the ablation rate evolution during laser drilling of high aspect ratio micro-holes

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The recent development of ultrafast laser ablation technology in precision micromachining has dramatically increased the demand for reliable and real-time detection systems to characterize the material removal process. In particular, the laser percussion drilling of metals is lacking of non-invasive techniques able to monitor into the depth the spatial- and time-dependent evolution all through the ablation process. To understand the physical interaction between bulk material and high-energy light beam, accurate in-situ measurements of process parameters such as the penetration depth and the removal rate are crucial. Furthermore, various dynamic factors related to the influence of laser pulse duration and peak energy have to be instantaneously assessed to improve the ablation efficiency and finally control the laser micromachining process.

We report on direct investigations of the ablation rate evolution within the capillary carried out by implementing a contactless sensing technique based on optical feedback interferometry. High aspect ratio micro-holes were drilled onto metal targets with different thermal conductivity (i.e. stainless steel and aluminium) using 120-ps/100kHz pulses delivered by a microchip laser fiber amplifier. The probe beam was coaxially aligned with the machining laser pulses and the displacement of the ablation front was measured during the drilling time with a resolution of 0.41 μm. The time dependence of the hole penetration depth per laser pulse was provided by sampling the periodical modulations of the interferometric waveform, enabling the instantaneous detection of the ablation rate during ultrafast microdrilling experiments. Results on the material removal rate correlate well with the theoretical prediction given by Hertz-Knudsen formula.

8243-30, Session 8

Real-time automatic depth control of laser processing at kilohertz rates

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Directly observing and controlling how far a laser has penetrated into a material is a challenging task because imaging and feedback systems must be able to overcome intense backscatter, plasma emissions and stochastic melt relaxation. Depth measurements required for feedback are particularly difficult to obtain from deep geometries where triangulation is restricted and multiple reflections confuse phase-based interferometry techniques. Inline coherent imaging (ICI) is a recently developed in situ depth imaging technique based on low coherence interferometry in the Fourier domain that overcomes these challenges to provide micron-scale depth information over multi-millimetre ranges at measurement rates exceeding 300 kHz.

ICI observation and manual control for percussion drilling have been previously demonstrated to increase hole depth precision by an order of magnitude[1]. Here, we demonstrate novel capabilities of ICI on three fronts: 1) Real-time observation of keyhole depth and stability in microwelding and trench cutting; 2) Single sided breakthrough anticipation and detection for thin metal parts (e.g. silicon vias, stents, aero engine cooling); 3) Fully automatic feedback control of percussion drilling with a 4 - 21kHz average imaging rate and total feedback latency of 270 - 460 us (PC limited). Combined with the ease of integration into existing laser processing platforms, these capabilities open a wide range of applications for ICI observation and control that benefit both micro- and macro-processing industries.

[1]Webster et al., Optics Letters 35, (2010).

8243-41, Session 8

In and out of resonance plasmonics enhanced ultrafast laser nanoablation of surfaces

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Ultrafast laser interaction with gold nanostructures deposited onto a silicon surface produces considerable field amplification that can result in the ablation of features smaller than the diffraction limit. While field amplification is the main phenomenon that permits this nanoablation, energy deposition processes cannot be neglected to interpret experimental results and amplification factors obtained, and compare them with conventional ablation. Atomic Force Microscopy (AFM) and Scanning Electron Microscopy (SEM) were performed on near field enhanced laser ablated holes produced by a 120fs Ti-Sapphire laser at 800nm. Various nanostructures, including nanospheres (100, 150 and 200nm diameter) and nanorods (25x57, 25x68, 25x81, 25x126nm) in and out of plasmon resonance were used and produced holes varying in shape and depth from a few nm up to a hundred nm. The field amplification being highly localized to a region much smaller than the electron diffusion length, our simple model shows that the diffusion process control the size of the features produced and explain the difference between the calculated field amplification factor and the much lower observed ablation amplification factor. Results also present striking differences between the fluence dependence of the features produced by resonant and out of resonance nanostructures, which is explained by a difference in the charge injection process. Finally, in colloidal suspensions, nanostructures are covered by a surfactant that produces a shell around it to reduce aggregation. The effect of this shell, usually overlooked in the literature, is also studied. Effects of pulse length will also be investigated.

8243-42, Session 8

Influence of pulse duration on the hole formation during short and ultrashort pulse laser deep drilling

S. Doering, S. Richter, Friedrich-Schiller-Univ. Jena (Germany); A. Tuennermann, S. Nolte, Friedrich-Schiller-Univ. Jena (Germany) and Fraunhofer Institute for Applied Optics and Precision Engineering (Germany)

We investigated the influence of the pulse duration on the laser drilling process in the femtosecond, picosecond and nanosecond regime by in-situ imaging of the hole formation in silicon for pulse energies from 25 µJ to 500 µJ. For percussion drilling, we used a Ti:Sa CPA laser system that provides pulses with a duration of 50 fs up to 10 ns at 800 nm. At this wavelength, silicon shows linear absorption and its ablation behavior is comparable to metals. The temporal evolution of the longitudinal silhouette of the hole was visualized during the drilling progress. Deep holes with a depth larger than 1 mm and aspect ratios up to 30:1 were generated. In terms of maximum achievable depth, ultrashort pulses with a duration below 5 ps show comparable efficiency for pulse energies below 100 µJ, while ns-pulses only lead to shallow depths. The situation changes for pulse energies higher than 100 µJ. The depth of holes drilled with ns-pulses increases linearly with pulse energy, while ultrashort pulses show a saturation of achievable depth, which is most distinctive for the shortest pulse duration of 50 fs. The increase in depth for ns-pulses is accompanied by an increasing in the number of pulses, which can be 10 times as much as for ultrashort pulses at the same pulse energy. The drilling process consist of an iterative sequence of forward drilling and increase of hole diameter. The increase in diameter leads to numerous deviations from a cylindrical hole shape in the form of bulges, cavities and finger-like structures. This is less pronounced for ps-pulses. Fs-pulses show the best achievable hole geometry at a tapered shape without noticeable deviations.

8243-46, Poster Session

Development of laser-base application system with high precision and speed

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Multiplex machine needs precision motion stage and adjust optic system for fast and precision processing in PCB. We design a stage to air bearing, DD motor, servo amplifier with current type and motion control with pulse vibration and ZPET (Zero Phase Error Tracking). Orifice type air bearing is high hardness and minimize tracking error by connected scanner. Stage jitter is improved by current type servo motor about X axis 60 nm, Y axis 20 nm. We develop the laser power controller using HWP (Half Wave Plate), thin film plate polarizer, photo diode and control board. The power control is possible real-time power monitor and adjusts laser power using HWP and photo diode. We tested four processes such as cutting, repair, trimming and structuring. Tested PCB is 0.4 mm thickness with 5 layers and trimming sample is coated carbon layer in 20 um thickness. Laser power is maximum 20W, wavelength 355 nm, repetition rate 10~150 kHz, spot size 20 um, scan speed maximum 2 m/sec and scan field 50 mm x 50 mm. PCB full cut get over 9W laser power with 85% overlaps, 30mm/s scan speed, if laser power 9 ~ 13W maintain constant debris and heat damage, but it is burning PCB about over 15W this condition.

8243-47, Poster Session

Reproduction a unit of power of the laser radiation in compliance with the redefinition of the optical watt

J. A. Owsik, Military Univ. of Technology (Poland); A. A. Liberman, A. A. Kovalev, S. A. Moskalyuk, All-Russia Research Institute of Optical and Physical Measurements (Russian Federation); A. Z. Rembielinska, LOT Polish Airlines (Poland)

The paper contains a description the proposal of a new definition of the value of the unit of power of the optical watt and has a close relationship with the measurement of energy characteristics of the laser beam. Determining of the optical watt is based on its experimental comparison to the electric watt. The problem of determining the optical watt is complex because there exists no single widely recognized method of its measurement. In principle there are two such methods. The first of them is calorimetric method, widely used earlier. It is based on comparing the thermal influence of the power of the laser radiation on the thermocouples of the receiver, with the thermal influence generated by the electric power in the heating coil of the receiver. This method permits to receive the accuracy ~ 0.005 % in the range [W] and ~ 0.1 % in the range of the power of the laser radiation ~ 1 [W].

In the range of the power of the laser radiation < [W] this method is useless and sensitive photodiodes are applied here. Photodiodes work on the principle characterized by counting photons. Registration of the current of the photodiode, that is the stream of free carriers, coming into existence in the photodiode under action of the laser radiation, it constitutes the result of photons counting. In the physical meaning the process of direct transforming the photon → electron + hole in photoreceivers suits the innovation in the SI system. The process of determining the optical watt is reduced to the measurement of the current of the photodiode and the frequency of the laser radiation. It is possible to do this with very high accuracy.

8243-48, Poster Session

Nanostructure formation on lithium niobate surfaces by high-repetition rate sub-15-fs near-infrared laser pulses

M. H. Straub, B. Weigand, K. König, Univ. des Saarlandes (Germany)

Due to its electro-optical, acousto-optical, ferroelectric, piezoelectric and nonlinear-optical properties lithium niobate is a material of high technological relevance. Thus, patterning of $LiNbO_3$ surfaces by laser light may significantly influence the performance of micro-optical devices made of this material. Here, we report on the generation of self-organized nanostructures on surfaces of polled $LiNbO_3$ crystals using tightly focused sub-15 fs pulsed Ti:Sapphire laser light (centre wavelength 800 nm, bandwidth 120 nm, repetition rate 85 MHz) at sub-nanojoule pulse energies. With the $LiNbO_3$ surface immersed in oil intensities close to the ablation threshold resulted in the formation of shallow ripples of 5 - 25 nm in height appearing at a periodicity of approximately 220 nm. The ripples were generated by local melting and re-solidification of $LiNbO_3$ involving minor admixture of hydrocarbons. At intensities well beyond the ablation threshold the $LiNbO_3$ surfaces were patterned densely with tiny cones of 100 - 500 nm in height featuring diameters of a few hundred nanometers. Moreover, lines scanned inside the $LiNbO_3$ crystals resulted in refractive index changes along the laser traces. In contrast, with the $LiNbO_3$ surface in air or water ablation was not observed even at prolonged exposure to highest intensities. We illustrate our findings by scanning electron microscope and atomic force microscope images, which were recorded subsequent to the laser treatment, as well as by optical microscopy. Our contribution includes analysis and discussion of these phenomena as well as a comparison with observations from other materials.

8243-49, Poster Session

Acoustic damage detection in laser-cut CFRP composite materials

M. Nishino, Advanced Laser and Process Technology Research Association (Japan); Y. Harada, T. Suzuki, H. Niino, National Institute of Advanced Industrial Science and Technology (Japan)

This paper has reported acoustic damage detection in carbon fiber reinforced plastics (CFRP) materials. CFRP samples were cut by laser irradiation with a fiber laser and CO_2 laser. To detect thermal damage at the laser cutting of CFRP materials, acoustic emission (AE) monitoring with a piezoelectric transducer was performed at the tensile test of CFRP samples. We have evaluated fracture behavior and thermal damage in CFRP materials by high-power laser processing.

8243-50, Poster Session

Femtosecond laser doping and nanostructuring of silicon for photovoltaics

B. Franta, M. Sher, Y. Lin, K. C. Phillips, E. Mazur, Harvard Univ. (United States)

We use femtosecond laser pulses to chemically dope silicon beyond the solid solubility limit (hyperdoping) with chalcogens (sulfur, selenium, and tellurium) as well as to obtain surface structuring on the micro- and nanometer scales. These laser-induced modifications of silicon give rise to drastic changes in the optical and electronic material properties and are of intense interest for photovoltaic applications, including the development of the intermediate band photovoltaic, a single junction device with a theoretical maximal efficiency of over 60%. Our femtosecond irradiation technique has been used in the past to create arrays of hyperdoped micron-scale spikes with near-unity sub-bandgap absorptance (black silicon). Here, we report on other types of modification obtainable with different irradiation parameters. Mid-fluence regimes (3 kJ/m^2) produce nanostructured surfaces exhibiting uniform arrays of ripples with periodicities on the order of 400 nm, and hybrid structures incorporating both ripples and spikes can also be obtained. Low-fluence regimes (2 kJ/m^2) give rise to chemical hyperdoping and sub-bandgap absorptance without attendant surface structuring, at which point additional processing and characterization techniques can be used without interference from a morphologically-irregular surface. Finally, we also explore the potential of nanosecond pulsed laser melting (PLM) for the microstructural post-processing of hyperdoped silicon. Our work shows that decoupling the effects of surface structuring and hyperdoping is possible and demonstrates the additional control over the modification process necessary for versatile device applications.

8243-51, Poster Session

Generation of new nanostructures in designed matrix by interfering femtosecond laser processing

K. Momoo, Y. Nakata, N. Miyanaga, Osaka Univ. (Japan)

Tens of thousands of nano-structures in matrix can be generated by Interfering ultra-short pulse laser processing in a single shot. Using this technique, we have generated nano-structures such as nano-waterdrop, nanocrown, nanobump etc. on thin metallic films. They are generated by thermally process such as melting and inflation like bubbling, and the structures change according to the characters of target and interference pattern on a target surface. The distribution of nano-structures is periodic, according to the interference pattern. The interference pattern can be changed by parameters of wavelength, correlation angle, intensity ratio and phase shifts between the beams. Here, we used a beam correlator composed of a demagnification system and a transmission beam splitter, and the system is very useful to change these parameters. In this experiment, we generated arranged and designed periodic structures, by using the system.. Furthermore, we simulated the interference pattern, and compared the simulated results with the structures generated in experiments. All the structures were observed by scanning electron microscope (SEM).

8243-52, Poster Session

High aspect ratio of near-field nano-lens for deep nano-crater patterning

I. Fujimura, M. Terakawa, Keio Univ. (Japan)

Enhanced optical field close to nano-dielectric spheres excited by a femtosecond laser enables high-throughput nano-crater patterning. With spheres larger than the incident wavelength, the focused far field is well known in optics to be governed by micro-lens, while the enhanced near field with spheres smaller than or equivalent to the incident wavelength is dominated by the resonant Mie-scattering. The crater fabricated by the near field nano-lens is much shallower than by the micro-lens. The knowledge of the maximal crater depth relative to the diameter will advance the smart applications for nanotribology, nano-sensors, and nano-biomedicine. Here, we study the aspect ratio (the depth profile in the substrate relative to the diameter of the intensity profile on the surface). It is because the fabricated nano-crater depth is empirically determined by the near-field intensity distribution. A maximal vertical intensity profile is found as a function of refractive index and sphere diameter. The dielectric spheres ranging from 400 to 800 nm diameter on the Si substrate are studied at 800 nm wavelength. Using a sphere with the smaller refractive indices, the larger aspect ratio is achieved. However, a maximal optical intensity is sacrificed for the high aspect ratio. Maximal aspect ratios for the near-field nanopatterning range from 3.0 to 3.7 using available spheres having the refractive indices from 1.6 to 3.0. Experimental results focusing on the fabrication of a deep crater will also be presented. This work was supported in part by a grant from the Amada Foundation for Metal Work Technology (AF-2010209).

8243-31, Session 9

Periodic nano trench structure fabricated by high speed scanning CW laser

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After annealing the surface of silicon wafer using CW lasers we found an asymmetric sheet resistance on the surface. The scanning electron microscopy revealed periodic nano trench structure on the annealing surface. The nano trench self-organized on the trace of one-time scanning by near infrared (NIR) and green lasers. Depending on laser power the period was varied from 500 to 800 nm, which correspond to the wavelength of NIR and green lasers, respectively. With irradiating white light the nano trench sructture showed brilliant structural color, indicating the structure was well-organized in long range of scale.

We propose a versatile method to form nano structure with a high speed scanning CW laser of 300 m/min. The nano-SGL was assembled not after hundreds of laser shots, but after only a single scanning laser irradiated the target materials. This phenomena was different than one produced using femtosecond laser, where the structure is considered to be resultant of interaction between solid and laser in the pulse duration of femtosecond (less than 10-9 sec. with thermal non-equilibrium). The nano trench structure self-organized using CW laser must be with an interaction through thermal equilibrium state. Using 3D finite element method (FEM), we evaluated time-dependent temperature distribution on the target materials. We proposed existence of a threshold for melting duration to form the nano trench structure.

8243-32, Session 9

Tribological enhancement of surface properties by multi-scale femtosecond laser texturing: relation between laser treatment, topography, and wettability

P. Bizi-Bandoki, S. Valette, S. Benayoun, Ecole Centrale de Lyon (France); E. Audouard, Univ. Jean Monnet Saint-Etienne (France)

The modifications of solid surfaces for tribological applications are of great technological importance, especially for energy saving and eco-friendly technologies. Processes like adhesion, friction, lubrication, coating and de-icing can be optimized for nowadays challenges through surface modifications.

In this work, tribological behavior of surfaces is approached in terms of wettability by measuring the contact angle of water droplets on textured surfaces. The effect of femtosecond laser surface texturing on roughness and wettability is studied on metallic samples. Firstly, multi-scale topography is generated. Laser-induced periodic and hierarchical surface structures (ripples) at micro and nano scales are induced depending on irradiation conditions. This allows to show that a perfect control of laser parameters can help to create a multi-scale topography on metallic alloys surfaces. Secondly, the influence of time and roughness over the contact angle is studied. The laser treatment leads the water contact angle to decrease immediately after treatment before increasing sharply to reach hydrophobic regime. This shows that initially hydrophilic materials become hydrophobic without a subsequent chemical coating. The switch from hydrophilicity to hydrophobicity is due to some chemical reaction initiated by the laser action on the irradiated surfaces. However, the effect of surface roughness is visible and predominant in the extreme wetting behaviors, i.e. immediately and days after the laser treatment when the effect of the chemical reaction is stabilized. This effect of topography is investigated with regard to Wenzel and Cassie-Baxter models.

8243-33, Session 9

Laser polishing

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A new approach to polish metallic freeform surfaces is polishing by means of laser radiation. In this technology a thin surface layer is molten and the surface tension leads to a material flow from the peaks to the valleys. No material is removed but reallocated while molten. As the typical processing time is 1 min/cm² laser polishing is up to 30 times faster than manual polishing. Due to the high cooling rates laser polished surfaces have a fine grain structure with the potential for enhanced wear and corrosion resistance. Reducing the roughness by laser polishing is achieved for several different materials such as hot work steels for the die and molding industries, titanium alloys for medical engineering or fused silica for optical applications. In order to enhance the appearance of design surfaces is achieved by creating a two-gloss effect by selective laser polishing (SLP). In comparison to conventional polishing processes laser polishing opens up the possibility of selective processing of small areas (< 0.1 mm²) on a tools surface. A two-gloss effect can be created by selective variation of process parameters and is therefore based on a space-resolved change in surfaces roughness. In Comparison to the initial surface the roughness of the laser polished surface is reduced significantly up to spatial wavelengths of 80 microns and therefore the gloss is raised considerably. The surface roughness is investigated by a spectral analysis which is achieved by a discrete convolution of the surface profile with a Gaussian loaded function similar to ISO 11562. In this way the surfaces roughness is split into discrete wavelength intervals and can be evaluated and optimized in a more sophisticated way. Laser polishing is carried out by using a special tailored five-axis mechanical handling system, combined with a three axis laser scanning system and a Nd:YAG fibre laser (ALPINE-Machine).

8243-34, Session 10

Formation of tribological structures by laser ablation

N. Schilling, M. Paschke, U. Klotzbach, Fraunhofer IWS Dresden (Germany); S. T. Hendow, Multiwave Photonics (Portugal)

For many technical applications, there is a good usage of tribological structures to minimize abrasive material wear and energy consumption without the integration of additional materials in a working assembly. Especially in lubricated friction systems the tribological character can be improved significant through the addition of oriented structure. Experimental analysis is presented of a small range of structure dimensions to verify the effect of optimizing the tribological contact performance. A ns-pulsed fiber laser is used to create test structures, different in dimension, form and direction for analysis. The quality of such a structure, especial form correctness, feathering and material modification in the ablation area and around it are parameters, which have to be optimized by the validation of such structures.

With this paper a flexible laser system will be presented for the execution of tribological structures on different materials and design. The influence of pulse duration, pulse energy and pulse delay from normal pulsing versus burst modes will be discussed and demonstrated by reference on applications. The use ns pulse bursting at 1064 nm offers the application to vary pulse duration and pulse spacing over a broad range. The paper will show different ways of optimizing application-based tribological structures and their effect on the traction.

8243-35, Session 10

Laser-induced front side etching of commercial glasses with short and ultra-short laser pulses

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The successful structuring and preparation of commercial glasses, e.g. for optical components, requires high demands on the applied methods. The usage of laser radiation is a possibility for fast as well as high-quality preparation of transparent materials. In particular, the laser-induced front side etching (LIFE) method has an excellent potential for a nm-precision structuring of dielectrics with very smooth machining surfaces.

Within this study the LIFE of BK7, LiF, CaF2, MgF2, and fused silica using ns-, ps-, and fs-laser radiation is presented. An excimer laser with a wavelength of 248 nm as well as 351 nm and with a pulse duration of 25 ns, a Nd:YAG laser with 355 nm, 532 nm as well as 1064 nm and 10 ps, and a Ti:sapphire laser with 780 nm and 150 fs were used, respectively.

As absorber layer a 50 nm thick chromium metal layer was used.

The influence of the laser fluence and the pulse overlap on the etching process for the different laser radiations was investigated.

The surface morphology of the treated surfaces of the commercial glasses was analysed by white light interferometry (WLI) and scanning electron microscopy (SEM). Furthermore, the etching depth was measured by WLI.

8243-36, Session 10

Facile and flexible fabrication of gapless microlens arrays using a femtosecond laser microfabrication and replication process

H. Liu, F. Chen, Xi’an Jiaotong Univ. (China)

In the past decades, a variety of strategies have been developed to fabricate microlens arrays (MLAs) due to their wide applications in micro-optics, MEMS, sensors and so on. But low-cost and rapid fabrication of gapless MLAs is still challenging. Here, a facile and flexible method is proposed to generate close-packed MLAs, and the method is based on a special femtosecond (fs) laser microfabrication and molding replication process. Glass molding templates with concave structures are generated by the fs-laser exposures followed by a chemical polishing treatment; convex MLAs are subsequently replicated on Poly(methyl methacrylate) [PMMA] by hot embossing technique. The method does not require expensive mask templates and high vacuum environments, and the flexibility is also demonstrated by producing 100%-fill factor hexagonal and rectangular-shaped MLAs. We demonstrate that the profile of microlenses can be tuned by different experimental conditions including laser power, exposure time and chemical etching time; the formation mechanism is related to the laser-induced material modifications which enhance the chemical etching rate compared to original regions. The morphology of the fabricated microlenses is investigated by a scanning electronic microscope and the profiles are measured by a laser confocal microscope. The diameter of the rectangular and hexagonal-shaped microlenses is 22 um and 60 um, respectively. The average surface roughness (Ra) of the microlenses is smaller than 10 nm, which is obtained by an atom force microscope. In addition, the optical properties of the MLAs are evaluated experimentally.

8243-37, Session 11

Control of material properties by simultaneous photoexcitations at multiple light spots using a spatial light modulator

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Parallel laser processing by multiple light spots has attained much attention as a method to improve processing efficiency. Multiple light spots can be generated by modulating the spatial phase distribution of a laser beam with a spatial light modulator (SLM) and focusing the phase modulated laser beam. When the light spots are sufficiently separated from each other and the energy of the excitation laser beam is weak, there is little interaction between photoexcited regions. Normally, no interaction is ideal for laser processing, because thermal energies and stresses could reduce the processing accuracy. On the other hand, we found that the interaction of thermal energies and transient stresses in a parallel femtosecond laser processing inside transparent materials can be applied for controlling the spatial distributions of material properties. One is the control of crack generation inside rock-salt crystals by the interference of stress waves generated at multiple spots. We demonstrate that the constructive interference of several stress waves generated from multiple photoexcited regions can facilitate the propagation of laser induced cracks in the specific direction. Another application is the control of the material flow in the temperature distribution controlled by photoexcitation at multiple spots. We demonstrate that arbitrary shapes of structural changes can be generated inside glasses.

8243-38, Session 11

Green line-shaped focus and multiple-foci parallel processing in photovoltaic and other applications on Si

M. Ivanenko, K. Bagschik, W. Grimm, A. Krasnaberski, LIMO Lissotschenko Mikrooptik GmbH (Germany)

Earlier* we have reported on the development of a 8µm narrow and 65mm long green laser focus for sequential lateral solidification of Si, and discussed the advantages of DPSS systems in the production of TFT panels. Similar focus geometry is required for other laser surface treatments. In the manufacturing of solar cells it is used for Si doping, which results in a higher blue sensitivity.

We describe the optical solutions, which include an anisotropic transformation and homogenization of a multimode laser beam, and present several line-beam shaping systems for industrial applications. The influence of the laser characteristics on the optical design and focus quality will be discussed (2nd harmonic of Nd:YAG rod vs Yb:YAG disc).

Even more challenging focus geometry is required for efficient selective doping of the solar cell emitter underneath the front contacts. For this application we developed the optics providing a number of line segments, each of these being 14 µm wide and 220 µm (flat topped) long. The pitch of the segments is oriented parallel to the long axis and amounts to 2.08 mm. The current 17-segment line spans 33.5 mm but can be extended to cover a whole 6” Si wafer. The intensity variation from segment to segment is < 5%pv. The system is designed and tested with a new Trumpf Yb:YAG 515 nm disc laser of 200W average power.

* M.Ivanenko, A.Mikhailov, Y. Miklyaev etl. Laser application, v. 5, 19 - 27 (2009)

Supported by Federal Ministry of Education and Research, 13N10104

8243-39, Session 11

Investigation of micro lens multi spot generator for parallel micromachining of silicon with picosecond and nanosecond laser

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Multi focus optics are used for parallelizing production and for large-scale material processing. These elements split the beam into a periodic spot pattern with a defined grid and spot size. The challenge lies in the generation of a homogeneous envelope. Mico lens arrays offer a high flexibility for the generation of different multi spot patterns dimensions and shapes.

Within the paper we present the investigation of a micro lens array in a fly’s eye condenser setup for the generation of homogeneous spot patterns. The multi spot generator can be combined with different optical elements like cylindrical lenses, diffractive optical elements or axicons for forming an arbitrary shaped laser beam into a spot-, ring or arbitrary array pattern. We show the principal functionality of the multi-spot generator by using wave optical simulation and principles of fourier optics. Furthermore constraints of this setup are demonstrated. The multi spot generator is used for micro structuring of silicon with a nanosecond and a picosecond laser with a wavelength of 355 nm. The multi spot generator splits the incoming beam into a linear spot matrix with 26 single spots. For the first time, the ablation rate and structure quality with and without using a multi spot generator are compared between the two different laser sources. We show that both ablation rate and structure quality can significantly be increased by using a micro spot generator.

8243-40, Session 11

Using acoustic energy for structuring light fields in laser processing and imaging

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Controlling the properties of light fields is crucial to achieve optimal results in applications such as laser processing or microscopy imaging. Adaptive optical systems allow a customizable modification of light, but common issues include low damage thresholds or pixilation effects. A tunable acoustic gradient (TAG) lens is an alternative device which allows structuring light fields of different intensities and wavelengths at high speeds and without pixilation. In this device, acoustic energy is used to excite a fluid-filled cylindrical cavity causing a modulation in the fluid density, and consequently, the index of refraction. In previous works, the theory behind lens operation at steady state was developed, and the ability to use the TAG as a beam shaper and as a varifocal lens was demonstrated. However, a detailed analysis of the characteristics and limitations of the lens have not yet been determined. In this study, we present a fundamental characterization of the TAG including the experimental determination of its response time and temperature dependence. Based on these results, we find the high speed and stability of the lens makes it adequate for integration in a ‘real’ system. As a proof of concept, we set up the lens in a commercial optical microscope and analyzed the TAG ability to vary the focal position. We present a detailed quantification of the lens scanning range and accuracy. The results offer promising perspectives for novel imaging systems.

8243-41, Session 11

New nanosecond Q-switched 213 and 224-nm lasers for fiber Bragg grating writing in hydrogen-free optical fibers

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In this paper, we demonstrate for the first time to our knowledge the use of 224 nm nanosecond laser source for fiber Bragg grating fabrication and compare it with the use of 213 nm laser radiation. These are compact turn-key solid-state laser systems and have significantly higher wall-plug efficiency than Excimer or Argon lasers. Prior hydrogenation of the optical fiber, which can be detrimental for some sensor applications, is not necessary to obtain strong gratings in standard fibers. Average emitted power range from 100 mW for the 213 nm and 250 mW for the 224 nm laser. Optical fibers show similar photosensivity response for these recently available solid-state laser sources.

Fiber Bragg gratings have been written into different types of fiber without hydrogenation using a phase mask technique. With both laser, a 3 mm long type IIA grating with an index modulation of ~1.2x10-3 can be obtained in ~ 10 minutes in photosensitive boron doped fiber. In SMF28 fiber, an index modulation of ~5x10-4 can be reached with both lasers, although it take 90 minutes using the 213 nm laser and twice as long using the 224 nm laser. It is also demonstrated that weak gratings can be obtained in pure silica fiber using 213 nm radiation.

The photosensitivity process is analyzed. In boron doped photosensitive fiber, photosensitivity is dominated by two photons absorption, while in SMF28 it is dominated by single photon absorption.

8243-42, Session 11

Laser cutting of carbon fiber reinforced plastics (CFRP)

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We report on the laser cutting of carbon fiber reinforced plastics (CFRP) with a nanosecond-pulsed UV laser and cw IR laser. CFRP is a high strength composite material with a lightweight, and is increasingly being used various applications. A well-defined cutting of CFRP which were free of debris and thermal-damages around the grooves, were performed by both the laser irradiation with a multiple-scan-pass method. UV laser ablation was used with a diode-pumped solid state UV laser (DPSS UV laser, P=4.5 W, 30kHz, 30 ns, 355nm). UV pulsed laser ablation is suitable for laser cutting process of CFRP materials, which drastically reduces a thermal damage at cut regions. In the case of cw IR laser (fiber laser, P=1kW, 1090nm), a fast beam scanning with a galvanometer scanner was effective to reduce thermal-damages around the grooves.

8243-31, Session 12

Laser sintering of Si and Ge nano- and microparticle films toward solar cells by solution process

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The global energy problem requires the science and technology innovation for renewable energy. One of the problems with solar cells is the high energy costs in comparison with other energy sources. Recently, the solution processes of solar cells without vacuum processes have attracted much interest as a cost-reducing process innovation. The challenge toward solution process of Si and Ge semiconductor materials has been made recently. The development of Si and Ge semiconducting films by solution process provides the possibilities to realize the low cost manufacturing of solar cells. In this presentation, the formation of Si and Ge films from the nano- and microparticle-dispersed solutions and the laser sintering are reported. The Si nano- and microparticle-dispersed solutions were prepared by ball milling of bulk Si with various kinds of dopant concentration with organic solvent and a binder polymer. As binder polymers, organosilicon nanocluster (OrSi) and organogermanium nanocluster (OrGe) were applied, which are organomettalic polymers having hyperbranched Si-Si or Ge-Ge chain and organic side chain solubilizing the inorganic cluster into an organic solvent. The laser sintering was carried out using CW and nanosecond pulsed DPSS laser (457 and 532 nm). The confocal micrographs showed the fusion of Si particles and the large grain formation by laser scanning irradiation. The influences of the laser irradiation under various conditions were discussed by measuring the I-V characteristics of n-Si/Au schottky diode solar cells. The performance of n-Si/Au schottky diode solar cells was improved by thermalannealing under hydrogen/Ar gas flow after laser sintering.

8243-32, Session 12

High quality micro-machining using ultracompact picosecond lasers

O. Haupt, S. Spiekermann, I. Freitag, InnoLight GmbH (Germany)

We will show that our new ultra-compact picosecond laser sources can be used very successful for many different micro-machining applications. Especially, where thermal sensitive materials like semiconductors, glass, or thin-films are used. Due to the compact and simple design these picosecond lasers bridging a gap between high cost ultra-short pulsed lasers and conventional ns lasers. We will demonstrate on glass, semiconductors, and thin-film PV materials that the process quality could be comparable high using ultra-compact picosecond lasers instead of ultra-short pulsed lasers. Due to the short pulse duration with corresponding low thermal penetration depths and ablation ratios suitable processes are more focused on the surface than bulk material processing. Micro-machining is typically done with ultra-short laser pulses or nanosecond laser pulses due to not existing laser systems with adequate power and pulse repetition frequency. The gap from 15 ps to 10 ns is enormous with two orders of magnitude. Especially, we show ablation threshold for thin-film and crystalline solar cells and achievable qualities in dependency of wavelength and pulse energy for pulse durations > 400 ps.

8243-43, Session 12

Structuring of functional thin films and surfaces with picosecond-pulsed lasers

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During the recent few years picosecond lasers have been proved as a reliable tool for microfabrication of diverse materials. We present results of our research on structuring of thin films and surfaces using the direct laser writing and the laser beam interference ablation techniques. The processes of micro-pattering were developed for metallic, dielectric films as well as complex multi-layer structures of thin-film solar cells as a way to manufacture frequency-selective surfaces, fine optical components and integrated series interconnects for photovoltaics. Technologies of nano-structuring of surfaces of advanced technical materials like tungsten carbide were prepared using picosecond lasers as well.

Experimental work was supported by modeling and simulation of energy coupling and dissipation inside the layers. Selectiveness of the ablation process is defined by optical and mechanical properties of the materials, and selection of the laser wavelength facilitated control of the structuring process.

Implementation of the technologies required fine adjustment of spatial distribution of laser irradiation, therefore both techniques are benefiting from shaping the laser beam with diffractive optical elements. Utilization of the whole laser energy included beam splitting and multi-beam processing.

8243-44, Session 12

Laser processes for future solar cells

A. Letsch, Robert Bosch GmbH (Germany)

The photovoltaic industry requires higher efficiencies at lower manufacturing costs to become competitive with other power generation techniques. There are several approaches to increase the efficiency of solar cells by enhancements of the way photons are absorbed and how they generate charge carriers with low losses. We will discuss several concepts and show examples how lasers could enhance the manufacturing, especially focussing on future concepts and the required properties of lasers and optics. Today, the so called first generation of photovoltaic devices based on crystalline silicon wafers are produced on a multi-GW-level, but in most production lines there is only one laser process used to electrically isolate front and rear side of the cell. Lasers are predestined to generate local structures which will be required to manufacture high efficient solar cells. As an example we will show results on the interaction of ultra short laser pulses with dielectric films on silicon. This process can be used to generate electrical point contacts through dielectric stacks which are required to enhance the optical absorption as well as to increase the carrier life-time. Second generation photovoltaic modules are based on thin films. These modules are monolithically interconnected by laser scribing of the films. Tools for amorphous silicon are well established, while there are a lot of challenges to scribe CIGS or organic photovoltaic layers, which offer new chances for thin film photovoltaics. New results on laser scribing these layers will be shown.

8243-45, Session 12

Selective ablation of thin films in latest generation CIGS solar cells with picosecond pulses

A. Burn, M. Muralt, Berner Fachhochschule Technik und Informatik (Switzerland); R. Witte, B. Frei, Solneva SA (Switzerland); S. Bücheler, EMPA (Switzerland); V. Romano, Berner Fachhochschule Technik und Informatik (Switzerland)

In order to conserve their efficiency, solar panels are subdivided into small, serially connected individual cells. The monolithic interconnect typically consists of three layer-selective ablation scribes. With increasing total scribe length, speed and precision of the scribing process becomes more and more important.

Picosecond pulsed lasers allow very precise and highly selective ablation of thin films in latest generation CIGS solar cells. This allows a significant reduction of the dead zone by a factor of more than two compared to current industrial standards.

High scribing velocities and good quality are achieved with high repetition rate, low pulse energy sources. Compact all-fiber picosecond lasers are ideally suited for this application and they are available at competitive prices.

In a comprehensive parameter study of picosecond laser sources at different wavelengths and pulse duration we identified possible process windows for the P1, P2 and P3 scribes. To demonstrate reliability, a functional mini module with low dead zone has been produced using all picosecond laser scribing.

We further identified and successfully exploited robust process windows in regimes traditionally inaccessible to picosecond lasers due to the non-linear absorption behavior of CIGS. We were able to produce very clean trenches of freely selectable width between 40 micron and 150 micron at constant pulse energy and repetition rate.

Conference 8244: Laser-based Micro- and Nanopackaging and Assembly VI

Tuesday-Thursday 24-26 January 2012

Part of Proceedings of SPIE Vol. 8244 Laser-based Micro- and Nanopackaging and Assembly VI

8244-33, Poster Session

Massive process parallelization for laser surface modification: approach and boundaries

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The laser is an extremely suitable non-contact tool for fast and automated in-line processes for example used to improve the efficiency of solar cells. With the aid of ultra-short pulsed laser sources it is possible to decrease the reflectivity by modifying the surface of silicon. For the proposed modification, the optimum process window for altering the silicon on a micrometer scale is found at low laser fluencies at finite repetition rates. A promising up scaling method is the massive process parallelization using in parallel a multiple set of interaction zones with the optimized process characteristics for the single interactions. Based on the single process, required laser and optic characteristics for parallel processing are derived theoretically in order to enable a wafer processing in standard cycle times. Exemplarily 5-inch mc-silicon solar wafers are machined using a linear 7-times diffractive optical element (DOE) and solar cells are built up to determine the efficiency gain by the laser surface modification. A preliminary absolute efficiency gain of $\Delta\eta > 0.2$ % is achieved with the used laser parameters and the optical set up.

8244-01, Session 1

Welding of transparent materials with ultrashort laser pulses

S. Richter, S. Döring, F. Zimmermann, Friedrich-Schiller-Univ. Jena (Germany); R. Eberhardt, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); S. Nolte, A. Tünnermann, Friedrich-Schiller-Univ. Jena (Germany) and Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

The realization of stable bonds between different glasses has attracted a lot interest in recent years. However, conventional bonding techniques are often problematic due to required thermal annealing steps which may lead to induced stress or glue and other adhesives which degrade over time.

These problems can be overcome by using ultrashort laser pulses. When focussed at the interface, the laser energy is deposited locally in the focal volume due to nonlinear absorption processes. While even single pulses can lead to the formation of bonds between transparent glass substrates, the application of high repetition rates offers an additional degree of freedom. If the time between two pulses is shorter than the time required for heat diffusion out of the focal volume, heat accumulation of successive pulses occurs leading to localized melting at the interface. The subsequent resolidification finally leads to the formation of strong bonds.

In this presentation, we will detail the experimental background and the influence of the laser parameters on the achievable breaking stress. In addition, induced stress and the occurrence of micrometer-sized voids within the molten volume will be discussed. Using optimized parameters breaking stress of 75% of the bulk material are obtained.

8244-02, Session 1

Direct welding of fused silica with femtosecond fiber laser

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Development of techniques for joining and welding materials on a micrometer scale is of great importance in a number of applications, including life science, sensing, optoelectronics and MEMS packaging. In this paper, we investigate transparent material welding with high repetition rate femtosecond (fs) fiber laser (1 MHz & 1030 nm). Two substrates are stacked and pressed together to achieve close contact. When fs laser pulses are tightly focused at the interface of the materials, localized heat accumulation based on nonlinear absorption and quenching occur around the focal volume, which melts and resolidifies, thus welds the materials without recourse to an intermediate layer. A systematic study of the laser parameters used for welding of glass substrates together with varying the translation velocity of the samples is presented. Moreover, the bonding strength and the transmittance through the achieved joint volume are also evaluated quantitatively for process optimization. A scanning electron microscopy is used to investigate the cross-section geometry of the welding zone and demonstrate successful joining without voids or cracks. This study is important for determining the optimal conditions for joining fused silica substrates using fs lasers and can be extended to welding of other transparent materials or semiconductor materials and various applications.

8244-03, Session 1

High throughput high accuracy laser soldering of optoelectronic chips

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Currently there are several competing technologies to solder optoelectronics chips as e.g. laser diodes to different types of submounts. For example can it be done by a heated pick up tool which heat the chip up for reaching soldering temperature or the submount can be heated locally from bottom side by laser or hot plate. Both technologies are slow since they either have to heat up a big mass or the heater is rather small. Slow soldering has the disadvantage that the whole device is presented to high temperature over a long period of time and the cycle time is long. Especially cycle time is critical for todays new high throughput application parallel to the requirement to solder only one chip at the time (selective laser soldering). The soldering which will be presented is Laser soldering from the components top side. We will demonstrate the short cycle times and the high accuracy which can be achived by this new technology.

8244-04, Session 1

End cap splicing of photonic crystal fibers with outstanding quality for high power applications

S. Böhme, A. Kliner, S. Fabian, T. Schreiber, R. Eberhardt, A. Tünnermann, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

The application of photonic crystal fibers (PCF) especially in high power fiber laser systems requires special preparation technologies with some significant differences compared to standard fibers. Features like air-clad structures, highly rare-earth doped core with low NA and stress applying parts of the PCFs require additional steps in fiber preparation and innovative splicing technologies to maintain the optical properties. Here we discuss a contamination free carbon dioxide laser splicing device, which is used for a defined air clad collapsing and end cap splicing to get a stable and sealed fiber end face while preserved high beam quality and additional functionality. The special design of the computer-controlled laser splicing process provides a versatile tool with high reproducibility for joining different geometries with an adjustable well-balanced heat distribution. A wide range of PCFs with different diameters, air clad structures and doped materials up to ~2mm have been spliced. For selected PCF- end cap splices cleave or polishing requirements as well as results on beam quality, tensile strength and further splice features are presented.

8244-35, Session 1

Highly precise and robust packaging of optical components

M. Leers, M. Winzen, H. Faidel, H. Plum, J. Miesner, W. Brandenburg, H. Hoffmann, Fraunhofer-Institut für Lasertechnik (Germany)

In this paper we present the development of a compact, thermo-optically stable and vibration and mechanical shock resistant mounting technique by soldering of optical components. Based on this technique a new generation of laser sources for aerospace applications is designed. In these laser systems solder technique replaces the glued and bolted connections between optical component, mount and base plate. Alignment precision in the arc second range and realization of long term stability of every single part in the laser system is the main challenge.

At the Fraunhofer Institute for Laser Technology ILT a soldering and mounting technique has been developed for high precision packaging. The specified environmental boundary conditions (e.g. a temperature range of -40°C to +50°C) and the required degrees of freedom for the alignment of the components have been taken into account for this technique.

In general the advantage of soldering compared to gluing is that there is no outgassing. In addition no flux is needed in our special process. The joining process allows multiple alignments by remelting the solder. The alignment is done in the liquid phase of the solder by a 6 axis manipulator with a step width in the nm range and a tilt in the arc second range.
In a next step the optical components have to pass the environmental tests. The total misalignment of the component to its adapter after the thermal cycle tests is less than 10arc second. The mechanical stability tests regarding shear, vibration and shock behavior are well within the requirements.

8244-05, Session 2

Amorphous Si crystallization by 405-nm GaN laser diodes for high performance TFT applications: advantages of using 405-nm wavelength

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It is crucial to achieve both high performance and low cost processing of backplane Si-TFTs for the next generation flat panel display. Crystallization of amorphous silicon (a-Si) is one of bottlenecks to meet such requirements. Although laser crystallization (annealing) is a promising way to provide high electrical performance TFTs, the conventional method using excimer lasers still has some issues with maintenance cost, process stability, power efficiency, and high equipment cost. Recently, for the alternative laser source, solid-state-lasers and LDs with visible wavelengths have attracted much attention. In this work, we focus on the 405 nm LDs crystallization process and apply it to the formation of bottom gate (BG) type microcrystalline (mc-) Si TFT for the first time. Except requiring additional a-Si crystallization step, processing and device structure of BG mc-Si TFT are almost identical to those of BG a-Si TFT of which low cost process has been well established on large-sized glass substrate. We have developed the 405 nm crystallization process of a-Si and successfully demonstrated superior characteristics of mc- and polycrystalline-Si TFTs. In addition, to verify the validity of our process, a heat flow simulation was performed. By comparing other visible wavelengths of 445 and 532 nm, we found that the wavelength is a key factor for its uniformity, energy efficiency, and process margin. Among the three wavelengths, 405 nm gave the best simulation result on those points. Also, the simulation results explained well the experimental results such as crystallinity distribution of mc-Si film.

8244-06, Session 2

Heat-induced structure formation in metal films generated by single ultrashort laser pulses

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Ultrashort pulsed lasers are increasingly used in micromachining applications. Their short pulse lengths lead to well defined thresholds for the onset of material ablation and to the formation of only very small heat affected zones, which can be practically neglected in the majority of cases. Structure sizes down to the sub-micron range are possible in almost all materials - including heat sensitive materials. Ultrashort pulse laser ablation - even though called “cold ablation” - in fact is a heat driven process. Ablation takes place after a strong and fast temperature increase carrying away most of the heat with the ablated particles. This type of heat convection is not possible when reducing the laser fluence slightly below the ablation threshold. In this case temperature decreases slower giving rise to heat-induced material deformations and melt dynamics. After cooling down protruding structures can remain - ablation-free laser surface structuring is possible. Structure formation is boosted on thin metal films and offers best reproducibility and broadest processing windows for metals with low hot shortness and weak electron-phonon coupling strength.

We investigated the formation of heat-induced structures in thin metal films generated by single ultrashort laser pulses. Results and images taken in pump-probe experiments will be presented and discussed.

8244-08, Session 2

Laser micromachining of organic LEDs

T. Petsch, J. Haenel, M. Clair, C. Scholz, 3D-Micromac AG (Germany)

OLED lighting is expected to be one of the fastest growing markets in the area of organic electronics. The state of the art production is mainly based on vacuum deposition processes, which, in order to simplify the material handling, will most probably be embedded in a roll-to-roll environment. While reducing the handling costs this also implies challenges to the patterning of the several OLED layers. Laser micromachining applying ultra-short pulsed laser sources has the potential to fully satisfy the requirements. Within this Paper the latest findings on the separate scribing steps P1, P2 and P3 will be presented.

8244-09, Session 2

Analysis and characterization of the laser decal transfer process

S. A. Mathews, R. C. Y. Auyeung, A. Piqué, U.S. Naval Research Lab. (United States)

We have studied the kinetics of a congruent, pixilated laser forward transfer process known as laser decal transfer (LDT). This process allows the transfer and patterning of silver nanoparticle inks such that the transferred pixels or “voxels” maintain the shape of the laser illumination. This process is capable of creating freestanding and bridging structures with near thin-film properties. We present an investigation of the dynamics of the release process in LDT as a function of ink layer thickness, ink viscosity, and laser fluence. The mechanism of the LDT process will be evaluated using high-speed video. An analytical model is proposed for calculating the threshold fluence for laser decal transfer as a function of ink layer thickness and laser spot size.

This work was sponsored by the Office of Naval Research.

8244-10, Session 2

Laser origami: a new technique for assembling 3D microstructures

A. Piqué, S. A. Mathews, N. A. Charipar, A. J. Birnbaum, U.S. Naval Research Lab. (United States)

The ability to manufacture and assemble complex three dimensional (3-D) systems via traditional photolithographic techniques has attracted increasing attention. However, most of the work to date still utilizes the traditional patterning and etching processes designed for the semiconductor industry where 2-D structures are first fabricated, followed by some alternative technique for releasing these structures out-of-the-plane. In this talk we will present a novel technique called Laser Origami, which has demonstrated the ability to generate 3-D microstructures through the controlled out-of-plane folding of 2-D patterns. This non-lithographic, and non silicon-based process is capable of microfabricating 3-D structures of arbitrary shape and geometric complexity on a variety of substrates. The Laser Origami technique allows for the design and fabrication of arrays of 3-D microstructures, where each microstructure can be made to fold independently of the others. Application of these folded micro-assemblies could make possible the development of highly complex and interconnected electrical, optical and mechanical 3D systems. This talk will describe the unique advantages and capabilities of Laser Origami, discuss its applications and explore its role for the assembly and generation of 3D microstructures.

This work was sponsored by the Office of Naval Research.

8244-11, Session 3

3D processing using femtosecond lasers for aperiodic volume optics

R. Piestun, Univ. of Colorado at Boulder (United States)

I review recent work in the fabrication of aperiodic structured optcal elements using femtosecond pulse lasers. We discuss direct laser writing in glass and photoresist to generate subwavelength structures, volumetric diffractive optics, and aperiodic photonic crystals. Of particular interest are techniques to deliver the beam and to improve resolution and precision. The three-dimensional fabrication capabilities enable novel optical functionalities for spatial, temporal, and spectral control of light.

8244-12, Session 3

Nano-structured surfaces by laser interference lithography and fs-laser direct writing as substrates for surface-enhanced Raman spectroscopy

T. Klotzbücher, L. Ben Mohammadi, N. Hundertmark, F. Kullmann, F. Fleissner, Institut für Mikrotechnik Mainz GmbH (Germany)

Nano-structured surfaces were generated by laser interference lithography and fs-laser direct writing of photo resists that subsequently were metallised by electroless plating or sputter deposition of silver. Laser lithography was performed with a 405 nm coherent diode laser in AZ9260, using two-beam interference with double illumination and 90° rotating of the substrate, leading to 2D periodic surface patterns with smallest features of the order of 200 nm. With fs-laser direct writing using a Ti-sapphire oscillator of 800 nm and 10 fs pulse length, feature sizes down to 100 nm could be realised in SU8, even with aspect ratios much larger than 1. Metallisation with electroless plating delivered either grainy silver coatings with a grain size around 100 nm or needle-like silver coatings with a needle length around 100 nm and a width of around 10 nm. The metallised substrates were exposed to aqueous solutions of Rhodamine 6G (Rh6G) of different concentrations and measured in a Raman micro-probe spectrometer. The nano-structured surfaces lead to formation of Raman bands attributable to Rh6G. In case of the grainy silver coatings, surfaces without nano-structures did not show Raman activity, indicating that grating-coupled surface plasmons play the dominant role for Raman enhancement. In case of substrates coated with the needle-shaped silver crystallites, Raman activity was also seen in regions without laser-generated nano-structures, indicating that localised particle plasmons play the dominant role for Raman enhancement. Comparison with Raman spectra measured in conventional Raman spectrometer demonstrated that the enhancement factor achieved by the laser-generated nano-structures itself is of the order of 104. Raman intensity as a function on Rh6G concentration showed a regular behaviour, as expected from a Langmuir isotherm.

8244-13, Session 3

In situ diagnostics on fs-laser induced modification of glasses for selective etching

M. Hermans, J. Gottmann, A. Schiffer, RWTH Aachen (Germany)

Non-linear absorption of focused ultra short pulsed laser radiation enables in-volume modification of transparent materials. At high intensities occurring in the focal volume initial free electrons are generated by multi-photon absorption and avalanche ionization resulting in thermally and/or electronically induced structural changes within a volume of ~1µm³. With the application of high repetition rates effect like heat accumulation, enhanced absorption of the laser radiation by thermally excited electrons give rise to large temperatures and pressures resulting in large heat affected volumes with modified material.

The induced modifications of the transparent material are perceivable as a localized refractive index change (used for waveguide writing) and a local change of the corrodibility by wet etching agent (used for in-volume selective laser-induced etching, ISLE). In-situ observation of the modification with an interferometer microscope allows for the spatially resolved measurement of the transient optical path difference (OPD) in the surrounding of the laser-induced modification. By the relation of refractive index and temperature an estimation of temperature during modification process is possible. The absorption of the laser radiation is measured and the resulting processing temperature during modification is estimated as a first step towards a process model for ISLE.

New results of parts manufactured with ISLE will be presented and a future outlook will be discussed.

8244-14, Session 3

Large area direct fabrication of periodic arrays using interference patterning

A. F. Lasagni, T. Roch, D. Langheinrich, M. Bieda, H. Perez, A. Wetzig, E. Beyer, Fraunhofer IWS Dresden (Germany)

Periodic patterned surfaces do not merely provide unique properties, but act as intelligent surfaces capable of selectively influencing multiple functionalities. One of the most recent technologies allowing fabrication of periodic arrays within the micro- and submicrometer scales involves Direct Laser Interference Patterning (DLIP). Differently from Laser Interference Lithography, DLIP permits the direct treatment of the material's surface based on locally induced photothermal or photochemical processes. Furthermore, the method is particularly suited to fabricate periodic patterns on planar and non-planar surfaces, and large areas can be processed within a short time offering a route to large-scale production.

In this paper, the fabrication of spatially ordered structures on different materials such polymers, metals and carbon-like films will be discussed. Although the smallest theoretically structure size that can be fabricated is given by half the used laser wavelength, we found that this dimension mainly depends on the nature of the laser light interaction with the processed material. For carbon-like layers and several polymers, sub-micrometers structures (150 - 800 nm) are possibly, while only micrometer scale arrays (> 1 µm) can be fabricated on metallic substrates. Moreover, within a family of materials also significant differences can be observed, which can be explained in terms of thermal diffusion processes as well as differences on optical properties.

Several application examples as function of the processed material will be introduced, including bio functional surfaces for cell guidance on polymers, wear resistant properties for carbon-like and metallic substrates, as well as micro-patterned flexible polymers with controlled optical properties.

8244-15, Session 3

Integration of a three-dimensional filter in a microfluidic chip for separation of microscale particles

N. Bellini, Politecnico di Milano (Italy); Y. Gu, Massachusetts Institute of Technology (United States); L. Amato, G. Cerullo, Politecnico di Milano (Italy); R. Osellame, Istituto di Fotonica e Nanotecnologie (Italy)

Miniaturization of microfluidic functionalities in lab-on-a-chip is highly on-demand. In particular, porous filters have become valuable building blocks in microbiological studies and biochemical analysis, providing further integrated functionalities on the same microfluidic platform. However, their integration typically poses severe problems in the chip design and fabrication. Femtosecond laser micromachining of micro/nanostructures by two-photon polymerization (2PP) is a powerful method for realization of sub-micron resolution, 3D devices. In contrast with existing fabrication technologies, 2PP enables precisely controlled direct-write of 3D structures with simple processing, easy integration and no need of cleanroom environments. This direct-write technique allowed us to integrate porous filters in a commercially available microfluidic chip by post-processing with a femtosecond laser.

We fabricate the 3D porous filter by 2PP directly inside a microfluidic channel. The filter layour has been studied in order to provide robustness and capability of blocking microscale elements letting nanoscale ones through. The filter is tested in several flow conditions. The first experiment makes use of a mixture of 3-µm beads in buffer solution and demonstrates the capability of blocking 100% of beads at the filter. Other experiments are accomplished with the same microbeads this time diluted in Rhodamine 6G. We observe that beads are stopped while fluorescent solution keeps flowing through the porous filter. In all cases, we demonstrate operation exceeding 25 minutes without any evidence of clogging. In addition, we show the possibility of cleaning the filter by reversing the flow; this allows multiple usage of the device.

8244-16, Session 3

Surface-enhanced Raman spectroscopy using Au-coated vertically aligned carbon nanotubes

X. He, H. Huang, M. Mahjouri-Samani, Y. Gao, W. Xiong, M. Mitchell, W. Hu, Y. Zhou, Y. Lu, Univ. of Nebraska-Lincoln (United States)

Surface-enhanced Raman spectroscopy (SERS) using Au-coated vertically-aligned carbon nanotubes (VA-CNTs) was carried out to investigation the plasmonic characteristics of this nanostructure. It was discovered that the Raman signals of Rhodamine 6G and B molecules were significantly enhanced. VA-CNTs were synthesized on Si/SiO2 substrates using a laser-assisted chemical vapor deposition (LCVD) method. VA-CNTs were utilized as templates to provide ordered tip-arrays of narrow gaps over a large area with controllable size and density. Uniform Au films were then deposited on the CNT templates and cap the CNTs with metallic tips with a narrow gap at nanoscales. Theoretical simulations using Finite-Difference Time-Domain (FDTD) algorithm were carried out to study the near-field effects of the tip-array plasmonic nanostructures. Large SERS enhancement factor of the fabricated plasmonic nanostructure array was demonstrated. Rhodamine 6G and B solutions with different concentrations in a range of 10-6~10-11 M were used in this study. The mapping mode of a commercial micro-Raman system was used to detect the molecules on the tip-array plasmonic nanostructures. The Raman spectroscopic data were analyzed to determine the information about the 2D distribution of the “hot spots” on the tip-array plasmonic nanostructures which determine a 2D map of the SERS enhancement factor over the substrates. Optimization of the fabrication process of the tip-array plasmonic nanostructures was carried out to obtain not only high SERS enhancement on local spots but also the capability of 2D detection in a large area.

8244-17, Session 3

Enhancement of laser-induced breakdown spectroscopy signals using both hemispherical cavity and magnetic field

L. Guo, Univ. of Nebraska-Lincoln (United States) and Wuhan National Lab. for Optoelectronics (China); X. He, B. Zhang, C. Li, W. Hu, Y. Zhou, Univ. of Nebraska-Lincoln (United States); Z. Cai, X. Zeng, Wuhan National Lab. for Optoelectronics (China); Y. Lu, Univ. of Nebraska-Lincoln (United States)

A pair of permanent magnets and an aluminum hemispherical cavity (diameter: 11.1 mm) were both used to confine plasmas produced by chromium targets in air using a KrF excimer laser in laser-induced breakdown spectroscopy. A significant enhancement of about 24 in the emission intensity of Cr lines was acquired at a laser fluence of 6.2 J/cm2 using the hybrid confinement; in comparison, only about 12 was obtained with just a cavity. The Si plasmas, however, were not influenced by the presence of the magnets as Si is hard to ionize and hence has less free electrons and positive ions. The hybrid confinement mechanism was discussed using shock wave theory in the presence of a magnetic field.

8244-18, Session 4

Laser structuring of metallic mould inserts by using µs, ns, and ps-laser ablation

S. G. Scholz, Cardiff Univ. (United Kingdom)

The increasing demand of microsystem-based products has led to the development of a number of processing chains complementary to those used for batch-manufacturing of micro electro mechanical systems (MEMS). Such alternative process chains combine micro and nano structuring technologies for master making with replication techniques for high throughput such as injection moulding (IM). Here, two new process chains for replicating micro-structured surfaces inspired by nature are presented. In particular, structures incorporating functional features found on the eye of a household fly and on a shark skin were replicated. Initially, 3D models of the features were designed by applying a bio-mimetic modelling approach. These models were used to manufacture mould inserts with microstructured cavities using micro-second (ms), nano second (ns) and pico-second (ps) laser ablation and focused ion beam (FIB) milling to perform micro and nano structuring, respectively. The feasibility of applying these technics for producing masters with bio-inspired surface structures was investigated by performing micro injection moulding trials. The results show that 3D micro and nano structured surfaces can be replicated successfully using both process chains, and the two process chains can be considered as promising manufacturing routes for serial production of parts incorporating bio-inspired surface structures. The results show expected limitation of the individual laser systems with respect to surface roughness and removal rates, i.e. the system with the fastest removal rates produces the roughest surface and vice versa. Optimum manufacturing strategy, i.e. to get best results, would be in the combination of the different laser systems in the sense of “roughing and finishing” as applied in the micro milling process.

8244-19, Session 4

Laser-chemical precision machining of micro forming tools at low laser powers

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Micro forming tools require both high surface quality and contour accuracy, i.e. close tolerances at small dimensions. Owing to the mechanical properties of the tool material on micro scale, however, their structuring with necessary sufficiency is limited to a small number of applicable technologies. This contribution reports on one of such machining techniques for precise tool finishing based on a laser-chemical etching method where a focused laser beam is guided coaxially to an etchant jet-stream onto the material surface. The material removal is a result of laser-induced chemical reactions between the etchant and the surface at low laser powers. The data presented show that the material removal is strongly affected by different process variables. In particular, high laser powers combined with high feed rates and low flow rates of the etchant lead to a break-off in material removal. As a consequence, the process boundaries have been experimentally determined and implemented in a quality control system. The latter consists of an automated path planning model and an inverse process model. While the first one computes position and Gaussian intensity profile for a sequence of overlapping laser beam paths to achieve the desired tool shape, the inverse process model renders specific process variables for every single beam path from a pre-assembled data pool within experimentally defined boundary conditions.

8244-21, Session 4

Process limitations in microassembling using holographic optical tweezers

R. Ghadiri, Q. Guo, C. Esen, A. Ostendorf, Ruhr-Univ. Bochum (Germany)

In this work the process limitations in Microassembling based on dynamic Holographic Optical Tweezers (HOTs) are investigated. Microassembling is realized by combining an appropriate particle binding technique with a micromanipulation method to precisely join the particles together. Preferentially HOTs are used for this approach due to the versatility of this technology. However, particle delivery is limited by inner friction within the medium and the forces exerted by the HOTs. In a classical optical tweezers setup, strongly focused laser irradiation is permanently directed to one microsphere exciting optical forces trapping the particle. To move the micro object the laser beam is distracted from the initial position, e.g. by a motorized tilt mirror. Thereby the particle will follow the beam spot migration. By contrast HOTs utilize spatial light modulators (SLM) to split the laser beam into different, accurately defined spot positions. For dynamic particle motion this position has to be changed slightly by imaging corresponding kinoforms on the SLM, thus displacing the laser beam position. Therefore the laser irradiation does not act continuously on the microsphere but switches between discrete positions of the desired itinerary in convenient steps. An optimization of this step size is crucial to reach maximum speed in particle movement. Also the trap stiffness of HOTs depends on the degree of beam deviation, as the diffraction efficiency decays with stronger beam deflection. These effects limit the dynamics of HOTs and will be investigated in our work. The influence of relevant parameters as the applied laser power, particle size and beam deflection level are considered and explored in individual experiments exploring the escape forces in the optical traps.

8244-22, Session 5

Laser machining of carbon fibre reinforced polymeric (CFRP) composite materials

L. Li, The Univ. of Manchester (United Kingdom)

Carbon fibre reinforced polymeric composite materials are widely used in the aerospace space industry and other industries as part of the light weight structures. Their machining is currently dominated by mechanical means, which results in very high tooling costs. Laser machining of CFRP is an emerging technology that is still in the basic R&D phase. Due to the significant difference in material properties between the carbon fibre and the polymer material, heat affected zones often occur in laser machining. An overview of recent development in laser machining of CFRP is given in this paper highlighting the basic process phenomena and challenges. The effects of laser pulse width and wavelengths on machining quality are discussed. The work by the author's research group on nanosecond (IR and UV wavelengths), micro-second, continuous wave and picosecond pulsed laser machining of CFRP is reported.

8244-23, Session 5

Plastic optofluidic chip fabricated by femtosecond laser ablation

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An optofluidic chip is a device that combines integrated optics and microfluidics to achieve enhanced performances. Nowadays there is a great tendency to fabricate these chips in plastic substrates to have cheap and disposable microfluidic devices; nevertheless it is still difficult to integrate the optical excitation and detection in them. In this work we integrate fluorescence optical sensing in a polymer (PMMA) microfluidic chip all fabricated by femtosecond laser micromachining. It consists of a central microfluidic channel (10 mm length, 125 μm width and 90 μm depth), and two grooves (125 μm width and 125 μm depth) to place optical fibers perpendicular to the microfluidic channel; this allows multipoint fluorescence excitation. In correspondence to the excitation point two Binary Fresnel lenses (BFLs) were fabricated on the back surface of the chip. These BFLs were designed to collect the fluorescence from the channel and focus it onto a detector. They have a 0.2 numerical aperture, 2.2mm focal length and 30% focusing efficiency, which is reasonably close to the maximum theoretical value of 40%. To demonstrate device operation and measure the limit of detection (LOD), the microfluidic channel was filled with different Rhodamine 6G solutions and a fiber (with green light coupled in it) was inserted into the grooves. Under these conditions our optofluidic chip achieved a 50nM LOD.

8244-24, Session 5

Control of element distribution in glass with femtosecond laser

M. Shimizu, M. Sakakura, M. Nishi, Y. Shimotsuma, K. Hirao, K. Miura, Kyoto Univ. (Japan)

The composition of a glass affects its material properties such as refractive index, light absorption, luminescence property, crystallization temperature, and miscibility. By controlling the glass composition three-dimensionally, we would add new functionalities to a glass. Femtosecond (fs) lasers have been recognized as powerful tools to modify transparent materials in a three-dimensional manner. Recently, element redistribution with fs laser at high repetition rate has attracted much attention, because it has the potential to control glass composition three-dimensionally. In the presentation, we report on the mechanism of element redistribution in glass during fs laser irradiation and application of this phenomenon.

The results of the numerical simulation, in which concentration- and temperature-gradient-driven diffusions were considered, were in good agreement with the experimental results. This suggests that the element migration is categorized as thermodiffusion. The migration tendency of the elements depends on the strength of the bond between cations and oxygen ions: the strongly bonded ions like Si^{4+} and Al^{3+} migrate to the center of the irradiated spot (hot region), whereas weekly bonded ions such as Ca^{2+} and Na^{+} migrate to the outside (cold region). This tendency can be understood in terms of the diffusivity of each element. By quantitative analysis using confocal Raman spectrometer, we observed 10 mol% compositional change within the 20 μm radius inside SiO_2-Na_2O glass after 5 second laser irradiation. As application of the element redistribution, we succeeded in fabrication of optical waveguide inside glasses and space-selective formation of nano-scale structure, which is due to phase separation, on a glass surface.

8244-25, Session 5

Compact high power ps laser and its application in large area engraving

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Material processing with ps lasers is generally known for nearly zero thermal influence and high precision and enables new possibilities in the manufacturing of high end products with extraordinary processing qualities. As an industrial requirement, high average power is needed to allow sufficient and economical processing speed. To scale the power for an industrial picosecond laser an oscillator and amplifier system has been developed, which consists of a seeder, a preamplifier and end amplifier. Both amplifiers are based on the INNOSLAB set up, which has the potential of multi kilowatt power at high beam quality. In this paper we will discuss the design and performances of a compact, reliable and affordable ps laser with 400W average power and application results in high speed and large area engraving of press cylinder.

8244-26, Session 5

Rotating optics for laser taper-drilling in research and production

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Drilling of micro through-holes in defined geometry, i.e. entrance diameter and taper, is gaining in importance in different fields of application and production. To exploit the advantages of laser technology for micro machining, versatile trepanning systems based on rotating optics have been designed and implemented. The advanced trepanning systems enable the controlled adjustment of beam displacement and inclination during operation. With a patented measuring device, the angular position of the rotating optics is determined online. The presented compact and low-weight trepanning systems can drill differently tapered through-holes with a diameter in a range of 50 to 1500 µm. Various solid-state laser sources have been used in combination with the presented laser trepanning system for material ablation. The wavelength und pulse width range from 355 to 1550 nm and sub-ps to 100 ns. The novel trepanning systems have been customized for different applications, ranging from basic research quest to industrial production. This presentation outlines the development steps and application results, accenting laser micro drilling of up to 1 mm thick metal, glass and ceramic samples.

8244-27, Session 6

Laser cutting of graphite anodes for automotive lithium-ion secondary batteries: investigations in the edge geometry and heat affected zone

B. Schmieder, Manz Automation AG (Germany)

To serve the high need of lithium-ion secondary batteries of the automobile industry in the next ten years it is necessary to establish highly reliable, fast and non abrasive machining processes. In previous works [1] it was shown that high cutting speeds with several meters per second are achievable. For this, mainly high power single mode fibre lasers with up to several kilo watt where used. Since lithium-ion batteries are very fragile electro chemical systems, the cutting speed is not the only thing important. To guarantee a high cycling stability and a long calendrical life time the edge quality and the heat affected zone (HAZ) are equally important. Therefore, this paper tries to establish an analytical model for the geometry of the cutting edge based on the ablation thresholds of the different materials. It also deals with the composition of the HAZ in dependence of the pulse length, generated by laser remote cutting with pulsed fibre laser. The characterisation of the HAZ was done by optical microscopy, SEM, EDX and Raman microscopy.

8244-28, Session 6

Laser adjusted three-dimensional Li-Mn-O cathode architectures for secondary rechargeable lithium-ion cells

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Three-dimensional cathode architectures for rechargeable lithium-ion cells can provide better Li-ion diffusion due to larger electrochemical active surface areas and therefore, may stabilize the cycling behaviour of an electrochemical cell. This features show great importance when aiming for long-life batteries, e.g. in stationary or portable power devices.

In this study, Li-Mn-O films were used as cathode material with the goal to stabilize their cycling behavior and to counter degradation effects which come up within the Li-Mn-O system.

Firstly, the laser ablation rate of cathode material and its impact on surface chemistry was studied in detail. For this purpose, the ablation experiments were performed under ambient air. In a second step appropriate laser ablation parameters were selected in order to achieve defined three-dimensional structures with features sizes down to micro- and sub-micrometer scale for large area sample patterning. Laser annealing was also applied onto the laser structured material in order to form an electrochemically active phase. Process development leads to a rapid annealing strategy for a flexible adjustment of crystallinity and grain size. Laser annealing was realized using a high power diode laser system operating at a wavelength of 940 nm. The control in temperature was realized on-line during the process by a pyrometer.

Information on the surface composition, chemistry and topography as well as studies on the crystalline structure of the bulk material were obtained using Raman spectroscopy, X-ray photoelectron spectroscopy, scanning electron microscopy and X-ray diffraction analysis methods. The electrochemical activity of the laser modified lithium manganese oxide cathodes was explored within cyclic voltammetry measurements and galvanostatic testing methods using a lithium anode and liquid electrolyte EC/DMC 1:1 containing 1 M $LiPF_6$.

8244-29, Session 6

Influence of laser-generated surface structures on electrochemical performance of lithium cobalt oxide

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The further development of energy storage devices especially of lithium-ion batteries plays an important role in the ongoing miniaturization process towards lightweight, flexible mobile devices. To improve mechanical stability and to increase the power density of electrode materials while maintaining the same footprint area, a three-dimensional battery design is necessary.

In this study different designs of three-dimensional cathode materials are investigated with respect to the electrochemical performance. Lithium cobalt oxide ($LiCoO_2$) is considered as a standard cathode material, since it has been in use since the first commercialization of lithium-ion batteries.

Various electrode designs were manufactured in $LiCoO_2$ electrodes via laser micro-structuring. Laser ablation experiments in ambient air were performed to obtain hierarchical and high aspect surface structures. Laser structuring using mask techniques as well as the formation of self-organized conical surface structures were studied in detail. In the latter case a microstructure density of >106 cm-2 was obtained with a significant increase of active surface area.

Laser annealing was applied for the control of the average grain size and the adjustment of a crystalline phase which exhibits electrochemical capacities in the range of the practical capacity known for $LiCoO_2$. An investigation of cycling stability with respect to annealing parameters such as annealing time and temperature was performed using a diode laser system operating at 940 nm.

Information on the phase and crystalline structure were obtained using Raman spectroscopy and X-ray diffraction analysis methods. The electrochemical performance of the laser modified cathodes was studied via cyclic voltammetry and galvanostatic testing using a lithium anode and a liquid electrolyte EC/DMC 1:1 containing 1 M $LiPF_6$.

8244-30, Session 6

Transient thermal analysis and mechanical strength testing of pulsed laser welded ribbons to feedthru joints

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In this work, a laser welding process for attaching conducting ribbons to a miniaturized feedthru is introduced. A pulsed 1064nm Nd:YAG laser was used as an example in this study. A numerical simulation by means of finite element method (FEM) for the prediction of temperatures in the feedthru assembly is presented. The approach used was intended to solve the energy balance equation with appropriate initial and boundary conditions. A laser weld joint strength test was conducted using a Mechanical Strength Tester. The influence of processing parameters, such as laser power and pulse duration, on the temperature distribution and the weld joint strength are investigated and discussed.

8244-31, Session 7

Laser sintering of Si and Ge nano- and microparticle films toward solar cells by solution process

A. Watanabe, Tohoku Univ. (Japan)

The global energy problem requires the science and technology innovation for renewable energy. One of the problems with solar cells is the high energy costs in comparison with other energy sources. Recently, the solution processes of solar cells without vacuum processes have attracted much interest as a cost-reducing process innovation. The challenge toward solution process of Si and Ge semiconductor materials has been made recently. The development of Si and Ge semiconducting films by solution process provides the possibilities to realize the low cost manufacturing of solar cells. In this presentation, the formation of Si and Ge films from the nano- and microparticle-dispersed solutions and the laser sintering are reported. The Si nano- and microparticle-dispersed solutions were prepared by ball milling of bulk Si with various kinds of dopant concentration with organic solvent and a binder polymer. As binder polymers, organosilicon nanocluster (OrSi) and organogermanium nanocluster (OrGe) were applied, which are organomettalic polymers having hyperbranched Si-Si or Ge-Ge chain and organic side chain solubilizing the inorganic cluster into an organic solvent. The laser sintering was carried out using CW and nanosecond pulsed DPSS laser (457 and 532 nm). The confocal micrographs showed the fusion of Si particles and the large grain formation by laser scanning irradiation. The influences of the laser irradiation under various conditions were discussed by measuring the I-V characteristics of n-Si/Au schottky diode solar cells. The performance of n-Si/Au schottky diode solar cells was improved by thermalannealing under hydrogen/Ar gas flow after laser sintering.

8244-32, Session 7

High quality micro-machining using ultracompact picosecond lasers

O. Haupt, S. Spiekermann, I. Freitag, InnoLight GmbH (Germany)

We will show that our new ultra-compact picosecond laser sources can be used very successful for many different micro-machining applications. Especially, where thermal sensitive materials like semiconductors, glass, or thin-films are used. Due to the compact and simple design these picosecond lasers bridging a gap between high cost ultra-short pulsed lasers and conventional ns lasers. We will demonstrate on glass, semiconductors, and thin-film PV materials that the process quality could be comparable high using ultra-compact picosecond lasers instead of ultra-short pulsed lasers. Due to the short pulse duration with corresponding low thermal penetration depths and ablation ratios suitable processes are more focused on the surface than bulk material processing. Micro-machining is typically done with ultra-short laser pulses or nanosecond laser pulses due to not existing laser systems with adequate power and pulse repetition frequency. The gap from 15 ps to 10 ns is enormous with two orders of magnitude. Especially, we show ablation threshold for thin-film and crystalline solar cells and achievable qualities in dependency of wavelength and pulse energy for pulse durations > 400 ps.

8244-43, Session 7

Structuring of functional thin films and surfaces with picosecond-pulsed lasers

G. Raciukaitis, P. Gecys, M. Gedvilas, B. Voisiat, Ctr. for Physical Sciences and Technology (Lithuania)

During the recent few years picosecond lasers have been proved as a reliable tool for microfabrication of diverse materials. We present results of our research on structuring of thin films and surfaces using the direct laser writing and the laser beam interference ablation techniques. The processes of micro-pattering were developed for metallic, dielectric films as well as complex multi-layer structures of thin-film solar cells as a way to manufacture frequency-selective surfaces, fine optical components and integrated series interconnects for photovoltaics. Technologies of nano-structuring of surfaces of advanced technical materials like tungsten carbide were prepared using picosecond lasers as well.

Experimental work was supported by modeling and simulation of energy coupling and dissipation inside the layers. Selectiveness of the ablation process is defined by optical and mechanical properties of the materials, and selection of the laser wavelength facilitated control of the structuring process.

Implementation of the technologies required fine adjustment of spatial distribution of laser irradiation, therefore both techniques are benefiting from shaping the laser beam with diffractive optical elements. Utilization of the whole laser energy included beam splitting and multi-beam processing.

8244-44, Session 7

Laser processes for future solar cells

A. Letsch, Robert Bosch GmbH (Germany)

The photovoltaic industry requires higher efficiencies at lower manufacturing costs to become competitive with other power generation techniques. There are several approaches to increase the efficiency of solar cells by enhancements of the way photons are absorbed and how they generate charge carriers with low losses. We will discuss several concepts and show examples how lasers could enhance the manufacturing, especially focussing on future concepts and the required properties of lasers and optics. Today, the so called first generation of photovoltaic devices based on crystalline silicon wafers are produced on a multi-GW-level, but in most production lines there is only one laser process used to electrically isolate front and rear side of the cell. Lasers are predestined to generate local structures which will be required to manufacture high efficient solar cells. As an example we will show results on the interaction of ultra short laser pulses with dielectric films on silicon. This process can be used to generate electrical point contacts through dielectric stacks which are required to enhance the optical absorption as well as to increase the carrier life-time. Second generation photovoltaic modules are based on thin films. These modules are monolithically interconnected by laser scribing of the films. Tools for amorphous silicon are well established, while there are a lot of challenges to scribe CIGS or organic photovoltaic layers, which offer new chances for thin film photovoltaics. New results on laser scribing these layers will be shown.

8244-45, Session 7

Selective ablation of thin films in latest generation CIGS solar cells with picosecond pulses

A. Burn, M. Muralt, Berner Fachhochschule Technik und Informatik (Switzerland); R. Witte, B. Frei, Solneva SA (Switzerland); S. Bücheler, EMPA (Switzerland); V. Romano, Berner Fachhochschule Technik und Informatik (Switzerland)

In order to conserve their efficiency, solar panels are subdivided into small, serially connected individual cells. The monolithic interconnect typically consists of three layer-selective ablation scribes. With increasing total scribe length, speed and precision of the scribing process becomes more and more important.

Picosecond pulsed lasers allow very precise and highly selective ablation of thin films in latest generation CIGS solar cells. This allows a significant reduction of the dead zone by a factor of more than two compared to current industrial standards.

High scribing velocities and good quality are achieved with high repetition rate, low pulse energy sources. Compact all-fiber picosecond lasers are ideally suited for this application and they are available at competitive prices.

In a comprehensive parameter study of picosecond laser sources at different wavelengths and pulse duration we identified possible process windows for the P1, P2 and P3 scribes. To demonstrate reliability, a functional mini module with low dead zone has been produced using all picosecond laser scribing.

We further identified and successfully exploited robust process windows in regimes traditionally inaccessible to picosecond lasers due to the non-linear absorption behavior of CIGS. We were able to produce very clean trenches of freely selectable width between 40 micron and 150 micron at constant pulse energy and repetition rate.

Conference 8245: Synthesis and Photonics of Nanoscale Materials IX

Monday-Tuesday 23-24 January 2012

Part of Proceedings of SPIE Vol. 8245 Synthesis and Photonics of Nanoscale Materials IX

8245-01, Session 1

The nano-optics of plasmonic optical tweezers, SERS substrates, and multi-colored silicon nanowires

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Field enhancement from surface plasmon structures presents new opportunities for optical manipulation and surface enhanced Raman spectroscopy (SERS). We demonstrate three configurations for manipulating nanoparticles using the optical forces from surface plasmons. In the first, we propel nanoparticles using surface plasmon polaritons (SPPs) on a thin gold film (NanoLett 2009). In the second, we trap microparticles with counter-propagating SPPs on a gold stripe (NanoLett 2010). In the third, we demonstrate a gold nanopillar plasmonic tweezer (Nature Communications 2011). The substrate acts as a heat sink, and simulations predict a ~100-fold reduction in heating compared to previous designs. We describe our work on metal nanoparticle substrates for SERS. We demonstrate that periodic metal nanoparticle arrays can exhibit spectrally narrow surface plasmon resonances, with numerical simulations predicting considerably enhanced optical near-fields (APL 2008). We describe a novel SERS substrate with double plasmon resonances, that enables field enhancement at both pump and Stokes frequencies (ACS Nano 2010). We describe a method by which we lithographically fabricate pairs of nanoparticles with gaps as small as 3 nm, producing SERS enhancements almost two orders of magnitude larger than those with 16 nm gaps (Small 2011). Lastly, we demonstrate that vertical silicon nanowires take on a surprising variety of (diameter-dependent) colors covering the entire visible spectrum, in marked contrast to the gray color of bulk silicon. This effect is readily observable by bright-field microscopy, and arises from the guided mode properties of the individual nanowires (NanoLett 2011).

8245-02, Session 1

Plasmon resonances in structures with atomic-scale gaps

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Plasmon resonances of metallic nanostructures can lead to strongly enhanced and confined optical fields, thus offering the possibility to strongly enhance the interaction of light and matter. Electromagnetic interaction and the resulting mode hybridization provides a versatile tool to engineer both field localization and spectral properties of plasmonic particles [1].

We investigate the plasmon resonances of two strongly coupled parallel aligned gold nanorods that exhibit gaps on the order of 1nm. These structures are of high interest since the gap dimensions reach molecular length scales, which opens possibilities for the combination of plasmonic nanostructures with functional molecules. Moreover the gaps are in the range where deviations from classical electromagnetic theory are expected to become observable [2].

References

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8245-03, Session 1

Multi-photon autocorrelation in Au dipole antennas

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Multi-photon photoluminescence (MPPL) processes are a valuable tool for the characterization of plasmonic Au nanoparticles. It is now well established that two-photon photoluminescence in Au results from two sequential single-photon absorption events, and that its dynamics is ruled by the relaxation time in the conduction band after the first photon absorption event [1]. Notably, higher order absorption processes have been reported in the literature in single Au nanoparticles, where three-photon [2] and four-photon processes [3] have been reported. So far, however, the underlying physical processes leading to such nonlinearities are not very well understood.

We performed interferometric autocorrelation of ultrashort laser pulses using the MPPL of single Au dipole antennas. Autocorrelation traces show a tail with a 1-ps relaxation time related to incoherent carrier thermalization. By exploiting the large local field enhancement in the gap, we are able to study the relaxation dynamics for different orders of MPPL, namely two- and four-photon processes. Together with a simple model for the multi-photon absorption process, this study unveils the strong similarity between processes of different orders and suggests that their dynamics is always ruled by the relaxation time of the excited distribution in the conduction band. This leads to the formulation of a tentative rationale to describe the various nonlinearities of the power dependencies for absorption that have been reported in the literature.

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8245-04, Session 1

Ultrafast plasmon dynamics of individual nano-rod antennas

D. Polli, M. Zavelani-Rossi, G. Della Valle, M. Marangoni, Politecnico di Milano (Italy); P. Adam, Univ. de Technologie Troyes (France); G. Cerullo, Politecnico di Milano (Italy)

During the last years, metallic nano-structures have attracted much attention because of the resonant optical response induced by surface plasmon (SP) excitation. Femtosecond pump-probe spectroscopy has been exploited to investigate the transient response of plasmonic nano-structures. Most of the studies deals with ensembles and are limited to a single probe wavelength, thus providing only limited information about the spectral features involved in the ultra-fast dynamics of an individual plasmonic nano-system.

In this study we use broadband pump-probe spectroscopy combined with confocal microscopy to investigate the ultra-fast optical response of individual gold nanorod antennas.

The pump-probe system is based on a mode-locked Er:fiber oscillator and delivers pump pulses at 780 nm and tunable probe pulses in the 840-1050 nm range. By scanning the probe wavelength, differential reflectivity (DR/R) spectra of individual nanostructures were detected as a

function of time with 100-fs resolution. The sample consists of individual gold nanorods with 60-nm width and 100-400 nm lengths, fabricated by electron beam lithography on quartz substrate. Their SP resonances are thus located from 800 to 1200 nm.

We observed a fast rising of positive or negative DR/R signal depending on the length of the nano-antenna, followed by ps-time decay leading to a long-lasting (~100-ps) residual signal, in in agreement with theoretical predictions from the two-temperature model. Modelling the single particle nonlinear response highlighted that the heating of the free electrons of the metal is responsible for a red-shift of the plasmonic resonance, whereas the heating of the lattice causes a resonance broadening.

8245-05, Session 2

Elucidating effects of nanoscale structural variations on local plasmonic modes via photon localization microscopy

A. S. McLeod, A. Weber-Bargioni, J. B. Neaton, S. Cabrini, P. J. Schuck, Lawrence Berkeley National Lab. (United States)

Plasmonic devices are primarily based on metallic (nano)structures with nanoscale feature sizes, and many are designed to enhance and concentrate fields at ~ 10 nm length scales. This leads to an enhanced sensitivity of plasmonic modes to locally-varying material properties, device substructure, and environment, which must be taken into account for each specific application - and it is expected that the properties of plasmon modes with localized fields will be influenced by unavoidable fabrication-related structural variations.

Here, we use the recently-demonstrated non-perturbative all-optical probing technique of two-photon photoluminescence-based photon localization microscopy as well as electromagnetic simulations to reveal how small structural variations often significantly impact plasmonic properties, particularly for devices with ~ zeptoliter mode volumes. The photon-limited localization accuracy of nanoscale mode positions is determined for many of the measured devices to be within a 95% confidence interval of +/- 2.5 nm. Specifically, we find that for our test devices, local plasmonic behavior is primarily influenced by two classes of fabrication-related variations: 1) random, "incoherent" localized defects; and 2) small changes in structure size, which are directly related to the cavity length of the plasmon resonator. For this second case, we show that relatively modest changes in device length of about 10% can nearly double the spatial separation between modes.

To investigate the effects of fabrication-related imperfections, we chose as our test samples asymmetric bowtie nano-colorsorter (ABnC) optical antennae. Here we correlated relative spatial movements of the two modes with the structural variations we observed via SEM characterization.

8245-07, Session 2

Putting plasmonic near-field probes in perspective: the case for campanile geometry

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Efficiently converting photonic to nano-plasmonic modes to localize and enhance optical near fields is of high interest in terms of new imaging techniques, sensing and computing. Based on extensive simulations of various optical transformer geometries, we propose a novel photonic-plasmonic hybridized Scanning Near-field Optical Microscopy (SNOM) probe called a "campanile" tip, where the geometry resembles a bell tower. These campanile tips couple the photonic to the plasmonic mode over a broad bandwidth with high efficiency, crucial for many optical spectroscopy techniques. The confinement of the optical near field is determined by the gap size between the two antenna arms, which can be below 10 nm given the appropriate resolution of the nanofabrication tool and film growth method. Based on their excitation through the back of the tip similar to traditional aperture-based SNOM tips, these campanile tips are an excellent candidate for background-free nanoscale imaging and spectroscopy application on dielectric, non-transparent substrates. We also used Finite Element Method (FEM) to simulate conventional aperture-based probes, the coaxial plasmonic probes, traditional apertureless SNOM and the state-of-the-art adiabatic-compression-type probes, and compared them all with the campanile tip geometry. The understanding of relative strengths and weaknesses of each SNOM probe geometry served as the guideline for the design of the campanile tips, resulting in their superior field coupling, enhancement and resolution capabilities for many applications.

8245-17, Session 2

Noble metal nanoparticles on quartz supports as SERS substrates excited by a diode laser system for SERDS

R. Ossig, Univ. Kassel (Germany); Y. Kwon, H. Kronfeldt, Technische Univ. Berlin (Germany); F. Träger, F. Hubenthal, Univ. Kassel (Germany)

Noble metal nanoparticle ensembles were prepared under ultrahigh vacuum (UHV) conditions by Volmer-Weber growth on quartz substrates for surface enhanced Raman scattering (SERS) of pyrene molecules. To determine the dependence of the surface plasmon resonance (SPR) frequency in respect with the excitation wavelength of the used diode laser the spectral position of the SPR was varied.

The substrates were mounted in a flow-through cell as part of the optical Raman set-up.

Three diode laser microsystems were used, each generates two slightly different emission wavelengths ($\Delta\lambda \approx 0{,}5$ nm) with a spectral width of ≈ 10 pm and an optical power of ≈ 20 mW. With this set-up SERS as well as shifted excitation Raman difference spectroscopy (SERDS) can be carried out.

Experiments were conducted with all systems. In this presentation, however, we will concentrate on the results obtained with the diode laser system with an emssion wavelength of 488 nm.

For trace analysis of pyrene in water SERS/SERDS experiments were accomplished as a function of molecule concentration and spectral position of the SPR.

The best results with a limit of detection of 2 nM of pyrene were obtained with a nanoparticle ensemble with a SPR in the vicinity of the excitation wavelength of l = 488 nm. If the SPR frequency is slightly off-resonance the detection limit is significantly lower.

The results demonstrate that with optimized noble metal nanoparticle ensembles excited at their plasmon resonance combined SERS/SERDS measurements can be effectively performed for in situ trace analysis of pollutant chemicals in water.

8245-08, Session 3

Laser direct writing of micro graphene patterns

Y. Lu, J. B. Park, Y. Zhou, Univ. of Nebraska-Lincoln (United States)

Rapid single-step fabrication of graphene patterns was developed using laser-induced chemical vapor deposition (LCVD). A laser beam irradiates a thin nickel foil in an ethylene and hydrogen environment to induce a local temperature rise, thereby allowing the direct writing of graphene patterns in precisely controlled positions at room temperature. Line patterns can be achieved with a single scan without pre- or post-processes. The growth rate is several thousand times faster than that of general CVD methods. The LCVD growth process provides a route for the rapid fabrication of graphene patterns for various applications. Transparent interconnections using graphene patterns were formed using this approach. The number of graphene layers was tightly controlled by laser scan speed. Graphene patterns were fabricated at a high scan speed of up to 200 µm/s. The process time is about a million times faster than conventional CVD methods. The fabricated graphene patterns on nickel foils were directly transferred to desired positions on patterned electrodes. The position-controlled transfer with rapid single-step fabrication of graphene patterns provides an innovative pathway for graphene-based transparent interconnections.

8245-09, Session 3

In situ optical diagnostics of graphene synthesis

A. A. Puretzky, D. B. Geohegan, N. Thonnard, J. Readle, C. Rouleau, G. Eres, M. Regmi, G. Duscher, M. Yoon, Oak Ridge National Lab. (United States)

Pulsed gas delivery during chemical vapor deposition (CVD) and pulsed laser deposition (PLD) approaches are used to synthesize few layer graphene on thin metal films at high temperatures. Time-resolved, in situ Raman scattering, in situ time-resolved reflectivity, and real-time imaging of graphene growth through a microscope are employed to understand the nucleation and growth kinetics of graphene resulting from well-controlled, pulsed fluxes of acetylene on electron-beam evaporated Ni films by CVD. These techniques permit real-time diagnostics to monitor and control graphene nucleation and growth. Growth kinetics measured at different temperatures and peak fluxes reveal a variety of flux-dependent effects including incubation behavior at low fluxes and rapid, sub-second film growth at high fluxes. Under most conditions in this study, in situ Raman spectroscopy shows that the majority of graphene growth occurs at high temperature before cooldown. Alternatively, PLD of pure carbon in vacuum is used to provide discrete pulses of carbon atoms and molecules to heated Ni films in order to understand the threshold dose for graphene island nucleation and growth. We show that high quality single- and double-layer graphene can be grown by PLD in vacuum.

Research supported by the U.S. Department of Energy, Basic Energy Sciences, Materials Science and Engineering Division, and performed in part at the Center for Nanophase Materials Sciences, which is sponsored at Oak Ridge National Laboratory by the Office of Basic Energy Sciences, U.S. Department of Energy.

8245-10, Session 3

Laser direct growth of graphene on semiconductor substrate

D. Wei, X. Xu, Purdue Univ. (United States)

Graphene is often grown on metal films such as Cu or Ni in a CVD system. For device development, graphene grown on metal must be transferred to other substrates. In this work, we demonstrate successful growth of few-layer graphene on a silicon substrate. In our experiment, we employed local laser heating of either solid or gaseous carbon sources on a silicon substrate. The carbon absorbed into the molten silicon was then extracted from silicon during the cooling process. Raman spectroscopy showed continuous few-layer graphene. This study opens up new opportunities for the combination of graphene devices and the traditional semiconductor silicon technology.

8245-11, Session 3

Femtosecond laser assisted photobleaching of single-wall carbon nanotubes

S. Shoji, H. Kobayashi, T. C. Rodgers, Osaka Univ. (Japan); S. Kawata, Osaka Univ. (Japan) and RIKEN (Japan)

We present femtosecond laser induced photobleaching of individually isolated single-wall carbon nanotubes. Commercially available HiPco single-wall carbon nanotubes monodispersed in aqueous gel were exposed under tightly focused femtosecond laser light. We measured photoluminescence spectra of the single-wall carbon nanotubes before/after the laser irradiation. Typical laser intensity and irradiation time of the femtosecond laser were 100 mW/µm2 and 4 ms, respectively. Because of their unique excitonic band structures, we clearly observed a strong selectivity in the chirality and the orientation of carbon nanotubes depending on the wavelength and the polarization of femtosecond laser light. The carbon nanotubes we used contains 8 kinds of different chiralities with E22 energy band gaps resonant to the tuning range of the femtosecond laser from 700 nm to 900 nm. In the experiment, the chirality (10, 2) was dominantly bleached when the wavelength of the laser was tuned at 740 nm, whereas (11, 3) was bleached at 800 nm. We show the experimental comparison to the case of continuous wave laser irradiation in the chirality selectivity and the bleaching efficiency, suggesting a unique mechanism of femtosecond laser induced photobleaching.

8245-12, Session 3

Density and orientation control of carbon nanotube synthesis

Y. Cao, T. Hong, Y. Xu, Vanderbilt Univ. (United States)

Carbon nanotubes (CNTs) have shown great potential for next-generation electronics, due to their unique electrical, optical and mechanical properties. Many techniques have been developed to grow CNTs. Among them, the chemical vapor deposition (CVD) method has been widely used to synthesize various CNTs by controlling growth conditions and catalyst preparation. In this study, we have developed two strategies to produce CNTs from low-density surface growth to high-density forest growth on catalyst pads with the same preparation process. We have demonstrated that when methane is used as the main carbon feeding gas, the density of CNTs can be enhanced by increasing the pulse time of acetylene that is added at the beginning of the growth. Moreover, the density of grown CNTs can be decreased when the growth temperature is risen. In both strategies, CNTs have shown three typical growth forms: horizontal CNTs, CNT grasses, and CNT forests. By adjusting the carbon feeding gas ratio and the growth temperature, the combination of horizontal CNTs and CNT forests can be created. Furthermore, we have characterized as-grown CNTs through Raman spectroscopy. Our results have shown that the D peak rises with increasing C2H2 pulse time, which indicates that extra C2H2 can introduce amorphous carbon during the growth. We have also found that the D peak intensity is reduced when the growth temperature increases.

8245-13, Session 4

XPS study of InP/InGaAs/InGaAsP microstructure irradiated by KrF and ArF lasers in different environments

N. Liu, K. Moumanis, S. Blais, J. J. Dubowski, Univ. de Sherbrooke (Canada)

Laser-induced formation of chemically and structurally modified surface of III-V quantum semiconductors has been investigated as a method leading to selected area bandgap nanoengineering achieved through the quantum well intermixing (QWI) process. In this study, we have investigated the effect of irradiating InP/InGaAs/InGaAsP quantum well (QW) microstructures with KrF and ArF excimer lasers on the modification of surface properties of the cap InP material. Typically, the irradiation was carried out with pulse fluence not exceeding 150 mJ/cm2, i.e., below the threshold for ablation, and with up to 100 laser pulses. Samples irradiated in air, water and liquids comprising different elements have been analysed with an X-ray photoelectron spectroscopy (XPS) technique. A significant increase of In and InP oxides has been observed following the irradiation in an air environment, which confirms some of the results reported earlier. In contrast, the samples irradiated in deionized water show a negligible change in chemical composition. Rapid thermal annealing (700°C in forming gas of N2 : H2 = 9 : 1 for 2 minutes) of laser irradiated QW microstructures leads to bandgap shifting that depends on both the chemical composition and the presence of nanoscopic defects induced by the laser. These findings have provided important arguments for the construction of a physical model concerning laser-induced defects mediating atomic intermixing in III-V semiconductors.

8245-14, Session 4

Designed near fields for parallel surface nanostructures

F. Hubenthal, S. Maag, A. Jamali, B. Witzigmann, F. Träger, Univ. Kassel (Germany)

Generation of highly ordered nanostructures with dimensions well below the diffraction limit is a great challenge in nanotechnology. To achieve this goal, irradiation of triangular gold nanoparticles with single laser pulses has been successfully applied [1,2]. However, with single pulses, only certain nanostructure shapes can be generated. To achieve a higher variability, time delayed double pulses or shaped laser pulses can be applied, which allow a better spatial control of the local fields.

In this contribution, we present experiments, where triangular gold nanoparticles supported on fused silica were irradiated with fs-pulsed laser light with a central wavelength of 790 nm. After irradiation, nanostructures with dimensions well below the diffraction limit were created on the fused silica surface by ablation. The shape of the nanostructures is explained by 3D simulations of the energy density of the local fields, using a finite integration technique in time domain. In addition, first studies will be presented, in which two time-delayed pulses with different polarisation directions are applied. This strategy allows the generation of more complex predetermined nanostructures and to monitor the ablation process of the triangular nanoparticles by investigating the nanostructure evolution as a function of time delay between the pulses.

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8245-15, Session 4

Surface plasmon-assisted nanolithography with nanometric accuracy

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Surface plasmons (SP) become increasingly important for implementation of optical lithography with sub-wavelength resolution. Typically, optical field of propagating or localized SP modes formed on nanoscale metallic features is used for contact exposure of photosensitive medium. Resolution of SP lithography generally depends on the size of metallic features. Here we demonstrate SP nanolithography in a commercial photoresist which exploits SP modes localized in a few nanometer-wide gaps between larger gold nanoparticles.

To facilitate the collective SP modes, arrays consisting of nanogap gold nanoblock pairs (one block: 80 nm x 80 nm x 35 nm) were fabricated on glass substrates by electron-beam lithography and lift-off techniques. This substrate works as a photomask. To achieve exposure by near-field, 70 nm thick film of positive photoresist spin-coated on a glass substrate was brought into direct optical contact with the top surface of nanoblocks. Light source was a beam of a femtosecond laser (f=82 MHz). The beam was polarized linearly along the diagonal of the blocks.

Films of positive resist attached to nanoparticle arrays were exposed to the laser beam with gradually decreasing total exposure dose, and size and shape of resulting pits in the developed photoresist surface was observed. As the result of the exposure, a pattern of pits with period of 400 nm, replicating arrangement of nanoblock pairs can be seen after the development. While typical lateral size of pits is 30-40 nm, at some locations one can see features with lateral size of about 5 nm.

8245-15, Session 4

Dynamics of TiO2 nanoparticle formation and deposition for nanostructured thin films

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The dynamics of the nanoparticle-assisted pulsed laser deposition (NAPLD) process for the formation of high surface-area aligned nanostructured TiO2 films are studied by time-resolved, in situ diagnostics in different background gas pressure regimes. TiO2 is a workhorse wide-bandgap semiconductor for applications including photocatalytic water splitting and photoanodes for dye-sensitized solar cells. Laser vaporization and condensation in background gases offers opportunities for both doping, and deposition of high surface area nanoparticle films. Here we study the NAPLD process of high surface area, vertically aligned TiO2 nanoparticle films not only in the typically-employed high-pressure regime (several Torr), but concentrating upon background oxygen pressure conditions of 30-200 mTorr more typically employed for PLD of many oxide thin films. The surface areas and film morphologies have been found to vary considerably as a function of target-substrate distance and the background pressure. In situ ICCD imaging of laser-induced incandescence and Rayleigh scattering from nanoparticles, and laser-induced fluorescence from atoms and molecules, are compared with in situ particle sizing analysis with a differential mobility analyzer in order to define the timescales for nanoparticle formation and transport in both high and low pressure regimes, including the effects of thermophoresis. Ex situ scanning and transmission electron microscopy, x-ray scattering, and optical analysis of materials collected at various positions are used to correlate the film morphology with the in situ studies. The low pressure nanoparticle deposition process is found to include dynamic multipulse interactions between cooling plasma plumes and nanoparticles condensed on previous laser shots.

Research supported by the U.S. Department of Energy, Basic Energy Sciences, Materials Science and Engineering Division, and performed in part at the Center for Nanophase Materials Sciences, which is sponsored at Oak Ridge National Laboratory by the Office of Basic Energy Sciences, U.S. Department of Energy.

8245-16, Session 4

Laser ablation and nano-material fabrication in supercritical fluids

K. Saitow, Hiroshima Univ. (Japan)

We developed a novel method of fabricating nanomaterials by conducting pulsed laser ablation (PLA) in a high-pressure supercritical fluid. This method has three distinct properties: (i) The plasma density is locally enhanced, because the plasma generated near the target is spatially confined by the high-pressure fluid, e.g. 20 MPa; (ii) cooling rate for the thermal relaxation processes is controlled during the generation of nanoparticles, because thermal conductivity and heat capacity of a supercritical fluid have infinite values at the vapour-liquid critical point, and vary easily by changing the pressure; and (iii) a variable density is achieved, from gas-like to liquid-like, by changing the fluid pressure in the absence of a phase transition. Here we show the nanosecond PLA of two systems, both of which fabricate the photofunctional nanomaterials. That is, red, green, and blue (RGB) light-emitting silicon nanocrysltals were generated. Note that changing the fluid pressure during the PLA varies the luminescence colours and increases the luminescence intensity by a factor of 100. As for gold nanoparticle, the morphology is changed significantly by the fluid pressure during the PLA, i.e. gold nanonecklace, nanosphere of the diameter ranging from 30 to 800 nm, and medusa-type gold particle. In particular, the medusa-type gold nanoparticle is a significant SERS (Surface Enhanced Raman Scattering) active material. Namely, the SERS enhancement factor becomes 109, whose value enables us to measure a single molecules detection of Raman spectrum.

8245-17, Session 4

Template-assisted metal nanoneedle/nanoprotrusion array fabrication at a sub-diffraction-limited scale

Y. Tanaka, Keio Univ. (Japan) and Harvard Univ. (United States); J. D. B. Bradley, E. Mazur, Harvard Univ. (United States); M. Obara, Keio Univ. (Japan)

We present a template-assisted sub-diffraction-limited method for patterning nanoneedles and nanoprotrusions on a metal film.

In recent years, methods for downsizing and fabricating arrays of such nanostructures have been widely studied. The diameter of apex of the nanostructures has been reduced to sub-diffraction-limited size using a tightly focused femtosecond laser pulse. Nanoprotrusion arrays fabrication has been achieved over a large area via interference of femtosecond laser beams (but with $\geq$ 1 um in period).

In this paper, we demonstrate fabrication of nano-spaced and nano-sized nanoprotrusion arrays by exposing a gold-film-coated nanohole template to 800 nm femtosecond laser pulses. We obtained the diameter and periodicity at the sub-diffraction-limited scale. Our method is based on exploiting near-field optical effects to overcome the diffraction limit imposed by conventional far-field optics.

FDTD simulations reveal that the electric field intensity is selectively enhanced in the holes due to the excitation of surface plasmons. We successfully fabricated nanoneedles/nanoprotrusions with diameters of approximately 100 nm and periodicity of 460 nm over a large area by a single femtosecond laser pulse with a spot diameter of 0.55 mm. In the applied template, diffraction-limited laser spot diameter is 642 nm. We observed spherical particle ejection from the top of the nanoprotrusions upon increasing the laser fluence. The fabricated structures could be useful for smart applications such as field emission devices, nanosurgery and surface enhanced Raman scattering. Our proposed method also has a significant potential as a repeatable and cost-effective fabrication technology for plasmonic devices and metamaterials.

8245-16, Session 5

Exploring exciton-plasmon coupling in laser- and electron-beam fabricated nanostructures

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As optical and electro-optic devices push toward the subwavelength scale, there are increasing opportunities for lasers to play a role both in fabrication and exploitation of the unique properties of plasmonic devices. This paper describes studies of the spatial and temporal dependence of exciton-plasmon coupling in ZnO-plasmonic heterostructures designed to allow continuous tuning from the weak- to the strong-coupling regime. We have developed a novel heterostructure that makes it possible to study coupling of the ZnO band-edge exciton and localized surface plasmons (LSPs) and propagating surface-plasmon polaritons (SPPs), over a continuous range from the weak- to the strong-coupling regimes. In weakly coupled systems, Purcell enhancement dominates the optical response; in strong-coupling systems, more interesting effects - such as Fano resonances and electromagnetically induced transparency - are observed. The heterostructures comprise a ZnO film or quantum well, a MgO or zinc-magnesium-oxide spacer layer of variable thickness, and a plasmonic element that could range from a rough metallic film to a lithographically fabricated array of metallic nanoparticles of gold, silver or aluminum. In these nanostructured model systems, it is possible both to study and to exploit the properties of exciton-plasmon coupling mechanisms that link the fundamental one-particle excitation in insulators to the many-particle excitation of metals in plasmonic structures. Using these heterostructures and photoluminescence (PL) and ultrafast pump-probe spectroscopy, we have also been able unambiguously to identify a Zni impurity transition previously conjectured theoretically, a state that shows up at the interface of the ZnO and the MgO spacer layer only after an appropriate annealing regime.

8245-18, Session 5

Characterization of silicon fibrous nanoparticles aggregate structure synthesized using femtosecond laser pulses

S. Manickam, Amrita Univ. (India); K. Venkatakrishnan, T. Bo, Ryerson Univ. (Canada)

Irradiation of silicon samples with femtosecond laser pulses at megahertz pulse repetition rate under ambient condition lead to the generation weblike fibrous nanostructure. Transmission Electron microscopy (TEM) analysis revealed that the fibrous nanostructure is formed due to aggregation of nanoparticles of size varying between 2 to 40 nm. Microraman analysis confirms that the nanoparticles in the aggregate structure were amorphous in nature. Further X-ray photoelectron spectroscopy (XPS) analysis reveals chemical composition of the nanostructure. The nanoparticles aggregate formation is explained by nucleation and condensation of vapour in the plasma plume generated during the irradiation process. This study provides evidence that femtosecond laser irradiation can be an ambient condition physical method for silicon fibrous nanoparticles aggregate structures generation.

8245-19, Session 5

Plasmonic control of far-field interference for regular ripple formation on various material substrates irradiated by femtosecond laser

G. Obara, N. Maeda, T. Miyanishi, M. Terakawa, M. Obara, Keio Univ. (Japan)

We present regular periodic ripple formation on various substrates by controlling coherent surface plasmon polaritons far-field excited by a femtosecond laser. Ripples are so-called LIPSS (Laser Induced Periodic Surface Structure). The LIPSS formed based on this mechanism with successive laser pulse irradiation has a period of eight hundred nanometers with 800 nm femtosecond laser. However, the shapes of the fabricated ripples were not regular but wavy ripples due to the randomness of surface roughness.

In this paper, we propose a new fabrication method of REGULAR ripples and dot. We deposit a gold linear nano-ridge on various substrates such as Si, Au, ZnO, SiO2, in advance. We irradiate the femtosecond laser to induce a 1D regular COHERENT (not spontaneous) surface plasmon far-field from the gold nano-ridge. The interference of the coherent plasmon far-field and the incident wave makes an accurate interference pattern on the substrate. This patters act as an INITIAL template for the accurate ripple formation. We calculated electromagnetic field distribution on the substrate surface when irradiated with 800 nm laser. Due to the simulation result, linear surface plasmon is generated on the several substrates and the optical field distribution is observed parallel to the linear gold nano-ridge. Using arbitrary 2D plasmonic templates, desired 2D dots are able to be fabricated. We will also demonstrate a new technology to fabricate 1D and 2D ripples on the substrates by femtosecond laser. This work is supported by a Grant-In-Aid for Scientific Research B (23360161) from the MEXT Japan.

8245-20, Session 5

Influence of the growing parameters on the size distribution of PbTe nanoparticles produced by laser ablation under inert gas atmosphere

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We report the fabrication of PbTe quantum dots grown under inert gas (Ar and He) atmosphere by pulsed laser deposition using the second harmonic of a Q-Switched Quantel Nd:YAG laser. For characterization, samples were prepared onto a 40Å carbon film deposited on a copper grid. The influence of background pressure, and number of laser pulses on the size distribution of the PbTe nanoparticles was investigated by transmission electron microscopy using a 200 kV TECNAI G2 F20 electron microscope with 0.27 nm point resolution. The size distribution was obtained by manually outlining the particles from several dozens of low- and high-resolution TEM images. Once digitized and saved in a proper format, the image was processed using the J-image software. Characterizations reveal an increase of the nanoparticle size both with the amount of material deposited (number of laser pulses) and the background pressure. Furthermore, measurements reveal a narrower nanoparticle size distribution by increasing the number of laser pulses or by decreasing the background pressure. HRTEM studies of the influence of different ambient gases on the structural properties of the PbTe nanoparticles are being conducted.

8245-21, Poster Session

Femtosecond ablation of aluminum for synthesis of nanoparticles and nanostructures and their optical characterization

G. K. Podagatlapalli, H. Syed, S. P. Tewari, S. Venugopal Rao, Univ. of Hyderabad (India)

Femtosecond laser ablation of bulk Aluminum substrate immersed in a liquid medium is an efficient way to generate nanoparticles since the conventional ablation has a disadvantage of producing oxidized nanoparticles due to the surrounding air medium.[1-4] Owing to the short pulse duration the generated nanoparticles will not be affected by the unwanted interaction with laser pulse and does not allow the metal substrate to expand because the heat transfer time between the fast electrons and lattice ions is of the order of picoseconds. The recoil pressure exerted by the evaporated liquid surrounds the laser pulse causes the formation of different gratings on the substrate. We performed the ablation (with ~40 fs pulses at 800 nm)of bulk Al substrate in purified water and liquids without the oxygen presence (eg. CCl_4, $CHCl_3$). SEM analysis of the solvents after ablation confirmed the presence of nanoparticles whereas the surface examination revealed the presence of nanostructures. Nonlinear optical studies of the nanoparticles were performed using 2 ps pulses at 800 nm. The formation of nanostructures was studied as a function of polarization, surrounding medium and input energy.

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8245-22, Poster Session

Direct observation of surface plasmon far field for regular surface ripple formation by femtosecond laser irradiation of silicon wafer

N. Maeda, G. Obara, T. Miyanishi, Keio Univ. (Japan); N. N. Nedyalkov, Institute of Electronics (Bulgaria); M. Obara, Keio Univ. (Japan)

We present the direct observation of the surface plasmon far field for the regular surface ripple formation by femtosecond laser. In the experiments, gold spheres with 200 nm diameter were spin coated on a silicon wafer. The silicon wafer was irradiated normally with 20 successive pulses of 400 nm femtosecond laser at a low laser fluence of 80 mJ/cm^2. The SEM image of the silicon surface after the laser irradiation shows the surface ripple pattern.

We simulate the electric field intensity distribution using a 3D FDTD method. The incident laser irradiates uniformly the 8 μm x 8 μm area. The simulated result well corresponds to the experimental result. The result shows that both scattered far field and the incident wave are interfered to make interference ripples.

The electric field intensity interference pattern with an arbitrary artificial scattering structure is also simulated. An L-shaped gold plasmonic structure is deposited on the silicon, and then it is illuminated with a circularly polarized femtosecond laser. The results of the intensity distribution are achieved. Two-dimensional intensity periodic dot arrays are observed.

In summary, we have directly observed the interference pattern between surface plasmon and incident laser where the plasmonic wave source of the gold nano-sphere is placed on the Si wafer. The precise ripples can be used for such applications as structural color, SERS template, nanotribology, cell culture substrate, efficient solar cell with surface nanostructures, etc. This work is supported by a Grant-In-Aid for Scientific Research B (23360161) from the MEXT Japan.

8245-23, Poster Session

Influence of ZnO buffer layer on ZnO nanowire growth by nanoparticle-assisted pulsed laser deposition

D. Nakamura, K. Okazaki, I. A. Palani, K. Kubo, K. Tsuta, M. Higashihata, T. Okada, Kyushu Univ. (Japan)

ZnO nanowires have been attracting increasing interest due to their unique electronic and optoelectronic properties. For the practical optoelectronic applications based on the ZnO nanowires, one of the important issues is control the growth direction, shape, density and position, etc. We have been succeeded in growing vertically well-aligned ZnO nanowires with low density by introduction of a ZnO buffer layer. The density of the nanowires grown on the buffer layer corresponds to the thickness of the buffer layer. In this presentation, effects of the buffer layer on the ZnO nanowire growth by nanoparticle-assisted pulsed laser deposition will be discussed.

8245-24, Poster Session

Femtosecond laser doped and nanostructured TiO_2 for photocatalysis

K. C. Phillips, E. C. Landis, C. M. Friend, E. Mazur, Harvard Univ. (United States)

We present a novel method for femtosecond laser doping of titanium dioxide (TiO_2) for above bandgap absorptance by irradiating titanium metal in the presence of oxygen and dopants. With a bandgap of 3.2 eV for the anatase crystalline phase, TiO_2 most strongly absorbs in the UV range ($\lambda < 387$ nm). However, doping with metals and nitrogen has been shown to create intermediate states in the bandgap. Using femtosecond laser doping techniques on titanium in a gaseous environment, we produce laser-induced periodic surface structures. Altering the gas composition and pressure does not change the surface morphology, but it does impact the chemical composition of the surface. We present compositional data from x-ray photoelectron and Raman spectroscopy and structural data from scanning electron microscopy. Our research presents an innovative approach using laser scanning techniques to alter the structure of TiO_2 and generate a new material for visible-light photocatalysis that has the potential for watersplitting.

8245-25, Poster Session

Novel beam splitter for high-order harmonics with WO3/TiO2 bilayer grown on c-plane sapphire substrate by sequential surface chemical reactions

Y. Sanjo, M. Murata, H. Kumagai, Osaka City Univ. (Japan); Y. Nabekawa, K. Midorikawa, RIKEN (Japan); M. Chigane, Osaka Municipal Technical Research Institute (Japan)

High-intensity high-order harmonics have been investigated intensively in recent years. In the development of a beam line for the high-intensity high-order harmonics, however, utilizing a conventional beam splitter (BS) (Si or SiC) that absorbs the fundamental waves has caused serious problems such as its thermal distortion. To solve these problems, we proposed and investigated a novel BS with transparent materials that transmitted the fundamental waves and then reflected the high-order harmonics. In BS for the high-order harmonics, reflection of the fundamental waves should be minimized by entering the p-polarized fundamental waves at the Brewster's angle, which could improve the separation between the fundamental waves and the high-order harmonics at the same Brewster's angle.

We have already investigated and fabricated WO3/TiO2 bilayers on c-plane sapphire substrates by controlled growth with sequential surface chemical reactions (SSCR) using sequentially fast pressurized pulses of the vapor sources. Our previous experimental results revealed that WO3 (221) and rutile TiO2 (200) thin films could be grown epitaxially on c-plane sapphire substrates by SSCRs. Then, in this study, we proposed a WO3/TiO2 bilayer grown on c-plane sapphire substrates, which could be utilized as a BS for the high-order harmonics. Reflectance characteristics were also investigated at the same Brewster's angle using monochromatized synchrotron radiation (SR) located at Ultraviolet Synchrotron Radiation Facility (UVSOR), Institute for Molecular Science, Okazaki, Japan.

Conference 8246: Free-Space Laser Communication Technologies XXIV

Tuesday-Thursday 24-26 January 2012

Part of Proceedings of SPIE Vol. 8246 Free-Space Laser Communication Technologies XXIV

8246-01, Session 1

Underwater blue-green laser communications in support of undersea dominance

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Considerable progress has been made in underwater optical communications, particularly Submarine Laser Communications (SLC). As Network-Centric operations expand, however, the Navy needs to be a fully integrated part of the Joint Force and communications must be improved to ensure Undersea Dominance.

The three fundamental communication technologies of RF, acoustics and optics all play a role in enabling the "networking" of underwater terminals. Legacy systems fall far short in meeting the requirements, either due to physics, the lack of stealth, insufficient bandwidth and/or the ability to be jammed or otherwise denied. Blue-Green Laser Communications (BGLC), however, is the most promising technology known today that can truly "connect" the undersea environment. Most importantly, only BGLC can provide high bandwidth communications that can operate through the air-water interface.

For most undersea nodes, real-world engineering limitations such as size, weight and prime power availability dominate design considerations. Based upon the physical characteristics and the performance of evolving blue-green laser comm terminals, relevant CONOPS will be developed that significantly benefit operational utility. If the network also includes above-water platforms (e.g., UAV's), the same "engineering limitations" for the above-water BGLC terminals are just as important.

Blue-Green Laser Communications is the "game-changer" in Undersea Dominance, connecting the Undersea Network. The overall objective of this paper is to address both the scope of performance that is possible (e.g., data rate and range), as well as address relevant engineering considerations (e.g., size, weight, and power).

8246-02, Session 1

Satellite-based quantum communications

R. J. Hughes, J. E. Nordholt, Los Alamos National Lab. (United States)

Satellite-based quantum communications

8246-03, Session 1

Achievable capacity using photon-counting array-based receivers with on-off-keyed and frequency-shift-keyed modulation formats

B. S. Robinson, D. M. Boroson, MIT Lincoln Lab. (United States)

We discuss the use of photon-counting array receivers for communications links employing on-off-keyed and frequency-shift-keyed modulation formats. The effects of detector non-idealities, such as reset time, timing resolution, and dark count rates, on achievable receiver performance are presented.

8246-04, Session 1

On approaching the ultimate limits of communication using a photon-counting detector

B. I. Erkmen, B. E. Moision, K. M. Birnbaum, S. J. Dolinar, Jr., Jet Propulsion Lab. (United States)

Because photons are fundamentally quantum mechanical, the ultimate limit of reliable communication using photons is determined by the Holevo capacity. Although coherent states are known to achieve this capacity with an optimal measurement, the form of this measurement is not yet known, and it is not equivalent to any standard measurements (e.g., photon-counting, homodyne, heterodyne). Furthermore, practical receiver architectures for coherent-state encoding that have the potential to improve upon the state-of-the art (i.e., coherent-state pulse-position modulation plus photon-counting) have high implementation complexity. This motivates the investigation of the ultimate limits achievable with a photon-counting receiver, coupled with novel quantum-state alphabets and signaling architectures that are tailored to this measurement. In this paper we consider two photon-counting communication architectures that approach the Holevo capacity of a pure-loss optical communication channel in the near-field limit (where the power coupling loss due to diffraction is small for at least one spatial mode) and in the photon-starved limit (where the mean photon number is less than unity). Our first architecture uses a single-photon number-state source and an ideal photon-counting photodetector. This architecture is sensitive to losses in the propagation path, and therefore it approaches the Holevo capacity only in the near field. The second architecture is a coherent-state transmitter that relies on feedback from the receiver to control the transmitted energy. This architecture can be interpreted as mimicking the photodetection statistics of a single-photon number state at the receiver, which is near-optimal when the mean photon number is much less than unity.

8246-05, Session 2

Low-frequency vibration isolation system for deep space optical communications payload

G. G. Ortiz, V. Sannibale, Jet Propulsion Lab. (United States)

A sub-hertz vibration isolation system for light (< 30 kg) deep space payloads has been demonstrated using extremely low stiffness mechanical oscillators as the only mechanical connection between the isolated payload and the supporting control mechanism and electronics. The integrated system has been measured and yielded 6-DOF isolation with resonance frequencies below 300 milli-Hertz and a very broad isolation frequency range.

8246-06, Session 2

Current development status of small optical transponder (SOTA) for satellite-ground laser communications

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Current development status of Small Optical TrAnsponder (SOTA) for satellite-ground laser communications

8246-07, Session 2

Directly-modulated, high-power semiconductor lasers

G. M. Smith, E. K. Duerr, A. M. Siegel, J. P. Donnelly, L. J. Missaggia, M. K. Connors, P. I. Hopman, A. K. Stimac, D. C. Mathewson, G. W. Turner, P. W. Juodawlkis, MIT Lincoln Lab. (United States)

Transmitters for free-space laser communication systems are typically the largest power consuming element of the system. We have developed a directly-modulated high-power fiber-coupled laser transmitter for free-space laser communication systems that has a high electrical-to-optical efficiency of 15% and fully contained in a common 14-pin butterfly package. The key to the high efficiency is the hybrid integration of the drive electronics inside the laser package, thereby significantly reducing the parasitic inductance of the packaging. The driver circuit consists of large charge-storage capacitors and 32 parallel CMOS-FET line drivers on two bare silicon die that are mounted directly adjacent to the laser chip. This driver is able to achieve an electrical efficiency of over 70% with a laser current slew rate of greater than 1 A/nsec. The laser transmitter operates at a peak optical power from the fiber of 2 W with a rise time of just a few nsec and pulse width of 25 nsec at 2.5 MHz. The laser is fiber Bragg grating (FBG) stabilized to produce a narrow-wavelength transmitter at 1060 nm that is very stable with temperature. The single-mode fiber coupling on the transmitter makes it very convenient to route the output and provide a diffraction-limited beam for long-distance transmission. Both a commercial laser chip and an internally developed large-mode Slab Coupled Optical Waveguide Laser (SCOWL) have been used as sources in the transmitter and performance of both will be compared. Very good reliability of the transmitter is predicted from accelerated aging studies.

8246-08, Session 3

Limits on achievable dimensional and photon efficiencies with intensity modulation and photon-counting due to non-ideal photon-counter behavior

B. E. Moision, Jet Propulsion Lab. (United States)

Consider the problem of designing an optical terminal to receive a free-space intensity-modulated signal received in background. Suppose we’ve chosen an aperture diameter and the focal plane is populated with an array of photon-counting photo detectors. The photo-detectors have a dead time (a period after the production of a photo-electron during which they cannot produce another photo-electron), and a dark rate proportional to their active area. We examine how the dark rate, blocking, and detection efficiency limit the achievable dimensional and photon efficiencies. We answer these questions on in the context of selecting an optimal focal length for the system.

What determines an optimum F-number? Here we optimize with respect to the capacity, or achievable data rate, and, in so doing, assume other subsystems, such as spatial tracking, have performance invariant to F. This assumption will allow us to focus on trade offs with respect to system capacity.

What, then, determines the maximum capacity? Suppose we are in the diffraction limited regime, where the signal intensity is an Airy pattern. Here a smaller F produces a smaller spot, with a higher signal intensity in focal plane. This leads to larger losses due to blocking, but, since a smaller integrated area is required, a smaller dark noise contribution. In the limit of no blocking the performance improves with decreasing F as one filters out dark noise. Conversely, in the limit of no dark noise, the performance improves with increasing F, as the signal and background noise become more diffuse, and blocking losses become negligible. In the general case there is an optimum focal length. In this paper we illustrate a method to select an optimum focal length with respect to the data rate for diffraction limited and atmospheric channels. We apply these results to several candidate photo-detectors, illustrating the sensitivity to the focal length, and the impact on achievable dimensional and photon efficiencies, for several sample free-space channels.

8246-09, Session 3

Development and evaluation of a digital signal processing for single polarization QPSK modulation format

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Single Polarization high-speed optical transmission is important for bidirectional free-space optical communication system in order to have enough isolation up-link and down-link because signal discrimination is possible by using orthogonal polarization states. Recent advance in digital coherent technology employing multi-level QPSK format is enabling such high-speed transmission with high receiver sensitivity. Polarization re-combining using polarization diversity receiver is widely used to overcome polarization aligning between signal and local, because the signal polarization state in the fiber in the receiver easily change by system vibration or shocks. However, in order to implement the re-combining function in digital signal processing, appropriate algorithm is required for realizing the system stability, especially avoiding the instability due to singularity condition at 45-degree-azimuth elliptic polarization. In this paper, we demonstrate a new algorithm implementation for single polarization receiver with maximal ratio-combining technique. By adding split-ratio dependent phase correction coefficient, system showed stable re-combining against all input polarization states by simulation. We also developed a stable real time digital signal processing system to receive single polarization QPSK signal at 50Gb/s, including our newly proposed MRC implementation.

8246-10, Session 3

Design of encoders and decoders for code/pulse-position-swapping (C/CPPS) based on sonar codes

A. J. Mendez, Mendez R&D Associates (United States)

The time slots of M-ary pulse-position-modulation (PPM) can be mapped to or replaced by M optical CDMA codes. This is variously known as Code/Pulse-Position-Swapping (C/PPS) or Code-Shift-Keying (CSK). Among the novel features that result from this concept are that it: (1) retains the intensity-modulation/direct-detection (IM/DD) and multiple-bits-per-symbol features of PPM; (2) supports multiple access communications like CDMA; (3) supports granular communications (concurrent multi-line rate communications) and bandwidth-on-demand where various users are dynamically assigned different numbers of codes (time slot or M equivalents); (4) supports tailoring quality of service (QoS); (5) applies to fiber or free-space communications; (6) can translate the received symbol (code) to its corresponding bit sequence without use of a look-up-table (LUT)) by using direct translating receivers; (7) can have a receiver based on planar lightwave circuits (PLCs) with integral erbium doped waveguide amplifiers (EDWAs) to reduce the effects of insertion losses; (8) has an common electronic bandwidth for all data rate and network configurations; (9) [in principle] can quickly reconfigure the network (reassign codes); and (10) can reconfigure the codes in hardware. In this paper we describe the design of the encoders and decoders and network architecture where the C/PPS network is based on fast frequency hopping (FFH) sonar codes. A specific example of 4x4 FFH codes is used in the discussion.

8246-11, Session 4

Overview and status of the Lunar Laser Communications Demonstration

D. M. Boroson, B. S. Robinson, D. A. Burianek, D. V. Murphy, MIT Lincoln Lab. (United States)

NASA's ongoing program, the Lunar Laser Communication Demonstration, is nearing its final phases. This first demonstration of high-rate laser communications between an Earth terminal and a terminal in Lunar orbit is slated to occur in the summer of 2013. We will give an overview of the planned demonstration, plus show photographs and measurements of the two terminals, both nearing completion.

8246-12, Session 4

Laser communication terminals for the European data relay system

R. Lange, F. F. Heine, M. Gregory, H. Kaempfner, Tesat-Spacecom GmbH & Co. KG (Germany); M. Lutzer, R. Meyer, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany)

Laser Communication Terminals will be operational for EDRS, the European Data Relay System. Future earth observation satellites call for high data rate GEO relay links to make their data immediately available to the user. GEO relay links - communication links from the earth observation satellite flying on a low earth orbit (LEO) to a geostationary (GEO) relay satellite transmitting the data to the ground - provide increased duration of communication. While RF communication limits the GEO relay's data rate to roughly 1 Gbps laser communication will extend its capacity into the 10 Gbps range.

Today, coherent (homodyne BPSK) laser communication links with data rates of 5.625 Gbps are operational for three years for campaigns with scientific objectives and for technology demonstrating purposes. The results achieved in LEO-LEO, LEO-to ground and ground-to-LEO links also verify the performance of LEO-to-GEO links and GEO-to-ground links. Laser communication terminals will be delivered for accommodation on Alphabus, EDRS-A and C, European GEO satellites and on Sentinel 1 and 2, European LEO satellites.

8246-13, Session 4

Free-space quantum cryptography over 144 km towards space applications

R. Ursin, Univ. Wien (Austria)

In a modern information based society secure communication is of utmost importance. An overnight breakthrough in mathematics or computer science could make electronic money transfer instantaneously worthless. The security of classical cryptography relies on the computational difficulty of certain mathematical functions, and can neither provide any indication of eavesdropping nor guarantee security. Quantum cryptography provides both as it is based on theoretical and experimental proven laws of nature. The use of satellites will enable us to perform quantum communication on a global scale. Currently, with present fiber and detector technology terrestrial quantum communication is limited to within some 100 of kilometers. Space-based QKD is expected to be of high technological impact in the future. In various feasibility studies and experimental tests over a 144km terrestrial free-space channel for adopting the concepts of fundamental quantum physics and quantum communications to a space infrastructure it was found, that based on present-day technologies, successful demonstration of quantum communication protocols in space. Here we present the basic principles of quantum key distribution (QKD) and its current state-of-the-art protocols implementations and resent results from ESA funded studies in this field.

8246-14, Session 4

10 Gb/s lasercom transceiver for LEO spacecraft

J. M. Kovalik, H. Hemmati, A. Biswas, Jet Propulsion Lab. (United States)

Will describe the development and testing of a 10 Gb/s lasercom terminal for use with on LEO spacecraft.

8246-15, Session 4

40-Gbit/s optical free space transmission experiment using QPSK modulation format

Y. Hashimoto, NEC Corp. (Japan)

Advantages of optical links like small, lightweight and power efficient terminals are practical for high data rate services of disaster preparedness and environmental research. This paper summarizes the experimental results of optical digital coherent transmission which has been carried out for 40 Gbit/s optical free space transmission experiment using single-polarization QPSK modulation format. Optical digital coherent detection is more attractive attention for free-space optical communication as its high sensitivity and tolerance of transmission on impairments without optical phase locked loop circuit. We integrated 50 Gbit/s SP-QPSK transmitter and offline-receiver with the optical antenna system. SP-QPSK optical modulation signal with a line rate of 50 Gbit/s including 20% FEC overhead was generated at 1565 nm, using commercially available tunable laser diode and I-Q modulator and was transmitted from optical antenna. The received optical signal, which was coupled into an optical fiber in receiving optical antenna, was amplified cascade by EDFAs consisting of a low noise pre-EDFA and an optical level controlled EDFA, and detected by an optical frontend module of coherent polarization diversity. By using Maximal ratio combining algorisms and carrier phase estimation algorisms at the offline-receiver, the detected diversity signal was combining and estimated QPSK signal. By trial experiment of free space transmission, we succeded 4-meter indoor free space transmission having same performance as that with fiber connection. The optical received power was -42 dBm at bit error rate of 10-3. While for outdoor 50-meter transmission, we confirmed the received bit error rate larger than FEC limit. This result shows that the optical free space link is feasible of 40 km free space propagation distance (altitude: 10,000 m, elevation angle; 15 degree).

8246-17, Session 4

Long range beam propagation for quantum communications

I. Capraro, Adaptica S.r.l. (Italy); A. Tomaello, A. Dall'Arche, F. Gerlin, G. Vallone, P. Villoresi, Univ. degli Studi di Padova (Italy)

The study of the free-space propagation of photons is necessary for any future application of quantum communication aiming to connect two remote locations. The problem related to the freespace propagation is represented by the athmospherical turbulence, that acts as a temporal and spatial variation of the air refraction index. A turbulent channel acts as a possible decoherence on the qubit and an increment of the losses on the transmitted photons due to beam-wandering of the beam-centroid or scintillation. The understanding of the propagation effects induced by turbulence at the receiver as well as the temporal statistics of the incoming photons is crucial to assess the quality of the communication and eventually the feasibility of the link.

In this work we study the propagation of a coherent laser beam over 20 Km (between two different localities of Italian Alps) and over 144 Km (between Tenerife and La Palma Islands of the Canary archipelagos). By attenuating the beam we also studied the propagation at the single photon level. We investigated the statistic of arrival of the incoming photons and the scintillation of the beam.

Our study aims to point out the optimal confguration for the optical setup for the long range quantum communications, as well as to measure the modifcations of the photon statistics due to turbulence effects.

8246-18, Session 5

All-semiconductor-based narrow linewidth high-power laser system for laser communication applications in space at 1060 nm

S. Spiessberger, Ferdinand-Braun-Institut (Germany); M. Schiemangk, Humboldt-Univ. zu Berlin (Germany); A. Sahm, F. Bugge, J. Fricke, H. Wenzel, A. Wicht, G. Erbert, G. Tränkle, Ferdinand-Braun-Institut (Germany)

Narrow linewidth high-power laser sources emitting at a wavelength of 1064 nm are in particular interesting as replacements for optically pumped solid state lasers that are already used in coherent optical communication systems. Semiconductor lasers combine high efficiency, robustness, small size, high modulation bandwidths, and can provide narrow linewidth emission. These features make semiconductor lasers particularly interesting for high performance spacecom systems, specifically for future deep space science missions that require large data transfer rates at long communication distances.

Recently [1] we presented a micro-integrated master oscillator power amplifier (MOPA) system with a footprint of 10x50 mm2, an optical output power of 1 W, an intrinsic linewidth (excluding technical noise) of 3.6 kHz, and a FWHM linewidth of 100 kHz. Furthermore, the laser source can be tuned continuously over 450 GHz.

In this paper we present results of environmental tests, that have been carried out to prove the suitability of this technology for applications in space. Results of lifetime tests, vibrational tests, and thermal cycling tests will be presented. Furthermore, we introduce a concept that provides about 2 nm of fast tuneability of the oscillator wavelength without any crosstalk to the amplifier. This is realized by placing on-chip heater sections close to the Bragg grating of the distributed Bragg reflector master oscillator.

Furthermore, the laser concept presented here can be transferred to other wavelengths.

8246-19, Session 5

-1.5 micron MOPA deep space downlink transmitter

D. L. Sipes, Jr., J. Tafoya, Optical Engines, Inc. (United States)

1.5um transmitter technology is attractive for deep space downlinks due to the availability of well established components such as sources, isolators and Er gain fiber. The 1 kW peak power and 10W average power requirements for MOPA systems require the use of cladding pumped LMA type gain fiber with multiple stages to create a 30-40dB total gain system. We report on a 3-stage MOPA with a single mode first stage, a single mode cladding pumped second stage and a cladding pumped LMA third stage. The development of such a 1.5 um MOPA system will be presented with results on efficiency, and power handling capability. Trade offs between 1480 nm and 1532 nm pumping will also be presented.

8246-20, Session 5

Short-wavelength (1010-1030-nm) Yb-fiber-MOPA based multi-aperture high-power uplink laser beacons for space communication

D. Engin, F. Kimpel, S. Gupta, Fibertek, Inc. (United States)

Laser beacons with scalable powers are needed for ground to LEO, lunar, interplanetary and deep-space optical communication uplinks. These serve as absolute reference for precise pointing/tracking of spacecraft during the downlink laser communication. High-reliability silicon avalanche photo-detectors (Si-APD) are used on the spacecraft to detect the uplink beacon. For improved SNR in pointing/tracking, and reduced uplink laser power requirement, it is desirable to operate at shorter wavelengths near 1000nm, where near-IR Si-APDs have improved (>3X) spectral responsivity. Instead of a single transmit aperture, use of multi-aperture laser beacon with 4 to 8 beams is also needed, to alleviate the scintillation and improve fade characteristics due to the atmospheric turbulence. An Yb fiber-amplifier based source is naturally amenable to a multi-aperture configuration, and the broad gain spectrum (1000-1100nm) allows operation at shorter wavelengths favored by the Si-APD detector.

We demonstrate a power scalable Yb-fiber-MOPA (master-oscillator-power-amplifier), optimized for efficient operation at shorter wavelength of 1010-1030nm. The fiber-MOPA is fully controlled by state-of-the-art high-speed FPGA, for programmable M-ary pulse-position-modulated (PPM) format pulse train. We previously reported Yb-fiber-MOPA at 1064nm with programmable 16-ary PPM format, where up to 12kW peak-power was obtained (600W average power). Using large core-to-clad ratio fibers to overcome re-absorption loss in a clad-pumped stage, and managing the amplified spontaneous emission (ASE) in a multi-stage Yb-fiber-MOPA, we optimize and demonstrate scalable Yb-fiber-MOPA operation down to 1010nm wavelength. At 1024nm, 250W cw operation with ~75% optical efficiency is achieved. Fiber-MOPA shows OSNR>30dB, 50GHz linewidth and diffraction-limited mode quality. Results on binary to 16-ary PPM format operation, as well as FPGA-based algorithms for controlling the pattern-dependent pulse dynamics will be demonstrated. In addition, we also illustrate the size, weight, power (SWaP) such a multi-aperture laser beacon system.

8246-21, Session 5

Preliminary results of space grade laser transmitters for optical communications

M. W. Wright, Jet Propulsion Lab. (United States)

JPL has developed in partnership with industry, pulsed fiber based laser transmitters suitable for optical communications in both near Earth and deep space scenarios. Interplanetary ranges require systems that support high peak powers at moderate data rates while LEO demonstrations require systems that match terrestrial performance but with more stringent environmental requirements. As a precursor to a full space qualification process, commercial components were integrated into a 1550 nm PM fiber based MOPA laser transmitter designed to support pulse position modulation and operation in the vacuum environment. This optically pre-amplified seed laser generated sub-ns pulses at up to 100 MHz with high extinction ratio over variable duty cycle. A second system was developed to support a near Earth optical communications demonstration but for operation in a sealed enclosure at atmospheric pressure. The system was capable of 2.5 W average output power at 1550 nm at up to near Gbps data rates and met stringent vibration requirements. Test results in both ambient and under vacuum conditions will be reported for these space grade laser transmitters including preliminary life-tests.

8246-22, Session 5

Design of a 40 Watt 1.5 micron uplink transmitter for Lunar Laser Communications

D. O. Caplan, J. J. Carney, MIT Lincoln Lab. (United States); R. E. Lafon, W. M. Keck Observatory (United States); M. L. Stevens, MIT Lincoln Lab. (United States)

We describe the design of a ground-based high-power 1.5 micron uplink transmitter for NASA's Lunar Laser Communication Demonstration (LLCD) program. The 40W transmitter is implemented using a four-channel spatial-diversity design that reduces far-field fading due to near-field atmospheric turbulence and facilitates high-power signal generation through the spatial combining of four commercially-available 10W EDFAs.

Each 10W channel is implemented in a master oscillator power amplifier configuration that generates 4-ary pulse-position modulation (4-PPM) signal waveforms at a 311 MHz slot rate with 16:1 and 32:1 variable duty cycle waveforms to support 38.9 Mbit/s and 19.4 Mbit/s channel rates, respectively. In addition to communication waveforms at 1558nm, each channel also contains a 1 kHz modulated beacon wavelength at 1568nm used for spatial acquisition at the receiver. The power ratio between the communication and beacon signals is adjustable so that power can be delivered to the beacon during acquisition and subsequently redirected to support communications.

Each transmit channel uses a slightly offset communication wavelength with a spacing chosen to minimize the bandwidth of a single narrow-band optical filter in the preamplified LLCD receiver with negligible degradation of communication performance due to inter-channel coherent interference. High-peak-power four-wave mixing (FWM) and self phase modulation (SPM) nonlinear effects, which arise from the 320 W (peak) communication signal power propagating through > 8 m output fiber prior to the telescopes, are mitigated by using polarization splitting via 45-degree coupling into polarization-maintaining output fiber. Details on the transmitter design, implementation, and performance are discussed.

8246-23, Session 6

Anisoplanatism over horizontal paths: comparison of theoretical and experimental results

J. P. Bos, A. V. Sergeyev, M. C. Roggemann, Michigan Technological Univ. (United States)

The isoplanatic angle, in regard to adaptive optics (AO) systems, can be defined as the angular separation between a beacon and an imaging target where the phase perturbations introduced by atmospheric turbulence are no longer sufficiently similar. The correlation between the point spread functions (PSF) measured at different observation angles is one metric used to evaluate anisoplanatic effects in AO applications. However, the horizontal imaging paths found in surveillance and Laser Communication System (LCS) applications differ considerably from the astronomical case. Specifically, the limited aperture size, and distribution of turbulence along the imaging path leads to a increased correlation between PSFs at angles much larger than the predicted isoplanatic angle.

To explore anisoplanatism over horizontal paths a LCS experiment was developed. The experiment operated in real-world conditions over a 3.2km path, partly over water. The transmitter side of the LCS was equipped with a laser and a bank of 14 LEDs mounted in-line, horizontally. The receiver side consisted of two channels, one for WFS and another for PSF measurements. To compare the results obtained from the experimental data and established theory, we modeled the experimental path via simulation using a finite number of phase screens. The scale and location of the phase screens in the simulation were varied to account for a different turbulence conditions along the propagation path. Preliminary comparison of our experimental data and simulation show that adjacent PSFs are significantly correlated at angles much larger than the predicted theoretical isoplanatic angle.

8246-24, Session 6

Mitigation of time-spatial influence in free-space optical networks utilizing route diversity

J. Libich, S. Zvanovec, Czech Technical Univ. in Prague (Czech Republic)

Free-Space optical (FSO) systems are a modern communication technology, which brings many advantages in contrary to radio communication systems. Unlike fiber optical networks, their transmission parameters are highly influenced by atmospheric phenomena. Many factors affecting propagation of the optical beam in atmosphere have to be investigated for its full understanding. Although connecting of FSO links into whole networks offers many advantages, they are still usually used only for single last mile connectivity primarily owing to its high cost. The paper is focused on investigation of features of FSO networks using route diversity to improve availability of the whole network. Theoretical background is discussed as well as measured statistics are processed and parameters of a network are evaluated, especially with respect to route diversity gain. In order to ascertain network behavior under several atmospheric phenomena, a simple FSO network was proposed and realized. It consists of the four-beam laser FSO link FlightStrata G, MRV TeleScope700 transceiver and two Wavebridge 600 terminals, all working at wavelength of 850 nm and interconnected in a star topology. Two adjacent meteorological stations along with the special sensor line parallel provide atmospheric parameters. In order to increase network availability radio band link was incorporated. Using space-time simulations and measured data in a specific area under specific atmospheric conditions we investigated the behavior of the system as a whole. The proper utilization of the route diversity mechanism in the complex FSO system scenario will be highlighted in the paper.

8246-25, Session 6

Cloud attenuation models and availability of optical ground-space links

N. Perlot, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); J. M. Perdigues Armengol, ESA-ESTEC (Netherlands)

The impact of clouds on optical Earth-space links is assessed by means of theoretical analyses. Binary and continuous attenuations are analysed separately. The fact that cloud attenuation can easily be higher than 100 dB makes pertinent the use of a binary attenuation model with the two states “covered” and “clear”. However, some thin clouds can have an attenuation less than 30 dB. For these weaker attenuations, a performance evaluation should rely on a continuous-attenuation model. With a network of ground stations (GS), both spatial diversity and multiplexing are considered. Ground-station multiplexing is particularly meaningful for up-/downlinks with a GEO satellite. The impact of the GS network size and spatial correlation on the availability and on the throughput is studied. For the case of independent GSs, analytical formulas can be provided whereas for the case of correlated GSs results are obtained by means of numerical simulations.

8246-26, Session 7

Initial performance of the LLCD superconducting nanowire array receiver

E. A. Dauler, D. Rosenberg, R. J. Molnar, J. U. Yoon, M. E. Grein, MIT Lincoln Lab. (United States)

The Lunar Lasercom Demonstration (LLCD) downlink will support data rates up to 622 Mbits/second over a distance of ~400,000 km, by far the longest distance free-space optical communications link ever demonstrated. This downlink will operate at single photon/bit-level sensitivity, using a pulse-position modulation format and superconducting nanowire single-photon detector (SNSPD) arrays in the ground-based receiver. Each of the four arrays is 14 microns in diameter and incorporates four independent nanowires, for a total of sixteen elements. The arrays provide single-photon counting at 1550 nm with >60% efficiency, 30 ps timing resolution, and total count rates up to ~ 1GHz. The receiver also incorporates a novel optical design which uses an array of four 40cm telescopes each coupled to a weakly-multimode PM fiber to transfer the optical signals to the cryogenic detector arrays, which are illuminated by actively-positioned, fiber-pigtailed telescopes inside the detector cryostat. This scheme simultaneously provides low loss and insensitivity to atmospheric turbulence while maintaining polarization. In this presentation we will discuss details of the detector cryostat and optical coupling, and present initial measurements of the communications performance in a laboratory setting.

This work is sponsored by the United States Air Force under Air Force Contract #FA8721-05-C-0002. Opinions, interpretations, recommendations and conclusions are those of the authors and are not necessarily endorsed by the United States Government.

8246-27, Session 7

Superconducting nanowire arrays for multi-meter free space optical communications receivers

W. H. Farr, J. Stern, Jet Propulsion Lab. (United States)

Reception of faint optical communications signals from deep space requires multi-meter diameter optical receivers coupled to high detection efficiency photon counting detectors. Superconducting nanowire detectors have demonstrated the highest detection efficiencies at near-infrared optical communications wavelengths and presently offer the highest performance for high data rate photon starved optical communications. Square-millimeter sized arrays are required due to atmospheric turbulence and the classic solid angle-area invariant of an optical system, but most development of superconducting nanowire detectors has been targeted towards development of detectors of less than 0.001 square-millimeter area. One approach is to partition the detector area across multiple receive apertures (multiple telescopes) to use these small detectors, but this carries a large cost penalty compared to use of a single large aperture. At JPL we are instead pursuing the development of large superconducting nanowire arrays for free space coupling to multi-meter telescopes. We have developed a test facility for large area free-space coupled nanowire arrays and fabricated arrays up to 48 pixels in the NbTiN material system. We shall discuss our test results of these arrays, as well as very encouraging test results from detectors fabricated in a new WSi material system.

8246-28, Session 7

Optimum beam setting for near-field free-space optical communication system with bidirectional beacon tracking

Y. Arimoto, National Institute of Information and Communications Technology (Japan)

A new category of the free-space optical (FSO) communication terminal in which diffraction limited laser beams are directly transmitted from and coupled into a single mode fiber (SMF) has been developed at NICT to realize multi-Gbps to Tbps class point-to-point wireless link. This paper reports a new optimum beam setting to achieve minimum link attenuation and robust operation for near field direct SMF-coupled FSO system with bidirectional beacon tracking. In the previous paper, the author reported that there would be an inherent instability in such a system and enough tracking accuracy should be required to have a stable signal transmission between two SMF fibers. In this paper, the optimum signal beam configuration is found to be not a collimated beam but a symmetric confocal beam between the two FSO terminals. The results of many short range link experiments show that most stable and efficient link has been converged to be a symmetric confocal beam setting after the many alignment adjustment at the both FSO terminal. This paper also describes the detail of the optics in the FSO terminals and the method to measure the beam profile in an operational FSO link.

8246-29, Session 7

Conical refraction multiplexing for free space optical communications

Y. V. Loiko, K. Aradj, A. Turpin, T. K. Kalkandjiev, J. Mompart, Univ. Autònoma de Barcelona (Spain)

In conical refraction /CR/, when an incident light beam passes along the optic axis of a biaxial crystal it refracts conically giving rise to the characteristic CR ring. Every point from the ring has unique linear polarization state and two opposite points are orthogonally polarized. The annular CR beam may be backward transformed to the incident beam, e.g. Gaussian one, by an identical second crystal. By applying an amplitude mask before the second crystal we modulate a number of the ring segments. The obtained in this way exit beam propagates in the space like Gaussian one. However, it is encoded by the selected ring segments / polarization states. Indeed, with third crystal we may observe the selected ring segments. We present theoretical background of this technique for monochromatic spatial multiplexing / demultiplexing based on the fermionic transformation rules for the filtered CR beams [1]. The number of modulated segments defines the increase of the channel capacity in free space communications. We present experimental proof of the method, which provides an increasing of one order of magnitude of the channel capacity at an optical wavelength of 640 nm. For conical refraction we used KGd(WO4)2 crystals. The method can be extended to any wavelength in the optical and the telecommunication bands.

[1] Yu. V. Loiko, M. A. Bursukova, T. K. Kalkanjiev, E. U. Rafailov and J. Mompart, Proc. SPIE 7950 12 (2011).

8246-30, Session 7

The Lunar Laser Communications Demonstration time-of-flight system

B. S. Robinson, D. M. Boroson, M. L. Stevens, J. A. Greco, M. M. Willis, B. R. Romkey, J. E. Kansky, J. Matthews, S. Constantine, H. G. Rao, MIT Lincoln Lab. (United States)

In addition to demonstrating high data-rate duplex optical communications between a lunar spacecraft and a ground terminal, the Lunar Laser Communications Demonstration will demonstrate the use of the wide-band optical signals in those links for precise measurement of the two-way time-of-flight between the terminals. The ground terminal will compare the time between the transmission of an uplink frame and the receipt of a downlink frame in order to measure the two-way time of flight with <200 ps error. This information may be used to calculate the range between the two terminals with sub-cm accuracy. We present the design of the time-of-flight system, sources of error in the measurement, and performance characterization of the two terminals.

8246-31, Session 8

Throughput maximization of optical LEO-ground links

N. Perlot, T. de Cola, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany)

The long-term throughput of optical links between a circular-LEO satellite and a ground station is assessed for systems with fixed and variable data rates. For a fixed data rate, we evaluate the minimum elevation angle above which the link should be established in order to maximize the long-term throughput. Below this optimal minimum elevation, the path attenuation is too high yielding a too low data rate. Above this optimal minimum elevation, the visibility time of the satellite is too low. Ignoring atmospheric-turbulence penalties, the optimal minimum elevation is found to depend predominantly on the clear-sky attenuation at zenith and therefore can be estimated knowing the wavelength and the local atmosphere at the station. The derived formula for the optimal minimum elevation is based on several assumptions for optical LEO up-/downlinks. Although these assumptions are not likely to be all fulfilled, the simple derived formula provides a quick and useful optimization insight. We then consider an adaptive transmission with a data rate proportional to the received power. The ratio of the optimized constant-data-rate throughput to the throughput of an adaptive data rate is found to depend mainly on the satellite altitude.

8246-32, Session 8

Evaluation of deep-space laser communication under different mission scenarios

A. Biswas, S. Piazzolla, B. E. Moision, P. D. Lisman, Jet Propulsion Lab. (United States)

A number of space agencies, including NASA, are considering free-space laser communications as a means for returning higher data-rates from future deep-space missions. A survey of potential deep-space mission scenarios is presented in order to evaluate some critical design aspects for future laser communication systems. These include identifying: (i) the maximum deep-space distance out to which a ground transmitted laser beacon can serve as a viable acquisition and pointing aid; and (ii) operating points where the communication performance degradation is worse than the inverse square distance due to additive background limitations.

8246-33, Session 8

Simulation of a deep space optical transceiver

J. F. Shields, M. Regehr, A. Biswas, Jet Propulsion Lab. (United States)

Deep space laser communications requires extremely accurate pointing to take advantage of the narrow beams achievable at optical wavelengths. Such accuracy requires significant suppression of spacecraft pointing errors. Spacecraft disturbance suppression is accomplished by mounting the lasercom terminal on a soft suspension with active control.

Lasercom acquisition is the process of transitioning from an initial state with a large pointing error to a final state with tight pointing control. Acquisition is difficult to analyze because of the likely need to do an initial search to move the beacon image onto the detector field of view, and the subsequent need to move the image across multiple pixels to the target destination. To facilitate analysis, we have constructed a complete model of the terminal including its suspension, voice coil and steering mirror actuators, and a model of the detector. We present acquisition results from a representative Mars mission in this paper.

8246-34, Session 8

Radiation hardening techniques for rare-earth-based optical fibers and amplifiers

S. Girard, Commissariat à l'Énergie Atomique (France); M. Vivona, Univ. Jean Monnet Saint-Etienne (France); L. Mescia, Politecnico di Bari (Italy); A. Laurent, iXFiber SAS (France); Y. Ouerdane, Univ. Jean Monnet Saint-Etienne (France); C. Marcandella, Commissariat à l'Énergie Atomique (France); F. Prudenzano, Politecnico di Bari (Italy); A. Boukenter, Univ. Jean Monnet Saint-Etienne (France); T. Robin, B. Cadier, iXFiber SAS (France); M. Cannas, Univ. degli studi di Palermo (Italy)

Standard rare-earth (RE) doped optical fibers have been shown to be very radiation sensitive, limiting the integration of fiber-based systems in space. Among the different types of RE-fibers (Er, Er/Yb) operating around 1550 nm, Erbium/Ytterbium fibers are the less affected by radiations. In this paper, we present the approach we used to enhance the radiation tolerance of Er/Yb based amplifiers to space environment. This approach includes several successive hardening techniques. We demonstrated its efficiency through comparison between the radiation responses of amplifiers made with a set of four prototype active codoped double clad Er/Yb fibers. All fibers were developed by Ixfiber SAS in France. The amplifiers were exposed to gamma-rays at a low dose rate (~0.3 rad/s) and to doses up to 150 krad. Previous studies indicated that Er/Yb amplifiers suffered significant degradation for cumulated doses above 5-10 krad. As preliminary presented in [1], we will show that an appropriate composition choice for the glass matrix strongly reduces the degradation of the fiber amplifier's output power. Applying additional hardening techniques then allow us to significantly enhance the best amplifier radiation resistance again, resulting in very limited degradation for doses up to 100 krad. One research axis concerns the positive influence of some possible pre-treatments on the RE-fibers. Furthermore, simulation tools will be presented that can be used to harden more by design the amplifiers.

[1]S. Girard, et al., "Radiation effects on fiber amplifiers: design of radiation tolerant Yb/Er-based devices", Proc. SPIE 7914, 79142P (2011).

Conference 8247: Frontiers in Ultrafast Optics: Biomedical, Scientific, and Industrial Applications XII

Sunday-Wednesday 22-25 January 2012

Part of Proceedings of SPIE Vol. 8247 Frontiers in Ultrafast Optics: Biomedical, Scientific, and Industrial Applications XII

8247-01, Session 1

Biodegradable microsphere mediated cell perforation using femtosecond laser pulse

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We demonstrate the perforation of cell membrane by focused optical far-field generated by dielectric microspheres, polystyrene (PS) and polylactic acid (PLA), excited by an 80 fs laser pulse. The experiments using PS microsphere of 1 µm in diam. were performed for the proof-of-concept demonstration of the perforation using transparent microspheres. The incoming laser beam was weakly focused at a laser fluence of 1.06 J/cm2 (1.33×1013 W/cm2) to a spot size of 300 µm. The average number of the cells in the irradiated area was 77. The number of microspheres conjugated to the cell membrane ranged to 12. FITC-dextran and short interfering RNA (siRNA) have been successfully delivered to many NIH 3T3 cells by applying a single 80-fs, 800 nm laser pulse in the presence of antibody-conjugated PS microspheres. The fractions of the cells showing permeabilization were 38% and 21% for FITC-dextran and siRNA, respectively. In the study using PLA microsphere, which is a typical biodegradable polymer, it was theoretically shown that the optical intensity is enhanced by a factor of 9.7 in relation to the incident optical intensity 0.7 µm under the PLA microsphere of 2 µm diam. The PLA microspheres were conjugated to A431 cells by using anti-EGF receptor. The perforation by using biodegradable microspheres has the potential to become a much safe photo-therapy and gene delivery to patients. This work was supported in part by a Grand-in-Aid for Young Scientists (A) (23680058) by MEXT, Japan.

8247-02, Session 1

Basic mechanisms of out of resonance plasmonic enhanced laser (ORPEL) nanocavitation in water

M. Meunier, É. Boulais, R. Lachaine, Ecole Polytechnique de Montréal (Canada)

Out of resonance plasmonic enhanced laser (ORPEL) nanoprocessing is produced when the laser wavelength used to irradiate a metallic nanostructure does not match with any of its plasmonic absorption peaks. ORPEL produces of a highly localized electronic plasma in the surrounding medium of the nanostructures due to the enhanced scattering field, resulting through various energy transfer to a process on the nanoscale. Using a femtosecond (fs) laser (800nm 45fs), ORPEL was employed as a cell transfection method to create transient holes in cellular membrane, allowing exogeneous molecules to enter the cell. The basic mechanisms leading to nanocavitation and membrane disruption are not yet fully understood. This paper presents a complete finite-element model of the interaction between an ultrafast laser and an out of resonance nanoparticle (ORNP) in water as well as optical in situ measurements to probe the process. Simulation results show that nanocavitation in water is mainly a consequence of the fast plasma relaxation in the medium, leading to a fast temperature increase and the generation of a strong pressure wave in the medium along with a nanoscale bubble. Plasma energy relaxation is shown to dominate largely the heat conduction from the nanostructure's lattice. In situ probe results show indeed that the presence of those plasmonic nanoparticles reduces significantly the fluence threshold for shockwave and bubble cavitation generation. The fact that ORNPs are not broken was proofed unambiguously by performing in-situ spectroscopy and is a strong indication that ORPEL is highly suitable for biological applications.

8247-03, Session 1

Novel large-scale plasmon-based cell transfection

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Cell transfection - or, the introduction of foreign genetic material such as DNA or RNA into a cell - is a driving force in personalized medicine and molecular biology. Here, we present preliminary results for a novel, large-scale, plasmonic transfection method. Using a near-infrared, ultrafast laser beam, we scan an array of gold pyramids on top of which cells adhere. At the tip of the pyramids, the laser induces strong, localized electric fields that lead to the creation of nanobubbles that travel towards the cell. Subsequently, the cell membrane is perforated by the bubble and the foreign genetic molecules can be absorbed. We present both theoretical and experimental results for this plasmon-based transfection. Our FTDT simulations describe the geometry for the plasmonic hot spots that form the basis for our experimental design. We further show in-situ bubble measurements to characterize the nanobubbles in the perforation mechanism and, finally, we demonstrate preliminary results on the uptake of dyes and other molecules using our novel transfection method.

8247-04, Session 1

Cancer cell manipulation using femtosecond pulses and gold nanoparticles

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Conducting effective nanosurgery in cells is an important, but extremely difficult challenge in biological and clinical research. It requires the combination of highly confined physical processes and a mechanism for accurately targeting its effect. The synergistic effect between femtosecond pulses and gold nanoparticles allows true nanometer-scale effect in liquid environments, thanks to the instantaneous absorption of energy, small interaction volume, high efficiency, and high mechanical stability of the nanoparticles. When gold nanoparticles are conjugated to specific antibodies with high affinity to specifically chosen sites on the target cells, the effect could be delivered to multiple locations of the irradiated cells.

Our experimental system includes an optical parametric amplifier capable of single pulse irradiation at wavelength that could be tuned to the particles' plasmonic resonance, and a multi-purpose microscopy system for imaging the nanoparticles and the cells after irradiation. The technique is demonstrated by controlling the death of skin and blood cancer cells, and by inducing efficient cell fusion between various types of cells of different origin. Main advantages of the presented approach include low toxicity, high specificity and high flexibility in regulating cell damage and cell fusion, which would allow it to play an important role in various future clinical and scientific applications. The presentation will discuss the feasibility and the wide parameter space of this approach, the new opportunities it offers, as well as its practical challenges and limitations.

8247-05, Session 1

Nano particles insertion into individual mammalian cells using optical tweezers

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Transfection is the process of introducing DNA into cells so that the introduced DNA will function and produce proteins. This technique is useful to study the function of various DNA sequences and in the future may lead to gene therapy for curing genetic diseases. Currently, a number of techniques are available for both population and individual cells transfection. Although individual cells transfection is less commonly used than the population transfection, it has benefits because it allows controlled single cell analysis. In this paper, we present a new laser assisted transfection method for individual cells. In this technique, two lasers are used to perform the transfection procedure and third laser is used to detect the position of DNA coated particle which is inserted in the cell. This technique has relatively high transfection efficiency and good post-transfection cell viability.

8247-06, Session 2

Towards designer extracellular matrices

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The extracellular matrix influences the behavior of cells via various interactions. Not only chemical stimuli as the molecular composition of contact sites but also their spatial distribution and the mechanical properties of the cellular environment impact cell behavior. Modeling as close as possible this structural complexity in artificial scaffolds is an active field of biomaterials engineering. We fabricate three-dimensional scaffolds using direct-laser-writing in different photoresists. Combining protein-binding and protein-repelling photoresists allows for scaffolds with spatially well defined contact sites. The forces exerted by single cells inside the scaffolds are measured by tuning the elasticity of the scaffolds via geometrical parameters.

8247-07, Session 2

Femtosecond laser two-photon polymerization of three-dimensional scaffolds for tissue engineering and regenerative medicine applications

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3D scaffolds formed in biocompatible polymers can be exploited for tissue engineering and regenerative medicine. Here, we investigate the influence of the scaffold geometry on cell adhesion and morphology. We exploit two-photon polymerization (2PP) to form scaffolds with three different periodicities, in the order of cell size (10, 20 and 30 micron) to investigate the cell interaction with the scaffold. We apply a femtosecond laser oscillator focused by a 1.4-NA objective to form these scaffolds, in which the geometry was limited by outer walls, to contrast cell migration away from the structures. The structures were formed in a zirconium/silicon hybrid sol-gel which has a demonstrated biocompatibility. Higher net fluence exposures were required at larger spacings, since there were fewer lines to support the weight of the scaffold.

The structures were sterilized and seeded with MG-63 cells, expanded from an established osteosarcoma cell line, and the cellular constructs were cultured for six days and analysed by SEM. Cells were found to be well adhered to all the structures. In the 30 micron pitch structures, cells adhered to the external walls of the scaffold and entered it forming several filopodia on the scaffold's inner grid, and acquiring a roundish morphology. For the 20 and 10 micron pitch, fewer and no cells entered the scaffold, respectively; the cells migrated on the outer scaffold walls and maintained a spread morphology. In future work, we will seed mesenchymal stem cells (MSC) into the 30 micron structures, to investigate their differentiative response in immunofluorescence confocal microscopy.

8247-08, Session 2

Femtosecond laser micropatterned polypyrrole artificial muscle actuators with enhanced electrochemical strain response

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Polypyrrole (PPy) is an electronically conducting polymer, which exhibits large electrochemical stress and strain. In addition, PPy is light-weight and operates silently serving as a promising soft artificial muscle microactuator. However, the practical application of PPy actuator devices is hindered by the slow speed of electrical actuation, which is proportional to the diffusion rate of ions in and out of the polymer-electrolyte interface under an applied electrical potential. To counter this slow diffusion, uniform PPy films were textured with a femtosecond fiber laser (522 nm, 400 fs) to increase the surface area accessible for ion transfer, and, in turn, the actuator response time. Taking full advantage of the fast prototyping capability of the direct laser writing technique, numerous combinations of design variables including the hole diameter, depth, pitch, and pattern were examined and applied to finite element techniques to model the ion diffusion rates for various micro-structured surfaces. Optimally designed microhole array structures considered improving the ion diffusion response time while also retaining stiffness for maximum bending radius. The model predicted at least one order magnitude increase in actuation speed. PPy films were bonded to polyimide films, which acted as a passive, ion-impermeable layer, to form bilayer bending actuators. The PPy surface was laser micropatterned into an array of various microhole profiles. The bending radius and response time of both textured and non-textured bilayer actuators were recorded using a digital video camera, and compared to profiles predicted by the FEM. Prospects towards designing an actively controllable biomedical catheter will be discussed.

8247-09, Session 2

Laser microfabrication of polymer implants for stem cell growth and cardiovascular surgery

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We present experimental results on laser fabrication of microstructured 3D polymer implants and study of their biocompatibility based on stem cell growth experiments in vitro as well as reaction of living organism to polymer implants in vivo. The systematic study provides important information for further progress in controllable stem cell growth and tissue engineering. The chosen materials for implants were of several different classes: biocompatible hybrid ORMOCER (Ormocore b59), biodegradable di-acrylated poly(ethylene)glycol (PEG-DA-258) and high quality laser structurable material ORMOSIL (SZ2080). All of the materials were evaluated by their suitability for femtosecond laser structuring, which is well established as a technique enabling rapid and flexible production of 3D micro/nanostructures. All photopolymers could be 3D structured with < 1 µm spatial resolution and up to cm in overall size, thus materializing the computer models of the scaffolds with required pore sizes and porosities. In vitro studies of rabbit adult myogenic stem cell proliferation, adhesion and viability tests showed polymer films and microstructured templates to be as biocompatible as the control substrates such as polystyrene or glass. Additionally, all of the materials have been found at least as biocompatible as surgical suture judging by results of ex vivo histological examination of the tissues surrounding polymer implants after 3 weeks of implantation. This approach to engineering of artificial tissues based on laser fabricated microstructured 3D polymer scaffolds seems to offer good future prospects, especially if custom made implants are required. Microstructured porous polymeric implants with the tubular geometry of a blood vessel have been successfully fabricated and tested as scaffolds for applications in cardiovascular surgery.

8247-10, Session 3

Prospects for automated dissection and surgery with amplified ultrashort pulses of laser light

D. Kleinfeld, Univ. of California, San Diego (United States)

No abstract available

8247-11, Session 3

Microchip laser technology for precise and fast creation of Lasik flaps

N. Linz, S. Freidank, S. Eckert, Univ. zu Lübeck (Germany); K. Schlott, Medizinisches Laserzentrum Lübeck GmbH (Germany); S. Faust, S. Schwed, SCHWIND eye-tech-solutions GmbH & Co. KG (Germany); A. Vogel, Univ. zu Lübeck (Germany)

Using a novel experimental technique that detects transient laser effects as small as 50 nm [1], we demonstrate that low-density plasmas and nanoeffects can be produced not only using ultra-short laser pulses but also, in a much more cost-effective way, by means of temporally smooth nanosecond pulses of short wavelengths [2]. Controlled nonlinear energy deposition with widely tunable energy densities is, hence, possible in a large part of the parameter space spanned by wavelength (UV to IR) and pulse duration (fs to ns).

The tunability opens exciting perspectives for laser material processing, precision manufacturing, and surgery of cells and tissues. As one example, we present a new technique of flap dissection in refractive surgery (LASIK) using a UV nanosecond microchip laser emitting 355-nm, 1-µJ pulses at 150 kHz.

We employed a scanning optics producing a diffraction limited spot size (below 1 µm) in the cornea. LASIK flaps of 9.5 mm diameter with 90-130 µm thickness were produced in porcine cornea. During flap dissection, the central cornea was applanated by a removable suction device. The cutting pattern (spiral or meander) was documented by video. The cutting performance was evaluated by scanning-electron microscopy and histology.

To optimize the novel technique, we investigated the quality of the flap cut and the corresponding cutting time for different parameter sets consisting of laser pulse energy, application patterns, and point to point distance of the individual laser spots. The minimum laser pulse energy required for an easy detachment of the flap was determined for each parameter set. A safety assessment was performed using ray tracing software and temperature calculations.

The precision of cuts in porcine cornea was found to be better than with IR femtosecond laser pulses focused at the same NA because focus diameter and length are only one third of the values at 1064 nm. The generation of the flap bed lasted less than 10 s. A homogeneous, smooth, and very thin bubble layer in the cornea was achieved at laser pulse energies below 1 µJ. The flaps could be lifted easily without any tissue bridges, and both the electron microscopy and histology show a smooth flap bed. The reproducibility of flap thickness is excellent. The radiant exposure for cutting the flap bed is below 2 J/cm², slightly better than for most fs LASIK systems. This value is well below the thresholds for photochemical damage of the retina, UV-induced cataract formation, and endothelial damage.

The cutting performance of the new UV nanosecond laser system surpasses the precision of current IR femtosecond laser systems with comparable laser pulse energies due to the shorter focus length that allows a cutting between or within individual cornea lamella. The scanning system allows the cutting of flaps, lenticels and the preparation for the insertion of intracorneal rings and implants.

References

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8247-12, Session 3

Neuronal rat cell imaging using supercontinuum source

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We performed a FLIM-FRET application of a novel laser source: neuronal rat cell imaging by using a new supercontinuum source able to simultaneously provide light in at 458 nm, 550 nm and 630 nm.

The source is a new photonic crystal fiber pumped by a Ti:Sapphire. The pumping is at a wavelength close to the zero-dispersion wavelength of first order mode and we use off axis pump.

The set-up is stable and reliable. The alignment is very easy.

We also investigate the dependence on pump wavelength.

We modified pump power and pump wavelength and we observed the change in output spectrum. Both broadband light and light concentrated around specific peaks are generated.

Light down to 300 nm was generated paving way to simple UV imaging.

8247-13, Session 4

Octave spanning Ti:sapphire laser for cost effective multimodal CARS/OCT

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Octave spanning Ti:sapphire lasers were originally built to enable ultra-short laser pulses in the sub 10 fs regime but can be applied to other technologies that benefit from the ultrabroad bandwidth or the spectral coherence such as optical coherence tomography (OCT) or coherent anti-Stokes Raman scattering (CARS). In contrast to common picosecond multi-laser CARS, ultrabroad bandwidth light sources are thought to give poor spectral resolution due to their lack of a narrow detection linewidth. Recently, however, spectral chirping has been shown to allow straightforward and robust high resolution CARS microscopy device: the instantaneous linewidth becomes independent of the pulse bandwidth. In another approach Fourier transform (FT) CARS has been proposed that modulates the large bandwidth at high frequency.

In our design a similar approach that also utilizes interferometric amplification is realized with a single ultrabroad bandwidth Ti:sapphire laser with optimized spectral shape (less than 2 dB modulations), bandwidth and output power. This light source is integrated into a multimodal CARS/OCT imaging device and ultrashort pulses with more than 4000 cm-1 bandwidth are generated for both imaging modalities. Dispersion is pre-compensated before passing a dichroic beam splitter in front of the sample's high NA objective. Backscattered light from the sample is collected by the primary objective and recombined with the OCT reference, while the Anti-Stokes radiation is amplified with the spectrally modulated CARS-reference. This simple, parallel OCT/CARS approach permits the extraction of macroscopic tissue morphology down to the micrometer range with localized chemical specificity at cellular levels with data acquisition speeds and sensitivity suitable for in-vivo imaging of large specimen.

8247-14, Session 4

Alignment and maintenance free all-fiber laser sources for CARS microscopy based on frequency conversion by four-wave mixing

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Due to its label-free chemical imaging capabilities of living cells CARS microscopy is a highly desirable tool to provide real-time information e.g. in brain-cancer surgery. However broad use in real-world applications has so far been denied due to the lack of suitable lasers. Today's canonical CARS laser sources based on Ti:Sapphire and parametric frequency conversion in bulk crystals are not only expensive and large, but their operation requires additional technical staff to care for maintenance and alignment. This still restricts the application of CARS microscopy to a few research laboratories worldwide.

In this contribution we report on a novel approach for pump and stokes pulse generation in extremely compact all-fiber systems using parametric frequency conversion (four-wave-mixing) in photonic-crystal fibers. Both picosecond and femtosecond pump laser systems are investigated. Representing for the first time a completely alignment-free approach, the all-fiber ytterbium-based short-pulse laser system provides intrinsically synchronized tunable two-color picosecond pulses. In contrast to former fiber laser approaches based on continuum generation or soliton self-frequency shift, the presented laser can deliver high power spectral densities exceeding 10mW/nm in the converted wavelength. The system was designed to address important CH resonances. Strong CARS signals are generated and proved by spectroscopic experiments, tuning the laser over the resonance of Toluol at 3050cm-1. Furthermore the whole laser setup with a footprint of only 30x30cm² is mounted on a home-built laser-scanning-microscope and CARS imaging capabilities are verified. The compact turn-key system represents a significant advance for CARS microscopy to enter real-world, in particular bio-medical, applications.

8247-15, Session 4

Low noise laser system generating 27-fs pulse duration, 30-kW peak power, and tunability from 850 to 1250 nm for ultrafast spectroscopy and multiphoton microscopy

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There is a need for ultrashort pulse laser sources covering the IR part of the spectrum around and beyond 1 micron. A typical, currently available solution for ultrashort pulses within the spectral range from 1.0 to 1.3 microns is a Ti:sapphire laser, combined with an OPO. Such a complex system requires highly trained personnel for maintenance and its expense is prohibitive for wider applications. In addition, current tunable ultrafast systems are limited in pulse duration down to approximately 100 fs.

A novel low noise, tunable, high peak power, ultrafast laser system is developed based on a SESAM modelocked, solid-state Yb tungstate seed laser, spectral broadening via a microstructured fiber, and pulse compression. The spectral selection, tuning, and pulse compression are performed with a simple prism compressor. The long-term stable output pulses are tunable from 850 to 1250 nm, with a peak power up to 30 kW, and a pulse duration down to 27 fs. We will discuss the noise of the seed laser and the broadened spectrum, as well as the noise dependence on system parameters. Options to generate even shorter pulses and a wider tuning range will be elaborated. Such a low cost system is ideally suited for a variety of applications including ultrafast spectroscopy, multiphoton (TPE, SHG, THG, CARS) and multimodal microscopy, nanosurgery, and optical coherence tomography (OCT).

8247-16, Session 5

High Q laser femtoREGEN UC 8W for industrial micro-processing applications

V. V. Matylitsky, J. Aus-der-Au, H. Huber, High Q Laser Innovation GmbH (Austria)

High average power, high repetition rate femtosecond lasers with µJ pulse energies are increasingly used for bio-medical and material processing applications. With the introduction of the High Q femtoREGENTM UC 8W laser system, micro-processing of solid targets with femtosecond laser pulses obtained new perspectives for industrial applications. The unique advantage of material processing with sub-picosecond lasers is efficient, fast and localized energy deposition, which leads to high ablation efficiency and accuracy in nearly all kinds of solid materials. The sub-picosecond laser pulses are especially useful for structuring of transparent materials. When a femtosecond laser beam is focused inside a transparent material, only the localised region in the neighbourhood of the focal volume absorbs laser energy by nonlinear optical absorption. This leads to a sharp drop of the ablation threshold fluence with the pulse duration. Moreover, the processing volume is strongly defined, thus the rest of the target stays unaffected. Another interesting application for the sub-picosecond pulse laser is the precision cutting of multilayer stacks. The layers in these systems can often have different optical and thermomechanical properties, making the application of cw or long pulse lasers (pulse duration > 10 ps) not possible, giving advantage to the laser systems with sub-picosecond pulses. In this presentation, we will show aspects of the design and performance of the femtoREGEN™ UC industrial laser system, give an overview of actual applications and point out possible future applications.

8247-17, Session 5

Sub-picosecond laser amplifier with >1-mJ pulse energy and 33-W average power

M. Delaigue, S. Ricaud, C. Hönninger, E. Mottay, Amplitude Systemes (France)

High energy and high average power ultrafast lasers are highly demanded for industrial and scientific applications, like notably for precision micro- and nano-machining and for pumping optical parametric amplifiers or amplifier chains.

We have realised an Yb:YAG based thin disk regenerative amplifier in chirped pulse amplification (CPA) configuration. The advantage of the thin disk approach is the power scalability to potentially more than 100 W together with the energy scalability using a compact stretcher-compressor with only moderate pulse stretching. Despite high energy extraction >1mJ, the B-integral during amplification is negligible because of the large laser mode sizes and the short crystal lengths.

Our laser architecture consists of a broadband Yb-doped laser oscillator, an Yb:YAG thin disk regenerative amplifier pumped with a 200 W laser diode, and a compact grating-based stretcher and compressor. We extracted 45W average power out of the amplifier cavity and achieved an average power of 33 W after compression, which corresponds to a compressor efficiency of about 75%. The pulse repetition rate can be varied between 25 and 400 kHz by essentially maintaining the high average power. With decreasing pulse repetition rate and increasing extracted pulse energy, the pulse duration shortens from 870 to 790 fs. The spectral width remains below 3nm FWHM and is suitable for efficient second harmonic generation. The beam quality is excellent with a $M^2 < 1.2$ for all repetition rates.

8247-18, Session 5

Measuring two ultrashort pulses simultaneously using a single device and on a single shot

T. C. Wong, J. Ratner, P. M. Vaughan, V. Chauhan, R. Trebino, Georgia Institute of Technology (United States)

We demonstrate a simple device for measuring two independent ultrashort pulses, each of which can potentially be complex and can also have very different center wavelength, simultaneously in a single-shot. We call our device “double-blind” FROG and it is implemented using polarization-gate geometry. Our previous work on double-blind FROG showed the device is useful in measuring two independent simple pulses based on a multi-shot measurement. However, a single-shot measurement is essential in many circumstances, such as working with amplifier laser systems, which have a few percent of shot-to-shot jitter or laser systems with extremely low repetition rates. Here, we demonstrate single-shot double-blind FROG for simultaneous measurement of complex pulses.

Our device experimentally retrieves a pulse train generated from an etalon with known spacing and a Gaussian pulse simultaneously on single-shot. The FROG traces are retrieved with FROG errors of 0.8%. The etalon spacing corresponds to temporal peak separations of 156 fs, and the spectral peak separation of 13.5nm, in good agreement with the retrieved pulse, which has temporal peak separations of 158 fs and spectral peak separations of 13.3 nm. Independent measurement made by GRENOUILLE shows excellent agreement with the retrieved Gaussian pulse. Our device is capable of measuring ultrashort pulses with root mean square time bandwidth product up to 5.5.

8247-19, Session 5

Pulse repetition interval-based excess fraction method for an arbitrary and absolute distance measurement using a femtosecond optical frequency comb

D. Wei, K. Takamasu, H. Matsumoto, The Univ. of Tokyo (Japan)

The traceability of meter is the infrastructure for both scientific and industrial uses. In July 2009, the national standard tool for measuring length in Japan changed from an iodine-stabilized helium-neon (He-Ne) laser to a femtosecond optical frequency comb (FOFC). How to practically perform a distant measurement that is directly linked to an FOFC length standard tool is the most urgent challenge.

This paper is intended to give a description to the concept, the principle, and a demonstration of a new length measurement technique, called pulse repetition interval-based Excess Fraction (PRIEF) method, which was developed for an arbitrary and absolute length measurement that is directly linked to an FOFC. The basic idea of this new technique was inspired by the analogy between the wavelength of a monochromatic laser source and the pulse repetition interval of an FOFC. Just as a conventional Excess Fraction method can determine an arbitrary and absolute length of a gauge block based on the wavelength of a monochromatic laser source, the same Excess Fraction method can range an arbitrary and absolute length as a function of the pulse repetition interval of an FOFC.

A demonstration of the proposed method which is the length measurement of a 1.5-m long gauge block is presented. From the result of the preliminary experiment, it has been show the possibility that PRIEF method can be used for a high-accuracy distant evaluation.

8247-20, Session 6

Femtosecond laser waveguide writing for integrated quantum optics

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Photonics is a powerful framework for testing in experiments quantum information ideas, which promise significant advantages in computation, cryptography, measurement and simulation tasks.

Linear optics is in principle sufficient to achieve universal quantum computation, but stability requirements become severe when experiments have to be implemented with bulk components. Integrated photonic circuits, on the contrary, due to their compact monolithic structure, easily overcome stability and size limitations of bench-top setups. Anyway, for quantum information applications, they have been operated so far only with fixed polarization states of the photons. On the other hand, many important quantum information processes and sources of entangled photon states are based on the polarization degree of freedom.

In our work we demonstrate femtosecond laser fabrication of novel integrated components which are able to support and manipulate polarization entangled photons. The low birefringence and the unique possibility of engineering three-dimensional circuit layouts, allow femtosecond laser written waveguides to be eminently suited for quantum optics applications.

In fact, this technology enables to realize polarization insensitive circuits which have been employed for entangled Bell state filtration and implementation of discrete quantum walk of entangled photons. Polarization sensitive devices can also be fabricated, such as partially polarizing directional couplers, which have enabled on-chip integration of quantum logic gates reaching high fidelity operation.

8247-21, Session 6

Femtosecond laser writing of polarization devices for optical circuits in glass

L. A. N. P. 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)

Waveguides fabricated in fused silica by femtosecond laser exposure have birefringence properties inherent to the anisotropies of the nonlinear absorption mechanisms in the non-thermal accumulation regime. This may be useful in the fabrication of polarization dependent devices with a wide range of photonic applications.

A frequency doubled Yb:fiber laser (522 nm, 300 fs, 500 kHz repetition rate) was applied over a range of exposure conditions (80 nJ to 200 nJ pulse energy and laser polarization) to fabricate buried waveguides and directional couplers in fused silica glass. We report two modes of low and high birefringence associated with strong form birefringence and the orientation of nanogratings that align perpendicular to the writing laser polarization.

Through careful tuning of the exposure parameters, the birefringence properties of the waveguides were studied in order to control wave retardance and polarization dependent coupling. The birefringence was measured by noting the polarization splitting of stopbands between proper polarization modes in Bragg grating waveguides, together with cross polarization transmission study of uniform waveguides.

Birefringence values ranged from (10^-5) to (10^-4) respectively for parallel and perpendicular polarization of the writing laser. The trade-off between losses and birefringence was explored in order to find optimized fabrication parameters for these devices.

Zero-order retarders were demonstrated with 5% variation from ideal circular polarized light for a quarter-wave retarder and 35 dB linear polarization contrast ratio for a half-wave retarder. A polarization beam splitter is presented with polarization splitting ratios of -19 dB and -24 dB.

These devices offer the possibility for three-dimensional integration into quantum photonics systems, taking advantage of the stability of the fused silica substrate and the scalability, versatility and compactness enabled by the femtosecond laser writing technique together with the new ability of inserting polarization devices to tailor the response of future optical circuits.

8247-22, Session 6

Enhanced formation of nanogratings inside fused silica due to the generation of self-trapped excitons induced by femtosecond laser pulses

S. Richter, F. Jia, M. Heinrich, S. Döring, S. Nolte, Friedrich-Schiller-Univ. Jena (Germany); A. Tünnermann, Friedrich-Schiller-Univ. Jena (Germany) and Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

I want to be considered for the student competition.

The realization of sub 100 nm structural modifications in various materials has attracted a lot of interest in recent years. One promising and flexible technique for this is the inscription of nanogratings by ultrashort laser pulses inside transparent glasses, e.g. fused silica.

Recent results identify a stepwise formation of nanogratings from single nanomodifications to homogeneous nanogratings, which are induced by successive laser pulses. However, the intrinsic coupling between the individual laser pulses is not yet fully understood.

We performed double pulse experiments with various delay time between the laser pulses. After inscription, we measured the resulting birefringency, which is a measure for the strength of nanogratings. An enhanced nanograting formation was observable up to pulse separations of 500 ps, much longer than the plasma lifetime inside the glass.

We account this to the formation of Self Trapped Excitons (STEs). The STEs in fused silica exhibit various decay and excitations channels with life times partly in the observed range. We propose these STEs as the coupling link between the individual laser pulses due to their metastable state. The STEs assist the laser pulse absorption and thus the formation of colour centers, NBOHC and finally of the nanomodifications inside fused silica.

8247-23, Session 6

Bragg grating stopbands from nanogratings generated during femtosecond laser writing of optical waveguides

J. Li, M. Haque, S. Ho, P. R. Herman, Univ. of Toronto (Canada)

Femtosecond laser induced nanograting structure inside fused silica glass has opened doors to new photonic and biophotonic applications such as form birefringence enabled fabrication of polarization-dependent optical elements, preferential chemical etching assisted generation of buried micro/nano-fluidic channels, and re-writable data recording. Nanogratings will form only within a narrow laser process window and much effort has therefore been expended to identify the underlying femtosecond laser-material interaction physics. Direct evidence and characterization of bulk nanogratings are tedious and have been traditionally accomplished by scanning backscattering electron microscopy after first polishing the glass sample surface to intercept the laser modification zone where the nanogratings are formed. Alternatively, atomic force microscopy and scanning secondary or Auger electron microscopy of similarly polished samples following weak chemical etching will also reveal the grating structure. A non-invasive means of characterization is more desirable such as Bragg spectral response previously reported from an assembly of bulk nanogratings. We present a new diagnostic approach in this paper that collects transmission spectra through femtosecond laser written buried optical waveguides wherein nanograting planes were formed inside the guiding volume and oriented parallel with the guiding direction.

A frequency-doubled femtosecond fiber laser (523 nm, ~300 fs, 1 MHz) was applied to write the waveguides and nanogratings with laser polarization parallel to the sample scanning direction. Definitive Bragg grating stopbands in the visible and near-infrared spectrum and their shifting with scanning speed and pulse energy are reported. The Bragg periods inferred from the stopbands concur with the grating structure periodicity observed directly by scanning electron microscopy. In addition, a secondary Bragg grating stopband was observed when waveguides were scanned along the direction of pulse front tilt of the femtosecond laser beam that suggests a ‘quill’ effect. This new spectroscopic approach offers a convenient, fast, non-destructive and quantitative way to characterize bulk nanogratings that may facilitate further understanding of ultrafast laser glass interactions.

8247-24, Session 6

Femtosecond laser processing of hybrid micro- and nano-structures in silicate glasses

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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 a number of semiconductor-doped glasses it is possible to nucleate and grow semiconductor nanocrystals under certain thermal conditions (striking). The control over the precipitation process is achieved by controlling the temperature and treatment duration to produce semiconductor precipitate with the desired size distribution, and, in the quantum confinement regime, with the desired optical properties.

We’ve irradiated one of such glasses with high repetition rate ultrafast laser pulses. This had lead to desegregation of elements in the glass matrix on the micron scale. As a result, chemically distinct microscopic regions were formed, which exhibited markedly different phase separation dynamics from the original glass. This has been exploited to selectively precipitate semiconductor nanocrystals in the volumes defined by ultrafast laser exposure.

Characterization of glass modification was carried out using white light, fluorescence and electron microscopy, as well as wave dispersive x-ray spectroscopy. We explored the effect of laser parameters on the subsequent feature geometry, compositional variations, and, combined with heat treatment parameter space, its effects on particle precipitation and the optical properties of the latter.

8247-25, Session 7

Formation dynamics of femtosecond laser-induced phase objects in transparent materials

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Ultrashort pulse lasers offer the possibility to structure the bulk of transparent materials on a microscale. As a result, the optical properties of the irradiated material are locally modified in a permanent fashion. Depending on the irradiation parameters, different types of laser-induced phase objects can be expected, from uniform voxels (that can exhibit higher or lower refractive index than the bulk) to self-organized nanoplanes. We study the physical mechanisms that lead to material restructuring, with a particular emphasis on events taking place on a sub picosecond to a microsecond timescale following laser excitation. Those timescales are particularly interesting as they correspond to the temporal distances between two consecutive laser pulses when performing multiple pulse irradiations: burst microprocessing usually involves picosecond separation times and high repetition rate systems operate in the Mhz range.

We employ a time-resolved microscopy technique based on a phase-contrast microscope setup extended into a pump-probe scheme. This method enables a dynamic observation of the complex refractive index in the interaction region with a time resolution better than 300 fs. In optical transmission mode, the transient absorption coefficient can be measured for different illumination wavelengths (400 nm and 800 nm). The phase-contrast mode provides qualitative information about the real part of the transient refractive index. Based on the study of those transient optical properties, we observe the onset and relaxation of the laser-generated plasma into different channels such as defect creation, sample heating, and shockwave generation. The majority of our experiments were carried out with amorphous silica, but our method can be applied to the study of all transparent media.

8247-26, Session 7

Quantitative measurements of the densification observed in fused silica specimens exposed to low-energy femtosecond laser pulses

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Fused silica (a-SiO2) exposure to low-energy femtosecond laser pulses introduces induces a local increase of the etching rates and/or a local increase of the refractive index. Up to now the exact modifications occurring in the glass matrix after exposure remains elusive. Various hypotheses among which the formation of color center or of densified zones have been suggested. In the densification model, it is assumed that shorter rings in the a-SiO2 matrix are formed locally in the laser affected zone. Since the reduction of Si-O-Si bond angles and the increase etching rate are correlated, according to this model, laser-exposed region would etch faster.

In this paper, we investigate quantitatively the amount of densification present in well-defined laser exposed zones. Our method is based on the deflection of glass cantilevers and on hypothesis from classical beam theory.

Specifically, 20mm-long cantilevers are fabricated using low-energy femtosecond laser pulses. After chemical etching, the cantilevers are again exposed to the same femtosecond laser but only in their upper-half thickness. We measure micron-scale displacements at the cantilever tip that we compare to predictions of analytical and finite element mechanical models of the cantilever locally subjected to a theoretical densification. The analytical model is inspired from the Stoney equation while the finite element model considers a displacement induced by a localized volume reduction in the laser affected zone.

Our results confirm the validity of the densification hypothesis and provide a quantitative method to precisely determine the amount of densification as a function of the laser exposure parameters.

8247-27, Session 7

Long term reliability prediction of fluorescent silver nanoclusters embedded in glass for perennial optical recording

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The problematic of long term data archivage becomes a key element taking into account that our numerical civilization produces more and more information and knowledge. What support should be used to store essential data? Current magnetic and optical recording media suffer from a critical drawback: their lifetime, which is no longer than five to ten years. On the one hand, magnetic media mainly suffer from high sensitivity to electromagnetic radiations and can accidentally “crash”. On the other hand, it is now demonstrated that current optical media have limited storage capacity and material durability. We propose a new high capacity optical recording medium and we investigate the failure mechanisms of this medium for long term durability.

Here we show three-dimensional optical recording by exploiting the fluorescence properties of femtosecond-laser-induced silver nanoclusters in glass. The combination of a blue laser diode with a high numerical aperture focusing set-up, similar to the “Blu-ray” drive, enables the readout of the information inside the glass without cross-talk and photo-bleaching. In order to investigate the failure mechanisms of the nanoclusters embedded in glass relative to temperature, heat treatments at 100°C for thousands of hours have been performed. Fluorescence measurements at different times show a small decrease of the fluorescence features associated to unstable color centers Ag2+. However, the fluorescence features associated to the nanoclusters Agmx+ do not change, which shows that this medium is resistant to this stress for these conditions. A failure modeling is proposed here to predict the lifetime of this optical recording medium.

8247-28, Session 7

On the role of the scanning line density on the etching of fused silica specimens exposed to femtosecond lasers pulses

Y. Bellouard, Technische Univ. Eindhoven (Netherlands); A. A. Said, M. A. Dugan, P. Bado, Translume, Inc. (United States)

Fused silica (a-SiO2) exposure to low-energy femtosecond laser pulses, below the ablation threshold introduces a local increase of the HF etching rate. This property has been used to fabricate a variety of structures ranging from simple fluidic channels to more complex optofluidics and optomechanical devices.

In practice, the desire patterns are written by piling up laser exposed regions, so that the volume to be removed is defined. In earlier work, we showed that there was an optimum level of energy for maximizing the efficiency of the etching process. Here, we focus on the interaction between adjacent laser affected zones and its effects on the overall etching process. Experimentally, we exposed fused silica specimens to patterns consisting of matrices of lines with varying density under various laser exposure conditions.

Surprisingly, we show that for given laser affected zone densities and pulse energies, the exposed regions not longer etch while their constitutive element (i.e. the single laser affected zone) does. This paper will describe our recent experimental observations and propose a qualitative model to explain these findings.

8247-29, Session 7

Structural modification in Er-Yb doped zinc phosphate glasses with megahertz repetition rate femtosecond pulses

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By using high intensity femtosecond pulses at 1 MHz repetition rate, heat accumulation and elemental migration effects were systematically investigated in a series of Er-Yb doped zinc phosphate glass compositions. The zinc phosphate glass compositions tested all had a similar initial phosphate network structure owning to the fact that they had a similar oxygen to phosphorous ratio (O/P~3.25), but they differed in the type of network modifier ions that were present. The glasses, which showed good optical quality waveguide fabrication under slit writing in the low repetition rate regime at 1 kHz, were tested for guiding properties under high repetition rate writing as well. Structural changes to the glass were measured using fluorescence and Raman confocal spectroscopy. Fluorescence spectroscopy was used not only to probe the creation of phosphorous oxygen hole centers (POHCs) but also to ascertain the changes to the Er and Yb transitions due to changes in their local environment. Raman spectroscopy was used to understand the structural changes in the underlying phosphate glass network. Elemental analysis from an SEM was used to visualize the elemental migration found in the heat accumulation regime of writing. In particular, certain glass co-dopants lent themselves favorably to this migration whereas others appeared to hinder this process all together even over the wide range of powers used.

8247-30, Session 8

Present status and trend of femtosecond laser processing in display industry of Korea

S. Cho, Korea Institute of Machinery & Materials (Korea, Republic of)

No abstract available

8247-31, Session 8

Femtosecond direct writing of lab-on-a-fiber optofluidic sensors

M. Haque, J. R. Grenier, S. Ho, Univ. of Toronto (Canada); L. A. N. P. Fernandes, Univ. do Porto (Portugal) and Univ. of Toronto (Canada); P. R. Herman, Univ. of Toronto (Canada)

There is unabating desire for miniaturization of biological and chemical laboratory processes from bulky free-space systems to more compact and functional lab-on-a-chip devices. As a result, numerous directions in lab-on-a-chip applications are being investigated such as chemical analysis and synthesis, sample preparation, mixing and particle sorting. Optical sensing is frequently a core component of such microsystems, which our group is exploring along a different path of miniaturization that wraps micro-fluidic and optical components around the guiding core waveguide of optical fiber. The pure silica cladding now widely used in many types of standard and photonic crystal fiber presents an ideal platform on which to build a new generation of “lab-on-a-fiber” devices. This geometry naturally facilitates intimate optical interrogation of micro-fluidic and micro-reactor components on a large and standard base of existing fiber optics technology. This direction promises more functional and highly sensitive flow sensors, cytometers and spectroscopic tools than current lab-on-a-chip devices. Further, lab-on-a-fiber sensors are particularly advantageous for their resistance to chemical erosion, non-invasive in vivo detection capability, real-time sensing, compactness, biocompatibility and most notably their mechanical flexibility and robustness. Such devices may find their way into distributed sensing networks including Telecom and LAN networks, smart catheters for medical procedures, compact sensors for security and defense and low cost health care products.

In this paper, we present laser recipes for creating microfluidic and photonic devices inside cylindrical-shaped fiber cladding. Optical fibers were exposed with a focused Yb-fiber amplified femtosecond laser (IMRA, FCPA µJewel, = 522 nm) for direct laser writing of flow channels, reservoirs and fiber-Bragg-grating-waveguides (FBGWs). Subsequent hydrofluoric acid etching yielded the integrated optofluidic lab-on-a-fiber device. Reservoirs and channels were made to run parallel with or to cross the core waveguide for evanescent or direct optical interrogation, respectively. FBGWs were also embedded inside fiber cladding such that the modal evanescent field couples with fluid inside an adjacent microfluidic reservoir for enabling refractive index and other forms of optical sensing.

8247-32, Session 8

Rapid prototyping of biocompatible sensor chips by picoseconds laser structuring of a platinum/ tantalum pentoxide thin film layer system

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A new way for the flexible and rapid maskless patterning of a biocompatible sensor chip by laser structuring is presented. It is fabricated using a thin film layer system consisting of 200 nm platinum as the conductive layer on a glass substrate and a 100 nm tantalum pentoxide as insulator on top of the platinum. The complete removal of both, the platinum and tantalum pentoxide thin films to define conductors as well as the selective ablation of the transparent tantalum pentoxide thin films on top of the platinum to open windows in the isolating layer for contacts was investigated using ultra-short pulses (10 ps @ 1064 nm) of a Nd:YVO4 laser. The substrate-side and layer-side ablation for different thicknesses were compared. For a deeper understanding of the selective structuring process also single layers of platinum and Ta2O5 were investigated. We present results on the single pulse threshold measurements as well as on the patterning of a complete sensor chip. We observed that a Pt film covered with tantalum pentoxide shows a significantly lower ablation threshold than a single Pt film on glass alone when illuminated from the front side. Furthermore we explored that the tantalum pentoxide film can be removed by glass side illumination from the Pt film, leaving the Pt film on the glass substrate intact. Those ablation phenomena occur at laser fluences of about 0.2 J/cm^2 far below the evaporation limit of platinum.

8247-33, Session 8

Femtosecond laser fabrication of optical sensing devices in the cladding of optical fibers

J. R. Grenier, Univ. of Toronto (Canada); L. A. N. P. Fernandes, Univ. do Porto (Portugal) and Univ.of Toronto (Canada); J. S. Aitchison, Univ. of Toronto (Canada); P. V. S. Marques, Univ. do Porto (Portugal); P. R. Herman, Univ. of Toronto (Canada)

Femtosecond lasers have given access to nonlinear optical interactions which enable the fabrication of waveguides, Bragg grating Waveguides (BGW) and microfluidics in bulk glass with full three-dimensional (3D) integration. While these laser-written devices promise to expand the component toolkit for fabricating highly functional 3D integrated optical circuits, their integration in the cladding of a single-mode optical fiber (SMF) represents an attractive extension of this technology on a large and widely applied base of fiber optics technology.

In this work, the second harmonic (522 nm) of a femtosecond fiber 500 kHz pulse repetition rate laser was employed to fabricate BGWs in the cladding of a SMF and define 3D sensing microsystem. An acousto-optic modulator facilitated a burst writing method for the BGWs, while also enabling the accurate placement and fabrication of multiple components in the same laser exposure. To drive stronger interaction and avoid spherical and astigmatic optical aberrations, laser pulses were tightly focused by a 100X, 1.25 NA oil-immersion lens. The BGWs were single mode at 1560 nm wavelength, have approximately circular mode field diameters that are within ±1.4 µm of a SMF (10.4 µm) and have a 0.8 dB insertion loss for a 20 mm long grating waveguide. Various combinations of temperature and strain sensing were demonstrated by measuring the Bragg wavelength shift of four BGWs distributed uniformly around the azimuth of the cladding while the fiber was bent, twisted and heated. Various layout architectures that involved the precise placement of multiple BGWs enabling temperature independent strain measurements were explored together with distributed strain sensing arrangements for fiber position, torsion, and angle sensing.

Fabricating optical circuit components in the cladding of optical fibers opens new opportunities for compact and functional optical and optofluidic microsystems for telecom, sensing and lab-on-a fiber concepts.

8247-34, Session 8

Mechanism of selective removal of transparent layers on semiconductors using ultrashort laser pulses

T. Rublack, S. Hartnauer, M. Muchow, M. Mergner, G. Seifert, Martin-Luther-Univ. Halle-Wittenberg (Germany)

Anti-reflection coatings for solar cells and, more general, optical elements for the near-infrared spectral range are usually dielectric layers of a few hundred nanometer thickness or less. The selective ablation of such thin transparent layers from absorbing semiconductors is possible without noticeable damage of the substrate when ultrashort laser pulses at photon energies higher then the bandgap energy are used [1]. To get a broad understanding of this ablation mechanism, experiments with a variety of laser parameters were done, e.g. wavelengths from UV to mid-infrared and pulse durations between 50 and 2000 fs. Experiments were also conducted using different transparent materials on silicon, e.g. SiO2 and SixNy. Careful characterization of the ablated regions was done by light microscopy, atomic force microscopy (AFM), Raman spectroscopy, scanning electron microscopy (SEM) and transmission electron microscopy (TEM).

The absorption coefficient of silicon increases dramatically already within the interaction time due to nonlinear effects stimulated by the ultrashort laser pulse itself. Linear as well as two photon absorption only initiate the process of selective ablation, which is then governed by a high density of laser generated charge carriers. Therefore pulse duration and wavelength have significant influences of the operation range for selective ablation.

Ablation experiments using mid-infrared wavelength at pulse durations of 1-2 ps discourage ablation via vibrational resonances of the dielectrics (e.g. at 9.26µm for SiO2), because always damage of the semiconductor occurred before ablation of the dielectric layers.

The physical processes behind all these phenomena will be described and discussed in detail.

8247-18, Session 9

Applications of picosecond laser and pulse-burst in precision manufacturing

R. Knappe, LUMERA LASER GmbH (Germany)

Picosecond lasers are established as powerful tools for micromachining. Industrial processes like micro drilling, surface structuring and thin film ablation benefit from a process, which provides highest precision and minimal thermal impact for all materials. Applications such as microelectronics, semiconductor, and photovoltaic industries use picosecond lasers for maximum quality, flexibility, and cost efficiency. The range of parts, manufactured with ps lasers spans from microscopic diamond tools over large printing cylinders with square feet of structured surface. Cutting glass for display and PV is a large application, as well.

With a smart distribution of energy into groups of ps-pulses at ns-scale separation (known as burst mode) ablation rates can be increased by one order of magnitude or more for some materials, also providing a better surface quality under certain conditions.

The talk will report on the latest results of the laser technology, scaling of ablation rates, and various applications in ps-laser micromachining.

8247-19, Session 9

High sensitive concentration analysis of biochemical liquids using a microfluidic chip fabricated by femtosecond laser

Y. Hanada, K. Sugioka, K. Midorikawa, RIKEN (Japan)

Protein carry out many biological, chemical functions, including, but not limited to, catalyzing reactions in living organism, decoding information in cells, regulating biochemical activities, storing and transporting small molecules, providing mechanical support, and serving many other specialized functions. The onset of various diseases usually involves altered protein expression and distribution. Therefore, detection technique for certain proteins at low level is useful for the diagnosis of specific diseases in health care although most of the conventional techniques are only capable of detecting abundant proteins.

In the meanwhile, we have proposed using microchips with three-dimensional (3D) microfluidic structures to detect concentration of liquid samples. In this case, we have developed a technique for fabricating 3D microfluidic structures with smooth internal surfaces inside a photostructurable glass. This method uses femtosecond (fs) laser direct writing followed by annealing and successive wet etching. It permits rapid prototyping of 3D microfluidics with different structures, which is highly desired by biochemical processes. Furthermore, microoptical elements such as optical waveguide can be easily integrated with the microfluidic structure, permitting more functional analysis. In this talk, we attempted fabricating a microfluidic chip integrated with waveguide in the glass for protein concentration assay. By covering the internal walls of microfluidics with low refractive index polymer, high-sensitive protein concentration assay is performed at low level.

8247-20, Session 9

Ultrahigh precision surface structuring by synchronizing a galvo scanner with an ultrashort pulsed laser system in MOPA arrangement

B. Jaeggi, B. Neuenschwander, U. Hunziker, T. Meier, M. Zimmermann, K. Selbmann, I. Gut, Berner Fachhochschule Technik und Informatik (Switzerland); G. Hennig, Daetwyler Graphics AG (Switzerland)

Currently in industrial applications ultra short pulsed laser systems will be used, if high requirements concerning accuracy, defined surface roughness and small heat affected zone are demanded. For surface and 3D structuring these systems are usually used in combination with galvo scanners. Today, the available industrially suited ultra short pulsed systems are turnkey systems, set up in a MOPA arrangement with passively mode locked seed laser and rod or disk amplifier. The frequency of the amplified laser pulses is finally defined by the seed oscillator and can't be actively controlled. For high precise structuring applications this combination therefore suffers from certain inaccuracies due to the asynchronous motion of the scanner mirrors relative to the pulse train.

This work reports on the synchronization of the scanner mirror motion with the clock of the laser pulses, which is usually in the range of a 100 kHz and more, by a modification of the electronic scanner control. This synchronization facilitates the placement of the small ablation craters from single pulses with the precision of about 1 um relative to each other. The precise control of the crater positions offers the possibility to test and optimize new structuring strategies. Results of this optimization process with respect to minimum surface roughness, steepness of wall, accuracy to shape, moiré-effects and efficiency will be presented.

8247-35, Session 9

Three-dimensional silver nanostructure fabrication through multiphoton photoreduction

K. Vora, S. Kang, S. Shukla, E. Mazur, Harvard Univ. (United States)

Metal nanostructure fabrication techniques have become increasingly important for photonic applications with rapid developments in the fields of plasmonics, nanophotonics and metamaterials. While two-dimensional techniques to create high resolution metal patterns are readily available, it is more difficult to fabricate three-dimensional (3D) metal structures that are required for new applications in these fields. We present an ultrafast laser technique for 3D direct-writing of disconnected silver nanostructures embedded in a dielectric. We induce the photoreduction of silver ions through non-linear absorption in a solution doped with silver salts. Utilizing nonlinear optical interactions between the chemical precursors and femtosecond pulses, we limit silver-ion photoreduction processes to a focused volume smaller than that of the diffraction-limit. The focal volume is scanned rapidly in 3D by means of a computer-controlled translation stage to produce complex patterns. Our technique creates dielectric-supported silver structures, enabling the nanofabrication of silver patterns with disconnected features in 3D. We obtain sub-300 nm resolution and create 3D arrays of dots, grids and woodpile patterns. We show that the process is scalable and suitable for metamaterial applications.

8247-36, Session 9

Material specific effects and limitations during ps-laser generation of micro structures

J. Hildenhagen, K. Dickmann, U. Engelhardt, M. Smarra, Fachhochschule Münster (Germany)

The generation of micro structures by high power ps-laser radiation is increasingly becoming a common application. However, during the ablation processes different objectionable side effects might occur. These effects depends et al. on material properties and geometry of the structure. One obvious example is the variation of the flank angle. Next to general laser parameter like fluency or polarisation orientation the emerging angle is linked with physical characteristics of the substrate. Without specific setup modification best achievable edge steepness can show a variance of 10 degree and more among different materials. Also known is the formation of trenches on the ablation ground next to the flanks. Partly this effect is due to technical reasons and depends on insufficient synchronization between laser and acceleration/deceleration of the scanner system. A further reason is based on reflection of laser radiation at vertical flank walls leading to increased irradiation and thereby enhanced ablation of the surrounding area. These and more side effects lead to imprecise geometric micro structures. Application specific parameters and adapted setups can help to overcome or reduce these problems.

For this study the used ps-laser (Trumpf TruMicro 5050 Compact, 50 Watt, optical scanner) was attached with an x/y/z-stage and confocal chromatic sensor to measure the generated structure subsequently. The 3D-scan allows to analyze directly the influence of the last modifications and to reduce the optimisation process. Experimental research on a variety of different substrates (metals just as dielectrics) should help to understand the cause and effect of influencing variables.

8247-22, Session 10

Laser processing with ultrashort vortex pulses

C. Hnatovsky, V. G. Shvedov, W. Z. Krolikowski, A. V. Rode, The Australian National Univ. (Australia)

We present the results of material modification using tightly focused femtosecond laser vortex pulses. Double-charge femtosecond vortices were synthesized with a vortex beam converter [1] by using polarization singularities associated with the beam propagation in birefringent crystals. A vortex beam was focused using moderate and high numerical aperture optics (viz., NA = 0.45 and 0.9) to ablate fused silica and soda-lime glass. By controlling the pulse energy we consistently machine micron-size ring-shaped structures with down to 70 nm uniform groove thickness with single-pulse irradiation [2].

By focussing the vortex beam in the bulk of transparent material to the intensity above the optical breakdown threshold we demonstrate the ability to form a toroidally shaped plasma confined inside the solid. Our preliminary experiments with powerful femtosecond vortex beam demonstrate that the central volume of the cylindrical focus with zero intensity in the axis is indeed heated in the centre of the beam above the ablation threshold.

Using the pulse energy below the ablation threshold and irradiating the same spot on the surface with many, up to 1000 pulses, we demonstrate formation of nanostructured patterns which accurately replicate the vectorial structure of laser field of tightly focused beams and provide insights into the directionality of radiation pressure in the nanoscale domain [3]. These complex polarisation-replicating nanostructures may find applications in the fabrication of polarization micro-optic components and beam shapers, and in the synthesis of chiral materials.

[1] V. G. Shvedov, C. Hnatovsky, W. Krolikowski, A. V. Rode, “Efficient Beam Converter for the Generation of Femtosecond Vortices,” Opt. Lett. 35, 2660 (2010).

[2] C. Hnatovsky, V. G. Shvedov, W. Krolikowski, A. V. Rode, “Materials processing with a tightly focused femtosecond vortex laser pulse” Optics Letters, 35, 3417 (2010).

[3] C. Hnatovsky, V. Shvedov, W. Krolikowski and A. Rode “Revealing local field structure of focused ultra-short pulses”, Phys. Rev. Lett. 106, 123901 (2011).

8247-23, Session 10

Machining of glass and quartz using nanosecond and picosecond laser pulses

D. Ashkenasi, T. Kaszemeikat, N. Mueller, A. Lemke, Laser- und Medizin-Technologie GmbH, Berlin (Germany); H. J. Eichler, Technische Univ. Berlin (Germany)

New laser processing strategies in micro processing of glass, quartz and other optically transparent materials are being developed with increasing effort. Utilizing diode-pumped solid-state laser generating nanosecond pulsed green (532 nm) laser light in conjunction with either scanners or special trepanning systems can provide for reliable glass machining at excellent efficiency. Micro ablation can be induced either from the front or rear side of the glass sample. Ablation rates of over 100 µm per pulse can be achieved in rear side processing. In comparison, picosecond laser processing of glass and quartz (at a wavelength of 1064 or 532 nm) yield smaller feed rates at however much better surface and bore wall quality. This is of great importance for small sized features, e.g. through-hole diameters smaller 50 µm in thin glass. Critical for applications with minimum micro cracks and maximum performance is an appropriate distribution of laser pulses over the work piece along with optimum laser parameters. The presentation discusses several laser machining examples: long aspect micro drilling, slanted through holes, internal contour cuts, micro pockets and more complex geometries. Materials involved are soda-lime glass, B33, B270, D236T, AF45 and BK7 glass, quartz, and Zerodur. The LMTB development of a new trepanning system as a key beam delivery tool for micro machining of brittle materials will be presented.

8247-24, Session 10

Fabrication of photo-induced microstructure embedded inside ZnO crystal

Y. Ishikawa, Y. Shimotsuma, A. Kaneta, M. Sakakura, M. Nishi, K. Miura, K. Hirao, Y. Kawakami, Kyoto Univ. (Japan)

Zinc oxide (ZnO) has wide range of applications from a transparent conducting electrode, surface acoustic wave devices, to gas sensor. Especially ZnO is expected to high efficiency ultraviolet emitting material or excitonic semiconductors due to its wide band gap (3.4 eV) and large exciton binding energy (~ 60 meV). Recently, various studies relating to nanostructuring on ZnO surface using ultrashort pulse laser have demonstrated that polarization-dependent ripple structures were self-assembled, however, until now, there has been no observation of structural modification inside ZnO crystal by femtosecond laser irradiation and the mechanisms has not been fully understood. Here we demonstrate the space-selective oxygen defects were successfully induced inside ZnO crystal by means of focused femtosecond laser irradiation. The threshold energy for oxygen defect formation was estimated by changing the pulse width of the irradiated femtosecond laser. The mechanisms of the pulse-width dependence of femtosecond laser damage inside ZnO crystal was interpreted in terms of the excitonic Mott transition to the electron-hole plasma depending on the electron plasma density induced by the laser irradiation. We have also discussed the interaction of infrared ultrashort laser pulses (l = 1.24 um) with silicon. These results could be useful to the micromachining inside semiconductor using femtosecond laser based on the intense laser-plasma interaction.

8247-37, Session 10

Water assisted microhole drilling in fused silica using burst-train femtosecond laser pulses

T. Tamaki, Nara National College of Technology (Japan); S. Rezaei, J. Li, P. R. Herman, Univ. of Toronto (Canada)

In this paper, we present the investigation results on high aspect-ratio microhole drilling in fused silica glass by use of burst-train femtosecond laser pulses and water assistance. When the time interval between neighboring burst pulses is shorter than the thermal diffusion time of the material, residual heat remaining at the next burst laser pulse can be accumulated over multiple burst pulses to increase the temperature around laser interaction volume, which enables improved laser absorption and the realization of more efficient and ductile crack free femtosecond machining. A custom built burst resonator integrated with a commercial Ti:Sapphire laser system (800 nm, 50fs-5ps, 500 Hz) generates 38-MHz repetition rate burst-train pulses, which were focused on the rear face of fused silica glass (1 mm thick) either in contact with water or in the air. The microholes were drilled starting from the rear face by translating the sample along laser propagating axis during laser exposure. The dependency of microhole drilling on laser parameters including number of burst-train pulses, pulse energy, pulse duration, as well as sample scanning speed and background media (water or air) were investigated. The results have demonstrated both the benefit of the burst mode operation compared with single pulse mode, and water assisting on the depth of microholes: for example, the depth of ~780 µm by using 3-pulse burst trains and water contacting is approximately 2.6 times of that (~294 µm) by use of single pulse mode and water, while drilling in air with 3-pulse bursts resulted in ~2.6 times (~302 µm) shorter holes.

8247-25, Session 11

Comparison of picosecond and femtosecond laser ablation for surface engraving of metals and semiconductor

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Pico and femtosecond lasers present a growing interest for industrial applications such as surface structuring or thin film selective ablation. Indeed, they combine the unique capacity to process any type of material (dielectrics, semiconductors, metals) with an outstanding precision and a reduced affected zone. In this paper, we report on results about surface engraving of metals (Al, Cu, Mo, Ni), semiconductor (Si) and polymer (PC) using a picosecond thin disk Yb:YAG-amplifier, which could be used in the picosecond regime as well as in the femtosecond regime by simply changing the seed laser source. In the picosecond regime the oscillator pulses, ranging from 10 to 34ps, can be directly amplified which leads to a quite simple and efficient amplifier architecture. On the other hand, a broadband femtosecond oscillator and a CPA configuration can be used in order to obtain pulse duration down to 900fs. We compare these results to recently obtained achievements using commercial femtosecond lasers based on Yb-doped crystals and fibers and operating at comparable output power levels, up to 15Watt. Finally, we have considered etch rate and process efficiency for both ps- and fs-regimes as a function of average power, of fluence and of intensity

8247-26, Session 11

Correlating texturing, milling, and scribing of ceramics and metals using ns and fs pulsed fiber lasers

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The type of applications and the type of materials chosen for this discussion are meant address the middle-of-the-ground where neither laser dominates in performance. For example, processing of plastics, as well as stent cutting is avoided. On the other hand, texturing of ceramics or metals can be addressed by both systems, with certain advantages for both.

8247-38, Session 11

Sub-wavelength multi-period ripple phenomena on stainless steel irradiated with high repetition rate femtosecond laser pulses

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Femtosecond laser surface structuring is showing growing promise recently to transform highly reflective metal surfaces into grey-scale patterns for logo and parts labelling or into highly absorbing surfaces noted as “black metals”. Such enhanced absorption and colour rending arises from the ultrashort-pulsed laser formation of various nano- and micro-structures, including the widely observed phenomenon of laser-induced periodic surface structures (LIPSSs). Typically, the period of LIPSS structures is approximately similar with or slightly smaller than the wavelength of incident light. LIPSS is thought to arise from either the interference between the surface scattered wave and the incident wave or due to a non-uniform energy deposition. In this work, we expand on this LIPSS phenomena by controlling femtosecond laser exposure to create multi-colored metal surfaces. The colorful surfaces arise by optical interference from multi-periodic ripples generated simultaneously both on nano- and micro-scale periods and have a variety of potential applications, such as sensing, detection, embossing, and security or cosmetic marking. Polished stainless steel surfaces were irradiated with focused beams from two types of femtosecond lasers: a Ti:sapphire multi-pulse burst generator and a high-repetition rate fiber laser (IMRA America, FCPA µJewel D400-VR). A top-down approach of direct writing of grating lines was applied to generate large area colored metal surfaces with laser polarization oriented perpendicular to the scan direction for higher contrast surface grating formation. However, SEM and AFM images revealed the simultaneous formation of multiple periodic structures on wide ranging size scales: 2 to 20 µm periods that were operator controlled by the line-to-line laser scan separation; sub-wavelength LIPSSs with periods in the range of ~ 0.65 to 0.85 of the incident wavelength (= 800 nm) aligned perpendicular to the laser polarization direction; and nano-grating structures of ~70 to 100 nm that were aligned parallel to the laser polarization. The period of self-organized grating structures could be controlled from 340 to 720 nm by the pulse energy, laser wavelength, scan speed and focal positioning.

8247-39, Session 11

Structural changes of copper induced by high repetition rate femtosecond laser pulses

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High repetition rate micro machining of copper is performed with a 80-MHz femtosecond oscillator laser system and high focusing objective. Micro-grooves are machined at different fluences varying from 0.15 J/cm² to 0.36 J/cm². The number of scans necessary to perform the grooves is also studied, varying from 1 pass to 20 passes. Atomic Force Microscopy and Scanning Electronic Microscopy analyses show that structures obtained are above the surface and look like a continuous bump all along the machining. This overall of micro-machined copper is due to the experimental setup which allows to capture ablated copper. We put in evidence a relation between the laser parameters such as the number of pulses, the fluence used and the height of the structures obtained. High Resolution Transmission Electronic Microscopy puts in evidence microstructural changes occurred in copper between the grown matter and the bulk material. Depending on the analysed zones, high repetition rate femtosecond laser ablated copper exhibits nano-crystallisation and/or amorphization, to be compared with polycrystalline as-received sample. This confirms the thermal component of the femtosecond laser ablation in the case of a pure metallic sample and the highly severe quenching rate occurring in such a laser irradiation. Finally, SEM observations allow to make the hypothesis of an inter-granular propagation of the ablation intto the bulk material.

8247-40, Session 11

Femtosecond-laser-induced nanowires with very high aspect ratios at the surface fused silica

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Focused femtosecond pulses with energies of a few hundreds of nanojoules have become a key tool to modify the physical and chemical properties of materials in three dimensions. When exposed to a femtosecond pulse train focused inside the bulk, fused silica exhibits three different response regimes. At low fluence (type 1), the local refractive index (RI) change is isotropic. At intermediate fluences (type 2), the RI change is anisotropic due to the presence of “nanogratings”. At high fluence (type 3), micro-cavities with a low RI core and a high RI shell are formed.

The formation of micro-cavities is due to different processes occurring at different time scales. Within the first picosecond, photo-ionization and electron-lattice energy transfer take place. After 1 ps, thermodynamic and hydrodynamic processes start. In the third regime, the temperature and pressure conditions are such that shock waves and micro-explosions occur. When the laser is focused inside the sample close to the surface, viscous micro-jets could exit the material and solidify, resulting in the formation of nanowires.

Here we report on the formation of high aspect ratio nanowires at the surface of fused silica when a high (MHz) repetition rate femtosecond laser is focused inside the sample close to the surface. The length of these wires can be as high as hundreds of µms, while the diameter remains smaller than 1 µm, resulting in aspect ratios higher than 100. Silica nanowires of 40 nm diameter can be obtained. Phenomenological modeling is given to explain this unexpected phenomenon.

8247-27, Session 12

Probing ultrafast laser-matter interactions with fs x-rays

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Upon intense excitation with ultrashort laser pulses materials are driven into highly non-equilibrium states and can undergo structural changes on very rapid time-scales. Due to the unique combination of atomic-scale spatial and temporal resolution, the recent progress in the development of ultrafast short wavelength sources has provided new opportunities for studying such processes. This talk will discuss some examples of our recent work using ultrafast time-resolved diffraction/scattering with laser-driven as well as accelerator-based femtosecond short wavelength (XUV- and X-ray) sources.

8247-28, Session 12

Raman spectroscopy as a diagnostic means of sapphire dicing using ultrashort pulsed lasers

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Sapphire wafers are widely used for substrate in manufacturing photonic and optoelectronic devices such as light emitting diode (LED) for its good optical property and chemical robustness. Dicing sapphire wafers without defect has been a challenge as chipping and edge cracks due to mechanical dicing cause serious reduction of the emitting efficiency of LEDs. Recently, lasers became an attractive means for sapphire dicing by providing higher edge quality than diamond saws with new benefits including zero-width and chip-free dicing. However laser-induced thermal distortion of the edge leads to another degradation of LED quality. Therefore, ultrashort pulsed lasers are considered as an alternative to minimize thermal damage in LED fabrication. In order to examine the effectiveness of ultrashort pulsed laser dicing, characterization of microscopic structural changes in sapphire is necessary. In this paper, we investigate laser diced surfaces of sapphire wafers using micro-Raman spectroscopy to characterize laser-induced response in molecular scale as Raman spectroscopy is useful for probing structural changes. Systematic investigation among different laser parameters in nanosecond and sub-nanosecond regimes is presented. Micro-Raman spectra are acquired across the irradiated region therefore the strength of thermal effect is visualized in the vicinity of the laser focus. Transmission electron microscopy will be complementarity used to investigate the phase change of crystal structures.

8247-29, Session 12

Direct investigation of the ablation rate evolution during laser drilling of high aspect ratio micro-holes

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The recent development of ultrafast laser ablation technology in precision micromachining has dramatically increased the demand for reliable and real-time detection systems to characterize the material removal process. In particular, the laser percussion drilling of metals is lacking of non-invasive techniques able to monitor into the depth the spatial- and time-dependent evolution all through the ablation process. To understand the physical interaction between bulk material and high-energy light beam, accurate in-situ measurements of process parameters such as the penetration depth and the removal rate are crucial. Furthermore, various dynamic factors related to the influence of laser pulse duration and peak energy have to be instantaneously assessed to improve the ablation efficiency and finally control the laser micromachining process.

We report on direct investigations of the ablation rate evolution within the capillary carried out by implementing a contactless sensing technique based on optical feedback interferometry. High aspect ratio micro-holes were drilled onto metal targets with different thermal conductivity (i.e. stainless steel and aluminium) using 120-ps/100kHz pulses delivered by a microchip laser fiber amplifier. The probe beam was coaxially aligned with the machining laser pulses and the displacement of the ablation front was measured during the drilling time with a resolution of 0.41 µm. The time dependence of the hole penetration depth per laser pulse was provided by sampling the periodical modulations of the interferometric waveform, enabling the instantaneous detection of the ablation rate during ultrafast microdrilling experiments. Results on the material removal rate correlate well with the theoretical prediction given by Hertz-Knudsen formula.

8247-30, Session 12

Real-time automatic depth control of laser processing at kilohertz rates

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Directly observing and controlling how far a laser has penetrated into a material is a challenging task because imaging and feedback systems must be able to overcome intense backscatter, plasma emissions and stochastic melt relaxation. Depth measurements required for feedback are particularly difficult to obtain from deep geometries where triangulation is restricted and multiple reflections confuse phase-based interferometry techniques. Inline coherent imaging (ICI) is a recently developed in situ depth imaging technique based on low coherence interferometry in the Fourier domain that overcomes these challenges to provide micron-scale depth information over multi-millimetre ranges at measurement rates exceeding 300 kHz.

ICI observation and manual control for percussion drilling have been previously demonstrated to increase hole depth precision by an order of magnitude[1]. Here, we demonstrate novel capabilities of ICI on three fronts: 1) Real-time observation of keyhole depth and stability in microwelding and trench cutting; 2) Single sided breakthrough anticipation and detection for thin metal parts (e.g. silicon vias, stents, aero engine cooling); 3) Fully automatic feedback control of percussion drilling with a 4 - 21kHz average imaging rate and total feedback latency of 270 - 460 us (PC limited). Combined with the ease of integration into existing laser processing platforms, these capabilities open a wide range of applications for ICI observation and control that benefit both micro- and macro-processing industries.

[1]Webster et al., Optics Letters 35, (2010).

8247-41, Session 12

In and out of resonance plasmonics enhanced ultrafast laser nanoablation of surfaces

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Ultrafast laser interaction with gold nanostructures deposited onto a silicon surface produces considerable field amplification that can result in the ablation of features smaller than the diffraction limit. While field amplification is the main phenomenon that permits this nanoablation, energy deposition processes cannot be neglected to interpret experimental results and amplification factors obtained, and compare them with conventional ablation. Atomic Force Microscopy (AFM) and Scanning Electron Microscopy (SEM) were performed on near field enhanced laser ablated holes produced by a 120fs Ti-Sapphire laser at 800nm. Various nanostructures, including nanospheres (100, 150 and 200nm diameter) and nanorods (25x57, 25x68, 25x81, 25x126nm) in and out of plasmon resonance were used and produced holes varying in shape and depth from a few nm up to a hundred nm. The field amplification being highly localized to a region much smaller than the electron diffusion length, our simple model shows that the diffusion process control the size of the features produced and explain the difference between the calculated field amplification factor and the much lower observed ablation amplification factor. Results also present striking differences between the fluence dependence of the features produced by resonant and out of resonance nanostructures, which is explained by a difference in the charge injection process. Finally, in colloidal suspensions, nanostructures are covered by a surfactant that produces a shell around it to reduce aggregation. The effect of this shell, usually overlooked in the literature, is also studied. Effects of pulse length will also be investigated.

8247-42, Session 12

Influence of pulse duration on the hole formation during short and ultrashort pulse laser deep drilling

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We investigated the influence of the pulse duration on the laser drilling process in the femtosecond, picosecond and nanosecond regime by in-situ imaging of the hole formation in silicon for pulse energies from 25 µJ to 500 µJ. For percussion drilling, we used a Ti:Sa CPA laser system that provides pulses with a duration of 50 fs up to 10 ns at 800 nm. At this wavelength, silicon shows linear absorption and its ablation behavior is comparable to metals. The temporal evolution of the longitudinal silhouette of the hole was visualized during the drilling progress. Deep holes with a depth larger than 1 mm and aspect ratios up to 30:1 were generated. In terms of maximum achievable depth, ultrashort pulses with a duration below 5 ps show comparable efficiency for pulse energies below 100 µJ, while ns-pulses only lead to shallow depths. The situation changes for pulse energies higher than 100 µJ. The depth of holes drilled with ns-pulses increases linearly with pulse energy, while ultrashort pulses show a saturation of achievable depth, which is most distinctive for the shortest pulse duration of 50 fs. The increase in depth for ns-pulses is accompanied by an increasing in the number of pulses, which can be 10 times as much as for ultrashort pulses at the same pulse energy. The drilling process consist of an iterative sequence of forward drilling and increase of hole diameter. The increase in diameter leads to numerous deviations from a cylindrical hole shape in the form of bulges, cavities and finger-like structures. This is less pronounced for ps-pulses. Fs-pulses show the best achievable hole geometry at a tapered shape without noticeable deviations.

8247-45, Poster Session

Supercontinuum emission from water using fs pulses in the external tight focusing limit

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From the initial observation of self-channeling of high-peak power femtosecond (fs) laser pulses in air by Braun et. al. [1], propagation of intense ultrashort laser pulses in different media has become one of the most sought after research areas. Though the supercontinuum emission (SCE), a spectral manifestation of the spatio-temporal modifications undergone by a propagating ultrashort laser pulse in a nonlinear medium, has many applications, the extent of blue shift of SCE is reported to be constant due to the phenomenon of “intensity clamping” [2]. To further explore the recently observed regime of filamentation without intensity clamping [3,4], we measured the evolution of spectral blue shift of SCE resulting from the propagation of fs pulses (800 nm, 40 fs, 1 kHz) in distilled water under different focusing geometries. The efficiency of SCE from tight focusing (f/6) geometry was always higher than the loose focusing (f/12) geometry for both linear and circular polarized pulses. The λmin (blue edge of the SCE spectrum) was found to be blue shifted for f/6 focusing conditions compared to f/12 focusing geometry. The lower bound of the intensity deposited in the medium measured from the self-emission from the filament demonstrated the existence of intensities ~ 10^14 Wcm-2, far beyond the clamping intensities achieved erstwhile.

References:

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8247-47, Poster Session

Compact laser pulser for TOF SPAD rangefinder application

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Fundamental mode, ~100 ps, 40 W optical pulses are demonstrated from a laser diode with a strongly asymmetric waveguide structure and a relatively thick (~0.1 µm) active layer. A combination of low optical confinement factor (Γa<<0.1) together with a large active layer volume allows a high energy single pulse emission when the laser is operated in the gain switching regime. A simple avalanche transistor current pulsing circuit is used to produce ~15 A, ~1.5 ns injection current pulses.

The optical pulse energy is proportional to the total number of excess carriers above the threshold. Therefore, the excess density and the active layer volume must be as large as possible to obtain short high-energy pulses. However, to avoid the relaxation oscillation trail developing to get a single output pulse, the ratio of excess carrier density to the threshold carrier density must not be large. If a waveguide with a small optical confinement factor (Γa<<0.1) is used, a larger relative excess carrier density can be obtained without a trailing pulse appearing.

Using this compact laser source, pulsed time-of-flight laser rangefinding measurements were performed utilizing a single photon avalanche detector. The results show the feasibility of a very compact overall device with centimeter-level distance measurement precision and walk-error compensated accuracy to passive targets at tens to hundreds of meters in a measurement time of about ten milliseconds.

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8247-48, Poster Session

Combined time-resolved GASMAS spectroscopy for the nondestructive optical characterization of wood: application to the study of archeological Swedish ships

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The conservation and characterisation of water-logged archeological wood remains a significant challenge; few non-destructive and non-invasive techniques are available for the assessment of condition and chemical and physical properties of aged wood. There has been a limited application of optical techniques for the characterisation of the condition of archeological wood samples. However, photonic techniques have recently been proposed for the assessment of the chemical and structural properties of wood. In this work we suggest the combined use of non-destructive Time-resolved diffuse optical spectroscopy (TRS) and Gas in Scattering Media Absorption Spectroscopy (GASMAS) for the analysis of wooden samples. Due to their porous structure, both bulk material and trapped gases provide useful information about the degree of deterioration and general condition of wooden samples. TRS is particularly useful for the assessment of the absorption and scattering properties of the bulk material, while GASMAS gives an indication on the concentration of gases (water vapour and oxygen), and thus on its permeability and porosity. In this work, various hardwood and softwood samples have been studied with the combined techniques, both before and after artificial degradation. Results will be presented which highlight the physical and chemical differences between different types of wood, and the effect of degradation on the optical properties. Finally, we will report the first application of TRS and GASMAS on archeological wood coming from a 17th century waterlogged Swedish royal ship, and will suggest how photonic-based techniques can provide important information for the long-term conservation and preservation of wooden materials.

8247-49, Poster Session

Directly diode-pumped femtosecond laser based on an Yb:KYW crystal

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Ultrashort pulse laser systems are widely used in many areas such as microprocessing of various materials, the generation of terahertz radiation, nonlinear optics, medical tomography, chemistry, and biology due to the high peak power and large spectral width. For a practical usage of the femtosecond lasers, they must be fairly compact and stable. These conditions are most fully met when laser media are used that allow direct pumping with the radiation from semiconductor injection lasers, which are more compact, reliable, and inexpensive than pumping with solid-state lasers.

Since Ytterbium-doped crystals have a broad luminescence band for generating femtosecond pulses less than 500 fs wide, they are attractive as materials for lasers with direct diode pumping. Moreover, the position of the central luminescence wavelength of Yb:KGW and Yb:KYW crystals makes them promising priming sources of femtosecond pulses for amplifiers that operate at wavelengths close to 1 µm (Yb:KGW, Yb-glass, Nd-glass, Yb:YAG, etc.)

We developed a femtosecond generator based on the Yb:KYW crystal with direct pumping by the radiation of a laser diode with fiber output of the pump radiation. The use of such pumping, as well as of chirped mirrors to compensate intracavity dispersion, made it possible to generate a continuous sequence of optical pulses 90 fs wide at a frequency of 87.8 MHz with a mean radiation power of more than 1 W. The product of the pulse width by the spectral width is close to the theoretical limit, and this indicates that there is no frequency modulation.

8247-50, Poster Session

Development of an automatics joint-area-measurement system after ultrafast laser microwelding

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The present study is undertaken in order to develop an automatic measurement system for light transmissibility of jointed transparent materials using high-repetition-rate ultrafast laser microwelding. To measure joint strength, it is necessary to measure the tensile strength and joint area quantitatively. Especially, the joint area greatly influences joint strength in the microwelding. Thus, it is important to distinguish the joint part and non-joint part. The welded sample was irradiated by LED (light-emitting diode) light, and the light, which passed through the welded sample, was detected by a photo detector. The transmitted light has two intensity levels because the transmissibly for the light of light is different in the joint part and non-joint part of the welded sample. Wherein, the joint part and non-joint part are classified by irradiating the light of LED to the sample, and detecting the transmitted light. This technique is also applied to determine the accurate joint part after welding using various shapes such as spiral and rectangular, the relationship between joint strength and shapes will be presented.