SPIE

2013 LASE

SPIE Photonics West

2–7 February 2013

Technical Summaries

www.spie.org/pw

Conferences & Courses
2–7 February 2013

Exhibition
BiOS Expo: 2–3 February 2013
Photonics West: 5–7 February 2013

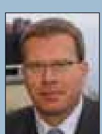
Location
The Moscone Center
San Francisco, California, USA

LASE

SPIE Photonics West

Symposium Chairs

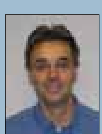
Bo Gu
Bos Photonics (USA)



Andreas Tünnermann,
Friedrich-Schiller-Univ. Jena (Germany)

Symposium Cochairs

Friedhelm Dorsch
TRUMPF Werkzeugmaschinen GmbH + Co. KG (Germany)



Alberto Piqué
U.S. Naval Research Lab. (USA)

Contents

Click on the Conference Title to be sent to that page

Conference 8599: Solid State Lasers XXII: Technology and Devices

Sunday - Tuesday 3 –5 February 2013

Part of Proceedings of SPIE Vol. 8599 Solid State Lasers XXII: Technology and Devices

8599-1, Session 1

Fluoride waveguide lasers grown by liquid phase epitaxy *(Invited Paper)*

Patrice Camy, Florent Starecki, Western Bolaños, Jean-Louis Doualan, Alain Braud, Richard Moncorgé, Ecole Nationale Supérieure d'Ingenieurs de Caen et Ctr. de Recherche (France)

High optical quality rare-earth-doped $YLiF_4$ layers were grown by liquid phase epitaxy (LPE). As a first result, continuous wave laser operation was demonstrated around 1.9 µm in a LPE Tm^{3+} doped $YLiF_4$ (Tm:YLF) planar waveguide. Internal propagation losses of the Tm:YLF waveguides were found equal to 0.11 dB/cm and spectroscopic characteristics comparable to bulk crystals. The laser cavity was formed by butting the input and output coupler mirrors at the end-facets of a 6 mm long sample with an index matching gel. The spatial distribution of the pump beam at the output of the waveguide, as measured with a CCD camera, was found elliptical with 10µm in the vertical direction and about 300 µm in the horizontal one. With a 30% output coupler, the 10 µm thick Tm:YLF waveguide laser delivered a maximum power of 560mW at 1.87 µm by pumping with a Ti:Sapphire laser at 780 nm, leading to an efficiency of 76 % with respect to the absorbed pump power. Laser emission (single line) was found to be ? polarized and centered at 1.877 µm with a FWHM of 4 nm. Given the thickness of the waveguide (10 ?m) and the refractive index of the substrate at 780 nm (1.473), the corresponding refractive index contrast was estimated to be at least 1.1?10-3, and the mode guidance conditions calculations give a single mode propagation at the laser wavelength. Other laser results based on other doping ions and fluoride hosts were also obtained and will be presented at the conference.

8599-2, Session 1

Highly efficient channel waveguide lasers at 1 µm and 2 µm in refractive-index-engineered potassium double tungstates

Koop Van Dalfsen, Dimitri Geskus, Sonia M. García-Blanco, Markus Pollnau, Univ. Twente (Netherlands)

Epitaxial growth of rare-earth-ion-activated $KY_{1-x-y}Gd_xLu_y(WO_4)_2$ co-doped thin layers onto $KY(WO_4)_2$ substrates has enabled lattice-matched waveguides with high refractive-index contract and large variation of the active rare-earth-ion concentration. In Yb^{3+}-activated micro-structured channel waveguides, we demonstrated lasers with 418 mW of continuous-wave output power at 1023 nm and a slope efficiency of 71% versus launched pump power at 981 nm. Channel waveguide lasers operating on the 981-nm zero-phonon line were demonstrated under pumping at 934 nm with an output power of 650 mW and a slope efficiency of 76% versus absorbed pump power. Lasing with a record-low quantum defect of 0.7% was achieved. In a feasibility study, a device comprising a tapered active channel waveguide and a passive planar pump waveguide, fabricated by multi-layer growth of lattice-matched layers, was demonstrated as a laser by diode-side pumping with a high-power, multi-mode diode bar. This approach offers the potential for significantly increased output powers from channel waveguide lasers. Tm^{3+}-activated channel waveguide lasers demonstrated a maximum output power of 300 mW and slope efficiency of 70%, when pumping near 800 nm. Lasing was obtained at various wavelengths between 1810 nm and 2037 nm. These lasers were operated with resonators exploiting either butt-coupled mirrors, providing only a non-permanent solution, or based on Fresnel reflection at the waveguide end-facets, resulting in laser emission from both waveguide ends and without control of the laser wavelength. Currently we are inscribing Bragg gratings into the top cladding to provide a stable resonator configuration that allows for effective wavelength selection.

8599-3, Session 1

2-µm waveguide lasers in monoclinic double tungstates *(Invited Paper)*

Joan J. Carvajal Marti, Carla J. Berrospe, Xavier Mateos, Maria Cinta Pujol, Magdalena Aguilò Diaz, Francesc Díaz, Univ. Rovira i Virgili (Spain)

No Abstract Available

8599-4, Session 1

Low-threshold, mirrorless emission at 981 nm in an Yb,Gd,Lu:KYW inverted rib waveguide laser

Amol Choudhary, Univ. of Southampton (United Kingdom); Western Bolaños, Ecole Nationale Supérieure d'Ingenieurs de Caen et Ctr. de Recherche (France); Pradeesh Kannan, Univ. of Southampton (United Kingdom); Joan J. Carvajal Marti, Magdalena Aguilò Diaz, Francesc Diaz, Univ. Rovira i Virgili (Spain); David P. Shepherd, Univ. of Southampton (United Kingdom)

Ytterbium-doped double tungstate media are traditionally operated as quasi-3-level laser media and have been extensively used to demonstrate efficient and low threshold lasers operating around 1040 nm. However, there have been very few reports of pure 3-level laser operation, i.e. operation at 981 nm. A Yb,Gd,Lu:KYW planar waveguide laser with threshold of 75 mW has been reported recently. In this work, we fabricated "inverted" rib waveguide lasers by etching 5 micron into a KYW substrate by ion beam milling with inert Ar^+ ions and then growing an active layer of Yb,Gd,Lu:KYW by liquid phase epitaxy followed by the growth of a 10 micron cladding layer of KYW. The waveguide was trapezoidal with a width of 25 micron at the top and 4.5 micron at the bottom. This waveguide was pumped by a Ti:sapphire laser at 932 nm and laser emission was observed at 981 nm with an absorbed threshold power of 23 mW and a slope efficiency of 58% without the use of any mirrors giving a quantum efficiency of 95%. With an HR/6% cavity, the threshold was reduced to as low as 13 mW. Due to a trapezoidal rib feature, the mode was found to be slightly asymmetric with mode radii of 4.8 micron and 3 micron in the x and y direction respectively which has a good correlation with the theoretical simulation. Laser emission was also observed at 999.8 nm with a threshold of 8 mW by using mirrors designed for 999.8nm and forming an HR/5% cavity.

8599-5, Session 2

Advances in visible and near-infrared fs-laser-written waveguide lasers *(Invited Paper)*

Sebastian Müller, Thomas Calmano, Fabian Reichert, Matthias Fechner, Günter Huber, Univ. Hamburg (Germany)

We report on visible and near-infrared laser emission of fs-laser-written waveguide lasers. The waveguiding structures were fabricated with a low repetition rate CPA fs-laser (Ti:Sapphire) in bulk crystalline oxide and fluoride host materials. We produced double track modifications in Nd:YAG, Yb:YAG, and $Pr:SrAl_{12}O_{19}$ and achieved polarization dependent low loss waveguiding. All fabricated waveguides in YAG had losses below 1.2 dB/cm. The $Pr:SrAl_{12}O_{19}$ waveguide losses were measured to be as low as 0.2 dB/cm. The waveguides supported single mode guiding with mode diameters of about 15 ìm and numerical apertures of 0.06 at a wavelength of 633 nm.

Laser operation in the infrared region at about 1 ìm has been demonstrated in Nd:YAG and Yb:YAG. Slope efficiencies of up to 75% and output powers of more than 2.2 W could be achieved (Yb:YAG). By pumping with a multimode blue emitting InGaN laser diode with an output power of 1 W visible laser operation in Pr:SrAl12O19 at 623 nm and 644 nm with output powers of 62 mW and 91 mW was achieved. Furthermore, dual wavelength and switchable laser operation between these two wavelengths were demonstrated by applying an adapted resonator setup. In Pr:LiYF4 waveguides were fabricated with a rhombic cladding of tracks around an unmodified core. Visible laser radiation in the orange and deep red region was obtained. Maximum output powers of 25 mW (604 nm) and 12 mW (720 nm) have been achieved.

8599-6, Session 2

Versatile fs laser-written ZBLAN chip lasers *(Invited Paper)*

David G. Lancaster, The Univ. of Adelaide (Australia); Simon Gross, Alexander Fuerbach, Macquarie Univ. (Australia); Heike Ebendorff-Heidepriem, Tanya M. Monro, The Univ. of Adelaide (Australia); Michael J. Withford, Macquarie Univ. (Australia)

We report on laser-written waveguide ‘chip’ lasers with potential to be a platform planar technology versatile enough to cover the visible through to the mid-infrared spectral region.

The first part of this talk covers fabrication and characteristics of femtosecond laser-written thulium doped ZBLAN glass channel waveguide lasers. The 9 mm long planar chip lasers we have developed for concept demonstration contain fifteen large mode-area waveguides that can operate in semi-monolithic or external cavity laser configurations. Results to date using 790nm pumping include operation with a 156% quantum efficiency ?=1.9 ?m wavelength and close to diffraction limited beam quality laser (M2~ 1.12 ± 0.08). Using a Littrow configured cavity they can be tuned continuously over 225 nm. The depressed cladding geometry supports the largest fundamental modes reported for a rare-earth doped waveguide laser, thereby favouring high peak-power operation. The advantages of these large modes is demonstrated by achieving 1.9 kW peak-power pulses when Q-switched.

The second part of this talk is an overview of further work towards increasing the versatility of these chip lasers. For instance we have demonstrated a thulium sensitised, holmium doped laser that operates at ?=2052nm with a 20% slope efficiency. We have also achieved progress towards demonstrating a distributed feedback monolithic laser by directly fs laser writing a Bragg grating structure with a 10.5 dB transmission dip within the depressed cladding structure. The Bragg structure is made up of a hexagonal lattice of smaller point features.

8599-7, Session 2

Er-doped planar waveguides for power amplifier applications

J. I. Mackenzie, G. S. Murugan, Univ. of Southampton (United Kingdom); A. W. Yu, J. B. Abshire, NASA Goddard Space Flight Ctr. (United States)

Place holder submission – thin films are currently being fabricated, and results expected soon.

New devices are required to provide effective tools for DIAL or LIDAR measurements from space that will enable improved mapping of the concentration and distribution of CO2 in our atmosphere. In this presentation we present characteristics of Er-doped thin film waveguides, with an extended gain bandwidth, which are applicable to planar waveguide power amplifiers for wavelengths around the 1572nm CO2 absorption peaks.

Planar waveguide films fabricated using RF magnetron sputtering of fluoro-phosphate and tellurite based glasses, deposited onto oxidised silicon wafers, and their properties characterized. The deposition parameters for undoped and Er,Yb-doped films have been assessed and optimized to achieve low loss [and high gain]. A comparison between the two host materials is made and the projected performance discussed.

8599-8, Session 2

Rare-earth-ion-doped ultra-narrow-linewidth lasers on a silicon chip and applications to intra-laser-cavity optical sensing

Edward H. Bernhardi, René M. de Ridder, Kerstin Wörhoff, Markus Pollnau, Univ. Twente (Netherlands)

We report on diode-pumped distributed-feedback (DFB) and distributed-Bragg-reflector (DBR) channel waveguide lasers in Er-doped and Yb-doped Al2O3 on standard thermally oxidized silicon substrates. Uniform surface-relief Bragg gratings were patterned by laser-interference lithography and etched into the SiO2 top cladding. The maximum grating reflectivity exceeded 99%. Monolithic DFB and DBR cavities with Q-factors of up to 1.35?~106 were realized. The Er-doped DFB laser delivered 3 mW of output power with a slope efficiency of 41% versus absorbed pump power. Single-longitudinal-mode operation at a wavelength of 1545.2 nm was achieved with an emission line width of 1.70 ?} 0.58 kHz, corresponding to a laser Q-factor of 1.14?~1011. Yb-doped DFB and DBR lasers were demonstrated at wavelengths near 1020 nm with output powers of 55 mW and a slope efficiency of 67% versus launched pump power.

An Yb-doped dual-wavelength laser was achieved based on the optical resonances induced by two local phase shifts in the DFB structure. A stable microwave signal at ~15 GHz with a .3-dB width of 9 kHz and a long-term frequency stability of ?}2.5 MHz was created via the heterodyne photo-detection of the two laser wavelengths. By measuring changes in the microwave beat signal as the intra-cavity evanescent laser field interacts with micro-particles on the waveguide surface, we achieved real-time detection and accurate size measurement of single micro-particles with diameters ranging between 1 ƒÊm and 20 ƒÊm, which represents the typical size of many fungal and bacterial pathogens. A limit of detection of ~500 nm was deduced.

8599-9, Session 2

Single-crystalline rare-earth-doped In_2O_3 waveguides epitaxially grown on Lu_2O_3

Sebastian Heinrich, S. H. Wäselmann, Christian Kränkel, Günter Huber, Univ. Hamburg (Germany)

The refractive index of crystalline In2O3 (3.2 at 413 nm) makes this material promising for waveguides with high numerical aperture. Rare earth (RE) ions are widely used dopants in solid state laser crystals and can deliver high laser efficiencies. Therefore RE-doped single-crystalline In2O3 films have been grown with the pulsed-laser-deposition method (PLD). The deposition took place in an ultrahigh vacuum chamber (P = 5•10-8 mbar) at an oxygen atmosphere of about 1•10-3 mbar. The used targets were pressed from powders with purities of at least 99.99% and sintered at 600 °C for 80 h to increase the target density. In2O3 targets doped with either neodymium or ytterbium have been prepared. Since both, In2O3 and Lu2O3 exhibit the bixbyite crystal structure and the difference in lattice constants is only 2.31 %, Lu2O3 was chosen as substrate material in {111}- and {100}-orientation. All Lu2O3 substrates were annealed prior to deposition to reduce defects on the epitaxial-grade polished surfaces. During film growth the substrate was heated with seven fiber coupled 20 W laser diodes to temperatures of up to 650 °C. For ablation a KrF excimer laser with a wavelength of 248 nm and a pulse width of 20 ns was focused (? ≈ 2.3 J/cm2) onto the surface of the target. Structural analyses with a reflection high-energy-electron diffraction system and by X-ray diffraction as well as spectroscopic analyses indicate an epitaxial growth of rare-earth-doped In2O3 thin films. Furthermore, planar waveguiding has been demonstrated in 2µm thick crystalline Nd:In2O3 thin films.

8599-10, Session 3

High-energy, kHz-rate, picosecond, 2-µm laser pump source for mid-IR nonlinear optical devices

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

High-energy, high-repetition-rate, picosecond, still compact, laser sources are of critical importance to the development of short-pulse mid-IR nonlinear optical devices. In part this interest is driven by successful implementation of femtosecond, 3-4-um optical parametric chirped pulse amplifiers (OPCPAs) for high harmonic generation.

2-um Ho-laser technology can provide efficient pump sources for such mid-IR OPA/OPCPAs. The emission bandwidth of Ho-laser materials supports generation of sub-ps pulses. Another advantage of Ho-doped materials is high gain, allowing efficient single- or multi-pass amplification as well as the use of regenerative-amplifier schemes. Also Ho-laser materials have high damage threshold and were used to generate >100W average power/>100 mJ pulse energy near 2 um.

Our overall goal is to develop a >50 mJ-pulse energy, ~ 1-5 kHz-rate, 2.05-um laser system which is based on singly-doped Ho:YLF laser media. Here we describe the development of the front end of such laser system based on master oscillator/regenerative amplifier combination.

The master oscillator is a cw-pumped, actively mode-locked Ho:YLF laser operating at 82 MHz rate and producing ps pulses with up to >10 nJ energy. The regenerative amplifier reduces the pulse rate to 1-5 kHz and scales the pulse energy to >1.5 mJ.

To the best of our knowledge this is the first demonstration of a 2-um laser source based on a Ho:YLF mode-locked oscillator/regenerative amplifier combination to produce picosecond pulse train at 1-5 kHz rate with up to 1.5 mJ pulse energy. Further scaling to >10 mJ pulse energy can be achieved in subsequent single-pass amplifier stage (s).

8599-11, Session 3

A broadly tunable continuous-wave iron-doped zinc selenide laser

Jonathan W. Evans, Patrick A. Berry, Kenneth L. Schepler, Air Force Research Lab. (United States)

Sources of Mid-IR laser radiation operating in the atmospheric transmission window from 3-5 microns enable long-range laser-driven technologies including active chemical sensing, optical communications, and other military applications as well as scientific and medical use at close distances. In contrast to the visible region of the spectrum, relatively few sources are available in the Mid-IR region. Thus, an ideal source would be wavelength tunable across the whole band and pulse agile without sacrificing total output power. Iron-doped zinc selenide has fluorescence bandwidth from 3700-4600 nm and thus represents an ideal candidate for a robust source of Mid-IR laser radiation. Its large fluorescence bandwidth gives it the potential to be operated in a mode-locked configuration. It has been demonstrated in both gain-switched and continuous-wave regimes and promises to match the power scaling potential of chromium-doped zinc selenide to multiple watts of output power.

We report a continuous-wave laser in Fe2+:ZnSe (polycrystalline) free-running at ~4.2 microns with greater than 800 mW output. This is a four-fold increase in power over the most recently published maximum of output power. A slope efficiency of ?≈45% was achieved using a concentric linear cavity. The performance of the laser was pump limited with >50% of the pump discarded by non-optimal incoupling optics. Improved coupling thus promises to deliver >1Watt of tunable output power. The beam quality was measured to be M2<1.2. We also demonstrate continuous tuning of this source using a blazed grating in the Littrow configuration.

8599-12, Session 3

Gain-switched single-pass Cr:ZnSe amplifier

Sean A. McDaniel, Univ. of Dayton (United States); Patrick A. Berry, Kenneth L. Schepler, Air Force Research Lab. (United States); Peter E. Powers, Univ. of Dayton (United States)

Chromium-doped ZnSe (Cr:ZnSe) is a highly robust, versatile laser source operating in the 2-3 ?m range. However, operation of a cavity with high-pulse energy has an associated risk of damage to optical components and coatings. A seeded, gain-switched amplifier removes most of the sensitive elements from high incident pulse energy, theoretically allowing for high pulse energies to be extracted from the amplifier. In this paper, we report on building and testing of a seeded Cr:ZnSe gain switched amplifier pumped by a Q-switched Ho:YAG and seeded by a CW Cr:ZnSe laser. In this experiment we used a 0.5%-doped, Brewster-cut Ho:YAG rod in an actively Q-switched, folded cavity producing pump pulses at 2.09 ?m with pulse widths on the order of 400 ns and pulse energies of 320 ?J at a 10 kHz repetition rate. These pulses were then used to gain-switch a Cr:ZnSe single-pass pulsed amplifier seeded with a CW Cr:ZnSe laser. The CW Cr:ZnSe laser had a free-running wavelength of 2.45 ?m and a spectral linewidth of 50 nm. The seeded Cr:ZnSe amplifier exhibited output pulse energy as high as 3.8 ?J at 2.45 ?m while pulsed with the Ho:YAG laser. The gain-switched process demonstrated in this experiment shows a peak gain greater than 300 and an extraction efficiency of 1.5%.

8599-13, Session 3

Fe:ZnSe laser oscillation under cryogenic and room temperature

Helena Jelínková, Czech Technical Univ. in Prague (Czech Republic); Maxim E. Doroshenko, A. M. Prokhorov General Physics Institute (Russian Federation); Michal Jelínek M.D., David Vyhlídal M.D., Jan Sulc, Michal Nemec, Václav Kubecek, Czech Technical Univ. in Prague (Czech Republic); Yuri A. Zagoruiko, Nazar O. Kovalenko, Andriy S. Gerasimenko, Vyacheslav M. Puzikov, Vitaliy K. Komar, Institute for Single Crystals (Ukraine)

The goal of this work was to design and investigate a bulk Bridgman-grown Fe:ZnSe laser operating at room (RT) and cryogenic (down to liquid nitrogen - LN) temperature. Pumping was provided by a Q-switched or free-running (FR) Er:YAG laser at the wavelength of 2.94 um. Q-switched operation was achieved by the Brewster angle cut LiNbO3 Pockels cell placed between the rear mirror and the Er:YAG laser active medium. Parameters of the pump radiation incident on the Fe:ZnSe crystal face were following: FR regime: 24 mJ in 160 us long pulse; Q–switched regime: 5 mJ in 300 ns pulse; repetition rate 1 Hz. The pump radiation was directed into the Fe:ZnSe crystal placed inside the LN dewar. The 55 mm long hemi-spherical cavity was formed by a dichroic pumping mirror (T = 78 % @ 2.94 um and R = 100% @ 4.5 um) and a concave output coupler (R = 95 % @ 4.5 um, r = 500 mm). Fe:ZnSe laser operation under FR pumping was reached at the active medium temperature below -150°C. The maximum output Fe:ZnSe laser energy was 750 uJ at FR pumping at the LN temperature, and 100 uJ at Q-switched pumping at RT in same resonator. Central emission wavelength at RT was 4.45 um with the spectral line-width of ~100 nm. Fluorescence spectra and lifetime of Fe:ZnSe in the range from RT down to LN temperature were measured and the results were compared with the same data obtained for novel bulk Fe,Cr:ZnMgSe laser material.

8599-14, Session 3

Ho:YAG (2.09 µm) MOPA-system pumped by cw thulium fiber laser (1.9 µm) with >120-mJ pulse energy at 100-Hz repetition rate

Karsten Schmidt, Christoph Reiter, Heike Voss, Frank Massmann, Martin D. Ostermeyer, IBL Innovative Berlin Laser GmbH (Germany)

Ho:YAG as laser material provides one possibility to realize a mid IR source at 2.09 µm. Furthermore o-lasers resonantly pumped by 1.9 µm with Tm-Lasers are attractive candidates for pumping mid-infrared optical parametric oscillator and generator materials to emit coherent light in the 3 µm to 5 µm spectral range. At 1.908 µm there is a maximum in the absorption spectrum of the Ho3+ Ions and a minimum in the absorption spectrum of water. Pumping near the emission wavelength yields high quantum efficiency and small thermal load of the laser active material. Thulium fiber lasers used as pump sources were additionally equipped with beam profile homogenizers to realize appropriate excitation profiles in the 3-level Ho:YAG-laser rods.

The laser system is realized as master-oscillator power-amplifier system (MOPA). The oscillator and amplifier rods are pumped by cw thulium fiber lasers with 50W and 70W respectively. There is a 15 % loss of pump radiation due to the homogenizer. Pump power from the Tm-laser transmitted through the oscillator rod, is back reflected to the rod to increase the pump efficiency. The amplifier is realized as a polarization coupled double pass ring. At a repetition rate of 100 Hz a maximum pulse energy of 125 mJ is realized. At this repetition rate the oscillator reaches a maximum output energy of 53 mJ with 20 ns pulse width. Scaling to higher pulse energies can be reached by additional amplifier stages.

8599-15, Session 3

Efficient Er:YAG lasers at 1645.55 nm, resonantly pumped with narrow bandwidth diode laser modules at 1532 nm, for methane detection

Haro Fritsche, Oliver Lux, Technische Univ. Berlin (Germany); Bastian Kruschke, DirectPhotonics Industries GmbH (Germany); Casey Schütt, Technische Univ. Berlin (Germany); Stefan Heinemann, Wolfgang Gries, DirectPhotonics Industries GmbH (Germany); Hans Joachim Eichler, Technische Univ. Berlin (Germany)

Resonant pumping of Er:YAG is rapidly emerging as one promising way to generate high power room temperature lasers operating around 1.6 µm. The resonant pumping process of Er:YAG involves pump sources emitting at 1455 nm, 1470 nm or 1532 nm wavelength. Apart from fiber lasers, high brightness diode lasers are suitable in order to realize Er:YAG lasers with high quantum efficiency.

Following this approach, we developed cw as well as Q-switched Er:YAG lasers pumped by fiber-coupled, wavelength-stabilized diode laser modules provided by DirectPhotonics. The high power pump modules feature narrowband emission at 1532 nm with a linewidth of only 0.18 nm. This allows for an absorption efficiency of up to 96%. At a pump power of 30 W the cw output power of the Er:YAG laser accounts for 9 W, corresponding to an overall efficiency of 30%. Utilization of a Pockels cell enables pulsed operation at a repetition rate of 500 Hz with pulse energy of about 9 mJ and pulse duration of 140 ns. Due to the high wavelength stability of the pump lasers, the free-running Er:YAG laser shows stable operation at 1645.55 nm with long-term fluctuations of less than 50 MHz while wavelength tuning can be obtained by employing intra-cavity etalons. The developed Er:YAG laser were applied for methane absorption measurements using a multi-pass absorption cell. Good agreement of the experimental results with theoretical simulations of the absorption characteristics demonstrated the potential of the developed Er:YAG lasers in terms of methane detection at low and high gas pressures.

8599-16, Session 3

Simulations and experiments on resonantly pumped single-frequency Erbium lasers at 1.6 µm

Ansgar Meissner, Jan Philipp Kucirek, Fraunhofer-Institut für Lasertechnik (Germany); SuHui Yang, Jing Li, Beijing Institute of Technology (China); Hans-Dieter Hoffmann, Fraunhofer-Institut für Lasertechnik (Germany)

Single-frequency laser pulses at 1645.2 nm (air) can be used to detect CH4 in the atmosphere with LIDAR methods. Erbium-doped laser crystals provide gain in this wavelength regime and are thus an alternative to non-linear frequency converters for this purpose. The crystals can be resonantly pumped at around 1532 nm with a small quantum defect.

An Erbium-doped YAG/LuAG mixed garnet crystal with the emission peak compositionally tuned to 1645.2 nm has been developed by the University of Hamburg.

With this crystal, a Q-switched laser oscillator was set up. When pumped with 7.5 W from single-mode fiber lasers at 1532 nm, pulses with 3.3 mJ and 90 ns at 100 Hz are measured. For single-frequency mode of operation, the Ramp-and-Fire technique is used and pulses with 2.3 mJ and 90 ns are observed. Efficiency scaling by increasing pump power and modifying the resonator design is currently under investigation.

As a comparison, fiber-coupled laser diode modules are used for pumping a thin barrel-polished laser rod as the gain medium. A pulse energy of 2.2 mJ at 100 Hz is achieved from 15 W of absorbed pump power. Work on this setup is on-going.

A simulation model for resonantly-pumped Q-switched lasers with Erbium-doped crystals has been developed. In this model, the absorbed pump light distribution is computed in two dimensions, time-resolved saturation of the pump light absorption by ground-level depletion is included and the rate-equations for the laser emission process are spectrally resolved. Results from the experiments are compared with the model predictions.

8599-17, Session 4

Coherent polarization locking of Q-switched Ho:YAG laser

Chern Fei Chua, Li Hao Tan, Poh Boon Phua, Nanyang Technological Univ. (Singapore)

Generating high energy laser pulse is often limited by optical damages in the laser cavity. Ho:YAG laser is a quasi-three-level laser system, thus its laser performance is sensitive to thermal issues. In this experiment, we used Coherent Polarization Locking (CPL) to mitigate the optical damage and thermal issues in high energy and high power Q-switch Ho:YAG lasers.

A single Tm:Fiber laser was split to pump two Ho:YAG laser rods. This lowers the amount of heat absorbed for each rod. The emissions from these two orthogonal polarized Ho:YAG arms were coherently combined in a common cavity arm. A pockel cell was placed in one of the polarized arms for Q-switching operation. We demonstrated that by Q-switching just one polarized arm, it results in pulse operation for the entire CPL cavity. This shows that passive coherent locking mechanism is fast enough to autonomously phase-locked two orthogonal polarizations in ns regime. Diffraction limited beam (M2 ~1.07) was generated with 9.13mJ pulse energy and 14ns pulse width, operating at 800Hz.

In CPL cavity, each polarized arm experiences half of the intracavity intensity of the common arm. For optical components with low damage threshold, we alleviate optical damage by placing them in one of the polarized arm. For comparison, we built a Q-switched Ho:YAG laser with same pump power and cavity mode. We observed optical damage that limit the output pulse energy to <5mJ. This shows that CPL cavity had successfully scaled the output energy by two times without imposing any optical damage.

8599-18, Session 4

Doped sesquioxide ceramic for eye-safe solid state laser materials

Woohong Kim, Colin Baker, U.S. Naval Research Lab. (United States); Catalin Florea, Sotera Defense Solutions, Inc. (United States); Guillermo R. Villalobos, Brandon Shaw, Steven R. Bowman, Shawn P. O'Connor, U.S. Naval Research Lab. (United States); Bryan Sadowski, Sotera Defense Solutions, Inc. (United States); Michael Hunt, Univ. Research Foundation (United States); Ishwar Aggalwar, Sotera Defense Solutions, Inc. (United States); Jasbinder Sanghera, U.S. Naval Research Lab. (United States)

Sesquioxides are very promising host materials for high-power laser applications, mainly due to their high thermal conductivity and the high absorption and emission cross-sections of trivalent rare-earth ions when doped in these materials. In fact, we have demonstrated a record efficiency of 74% in 10%Yb-doped sesquioxide ceramic laser materials. [1,2] Trivalent holmium has 14 laser channels from 0.55 to 3.9 µm. The laser emission of most interest is the transition 5I7?5I8 near 2 µm because of its potential for use in eye-safe systems and medical applications. We have fabricated high optical quality Ho3+:Lu2O3 ceramic using nano-powders synthesized by a co-precipitation method in various doping concentrations. In this paper, we present our recent results in the development of Ho3+ doped sesquioxides for eye-safe solid state lasers. The optical, spectral and morphological properties as well as the lasing performance from highly transparent ceramics are presented.

1. J. Sanghera, J. Frantz, W. Kim, G. Villalobos, C. Baker, B. Shaw, B. Sadowski, M. Hunt, F. Miklos and I. Aggarwal "10% Yb3+-Lu2O3 ceramic laser with 74% efficiency," Optics Letters, 36 576 (2011).

2. W. Kim, C. Baker, G. Villalobos, J. Frantz, B. Shaw, A. Lutz, B. Sadowski, F. Kung, M. Hunt, J. Sanghera, and I. Aggarwal, "Synthesis of High Purity Yb3+-Doped Lu2O3 Powder for High Power Solid-State Lasers", J.Am.Cer.Soc., 94 3001 (2011).

8599-20, Session 4

Supercontinuum generation in mid-IR using chalcogenide and germanate nonlinear fibers

Nikolai Tolstik, Norwegian Univ. of Science and Technology (Norway); Vladimir L. Kalashnikov, Evgeni Sorokin, Technische Univ. Wien (Austria); Dmitriy Klimentov, Vladislav Dvoyrin, Irina T. Sorokina, Norwegian Univ. of Science and Technology (Norway)

We demonstrate high quality coherent supercontinuum generation from 2 to 2.8 ?m in nonlinear chalcogenide fiber using femtosecond mid-IR pulses directly from the oscillator, and compare it with supercontinuum generated in germanate fibers.

The presently used for supercontinuum generation laser systems require either complex multistage nonlinear optical conversion or/and amplification as well as microstructured PCF fibers.

Using femtosecond pulses directly from an oscillator and a simple step-index single-mode fiber have an advantage of generation of coherent supercontinuum, required for such applications as metrology or high-sensitivity spectroscopy. Such continuum has not yet been demonstrated in the mid-IR before due to the absence of femtosecond sources.

In this work we demonstrate supercontinuum in a conventional (not PCF) step-index chalcogenide fiber, using a recently developed source of high power femtosecond pulses based on Cr:ZnS laser – a high power alternative to Cr:ZnSe, and compare it with the results using germanate fiber. A good coherency of the spectral components makes it useful for numerous applications, in particular for OCT and high-resolution spectroscopy. The OCT is particularly interesting since the tissue scattering drastically decreases with allowing for deeper tissue penetration in the water free 2-2.3 ?m region. On the other hand the wavelengthrange of 2.5-3 ?m is characterized by the increased water absorption of tissue, allowing for using the differential absorption OCT methods for early identification of the cancerous cells.

Summarizing, this is the first demonstration of the high quality coherent mid-IR supercontinuum. Optimisation of the focusing optics and thus increasing of the launched pulse energy from 1 to 3 nJ will further allow generation of over one octave coherent spectrum, well over 3 ?m.

8599-21, Session 5

Design of a rugged 308-nm tunable UV laser for airborne LIF measurements on top of a zeppelin

Michael Strotkamp, Bernd Jungbluth, Alexander Munk, Fraunhofer-Institut für Lasertechnik (Germany)

In this work a detailed analysis and redesign of a tunable UV laser for the airborne LIF measurements of the OH-radical concentration is presented. Since the laser is positioned on top of a zeppelin, it is exposed to temperatures ranging from 10 to 40 °C and outer pressures from 800 to 1000 hPa. In former flights the output power of an existing laser decreased rapidly during the flights and no measurement was possible.

The design concept of the laser comprises a frequency doubled Nd:YAG laser as pump source, a dye as active medium to emit light at 616 nm and a BBO crystal as intracavity frequency doubler. The output wavelength is tunable by a combination of dispersion prisms and an etalon.

The analysis of the existing laser combines theoretical study of tolerancing requirements with experimental testing of opto-mechanical components and of the entire laser system in a climatic chamber. The performance of the laser is measured over the expected temperature range. It is shown that changing the baseplate temperature by few Kelvin stops laser emission completely. The optical mounts that are used in the laser and worthwhile alternatives were tested separately in the climatic chamber. The stability of the best mounts exceeds those currently used by a factor of 50.

A new laser has been built based on the results of the analysis and further experiments for an optical redesign. This laser is currently on a field campaign for several weeks and has been working reliably.

8599-22, Session 5

Improved design of a pulsed UV laser source for application in space

Christian Kolleck, Alexander Büettner, Mathias Ernst, Michael Hunnekuhl, Thomas Hüelsenbusch, Anas Moalem, Marc Priehs, Dietmar Kracht, Jörg Neumann, Laser Zentrum Hannover e.V. (Germany)

The main scientific objective of the ExoMars rover mission of ESA and international partners is to search for organic molecules as possible signs for past or present life on Mars. The MOMA instrument (Mars Organic Molecule Analyzer) comprises a laser-desorption mass spectrometer for the analysis of large non-volatile molecules on Mars' surface. The excitation source for this instrument is a nanosecond UV laser with a wavelength of 266 nm and a pulse energy of about 250 µJ in bursts of up to 50 shots at 100 Hz. The realization of the laser head is a diode-pumped, passively q-switched Nd:YAG oscillator with two external second harmonic generation crystals. Compact prototypes were already developed in order to demonstrate the feasibility of the technology and also several of the space requirements.

An engineering qualification model of the laser head is being developed, the advancement of which is presented. The improved design deals with all space and laser issues to be considered for a long maintenance-free lifetime in a harsh environment. Cleanliness, ruggedness, compactness,

damage thresholds, and hardness to UV and ionizing radiation belong to the most important aspects. Besides the stability with respect to mechanical and thermal loads, the optical and mechanical design must ensure abrasive- and particle-free assembly and operation of the laser. Minimized use of organic materials and careful selection of components reduces the risk of molecular contamination on optical surfaces. Hermetical sealing processes keep gaseous atmosphere inside the laser head in order to prevent laser-induced contamination.

8599-23, Session 5

Space-based multi-wavelength solid state lasers for NASA's ISS CATS application

Ti Chuang, Patrick Burns, E. Brooke Walters, Ted Wysocki, Tim Deely, Andy Losse, Khoa Le, Bill Drumheller, Tom Schum, Mark Hart, Kent Puffenburger, Bill Ziegler, Floyd E. Hovis, Fibertek, Inc. (United States)

Fibertek has built two space-based lasers for NASA ISS CATS (Cloud Aerosol Transport System project) application. The application requires lasers capable of delivering multiple wavelengths at 1064 nm, 532 nm and 355 nm respectively, with each wavelength having multi-mJ pulse energy. The lasers will be based on International Space Station (ISS) for a life span up to 3 years. Among three wavelengths, 355 nm laser beam has the most significance in this application since it provides a technology demonstration to operate a frequency-stabilized UV laser in a space environment with relatively long lifetime. One of the two lasers delivers 1064 nm and 532 nm wavelength laser beams, each with greater than 2.5 mJ pulse energy at 5 KHz repetition rate. The other laser consists of a frequency-stabilized ring oscillator to provide a single frequency operation, and can deliver pulse energies near 2 mJ at 1064 nm, 532 nm and 355 nm wavelengths at 4 KHz repetition rate. In both lasers, master-oscillator-power-amplifier architecture (MOPA) is employed with Nd:YVO crystal as the laser medium. The frequency stabilization in the second laser is achieved by injection-seeding a space-qualified single frequency DFB laser into the ring oscillator. The build of these lasers utilizes beam delivery fibers to connect the optical pump sources to the laser media. The build of the two lasers is largely based on Fibertek's previous experience in building space-based lasers for NASA applications, including lasers for CLIPSO and VNS/STORRM programs. Both lasers have been flown in space successfully.

8599-24, Session 5

Space qualified laser transmitter for NASA's ICESat-2 Mission

Nicholas W. Sawruk, Slava Litvinovitch, Joel Edelman, Michael M. Albert, Ryan E. Edwards, Charles Culpepper, Joe Rudd, Elias Fakhoury, Floyd E. Hovis, Fibertek, Inc. (United States)

Fibertek has developed an environmentally hardened Technology Readiness Level-6 laser transmitter system for the NASA Ice, Cloud and land Elevation Satellite-2. The laser transmitter generated over 9 W of 532 nm output with a pulse repetition rate of 10 kHz and a FWHM pulse width of < 1.5 ns with an expected lifetime of > 1 trillion shots. The laser had a M2 of < 1.3 and a system wall plug efficiency of > 5 %. A Structural, Thermal and Optical (STOP) sensitivity analysis was completed for the laser transmitter, and the modeled results were validated with experimental results. The STOP model incorporated a finite element analysis (FEA) model of the laser transmitter to predict optical component motion and deformation under a range of environmental conditions. The FEA results were then input into an optical ray trace tool to predict system level optical performance. The laser transmitter was successfully tested to the NASA Goddard Space Flight Center's General Environmental Verification Specification (GEVS) standards for proto-flight vibration spectrums followed by thermal cycling and vacuum testing. GEVS proto-flight vibration levels are intended to envelope vibration environments of all launch vehicles and structures. Proto-flight random vibration levels had an overall load of 14.1 grms, spanning frequencies of 20-2000 Hz. The laser transmitter was vibrated along three orthogonal axes and met all specifications post vibration testing. This paper presents the results of the STOP analysis, details on the GEVS testing requirements, and laser transmitter performance through vibration and thermal vacuum testing.

8599-25, Session 5

A 16-beam non-scanning swath mapping laser altimeter instrument

Anthony W. Yu, Michael A. Krainak, David J. Harding, James B. Abshire, NASA Goddard Space Flight Ctr. (United States)

We have developed and successfully flown a 16-beam, non-scanning laser altimeter instrument with a swath width of 80 m and spatial resolution of 5 m. The Airborne Lidar Surface Topography Simulator (A-LISTS) instrument was developed to demonstrate key technologies and measurement efficiency for the Lidar Surface Topography (LIST) mission. A-LISTS operated successfully from 10 km on a Lear Jet during its first engineering flights in September 2011 and also on a P3-Orion from 8 km this past August 2012. The instrument used a 1-Watt average power (rep rate = 10 kHz and 100 µJ) laser transmitter to generate a 4x4 pattern with 0.5 mrad divergence in each beam and 2 mrad separation between beams. The 100 µJ was divided into 16 beams, or ~5 µJ each. The receiver system consisted of a 4x4 fiber bundle placed at the focal plane of the received telescope. Individual fiber has a field of view (FoV) of 0.7 mrad. A 4x4 Intevac intensified photodiode (IPD) array was used to capture the return signal from the telescope and via the fiber bundle. The IPD array was operated in linear mode to capture the return waveform. These waveforms were then digitized using a 16-channel 1.5 GSample/s 8-bit digitizer to extract the sampled area. In this paper we will present the instrument development effort and access the performance of our two airborne campaigns. We will also discuss our future plans on developing a pathfinder mission for LIST.

8599-26, Session 6

A highly energetic, multiwavelength, diode-pumped nanosecond laser system with flexible pulse-shaping capability

Andrey V. Okishev, Ildar A. Begishev, Robert Cuffney, Semyon Papernov, Jonathan D. Zuegel, Univ. of Rochester (United States)

Shaped high-energy nanosecond pulses at different wavelengths are required for specific applications such as laser-damage testing and optical parametric chirped-pulse–amplification (OPCPA) pumping. A diode-pumped Nd:YLF laser system that is able to produce pulses at fundamental (1053-nm), second, and third harmonic wavelengths with the energies of hundreds of millijoules depending on pulse width/shape and wavelength is described. These pulses can be arbitrarily shaped in the 1- to 10-ns temporal range.

The laser system consists of a commercial single-frequency 1053-nm cw laser, a pulse-shaping system based on integrated-optics modulator driven by arbitrary waveform generator, a regenerative amplifier (regen), two-pass amplifier, and frequency-conversion crystals. The pulse-shaping system produces subnanojoule pulses that seed the regen that produces up to 18-mJ pulses with a TEM00 beam profile at a 5-Hz repetition rate. The regen output beam is 2? up-collimated to optimally fill the 8 ? 120-mm Nd:YLF amplifier rod. A single-pass, small-signal gain of 40 has been measured. A double-pass amplifier configuration is realized using Faraday rotator–polarizer combination. Total gains of 14 and 24 have been measured for single-pass and double-pass configurations, correspondingly.

This laser system has been designed for nanosecond laser-damage testing with square pulses with 1-, 5-, and 10-ns FWHM durations. For frequency conversion in this range, two sets of crystals are used: DKDP/DKDP and BBO/BBO. Conversion efficiencies of 70% and 40% have been demonstrated for second and third harmonics, correspondingly. The detailed system design and performance will be presented.

8599-27, Session 6

Diode pumped high pulse energy and high repetition rate Q-switched Nd:YAG-lasers with excellent beam qualities with up to 400-mJ pulse energy

Martin D. Ostermeyer, Artur Napiwotzki, Kirko Stimmer, Frank Massmann, IBL Innovative Berlin Laser GmbH (Germany)

The Titan series of IB-Laser is designed for applications like Lidar, remote sensing, particle imaging velocimetry (PIV), Plasma generation, OPO-pumping, etc. that need simultaneously nanosecond pulses with higher pulse energies in the sub-Joule range, high repetition rates up to 1kHz combined with an excellent beam quality. We report on diode pumped, Nd:YAG-based, MOPA laser systems with end pumped oscillators and side pumped amplifiers. Pulse energies of up to 400mJ at repetition rates of 300Hz with an M2 < 1.5 and 280mJ at repetition rates of 500Hz with an M2 < 1.4 are reached optionally with injection seeding. Pulse durations between 8ns and 20ns are realized at pulse to pulse fluctuations of < 0.4% (rms). Frequency conversion to 200mJ at 532nm and 100mJ at 355nm is reported in addition at 300Hz repetition range. At smaller pulse energies repetition rates of 1 kHz are reached. Due to the advantages in energy deposition and extraction the laser rod is chosen as bulk geometry. Crucial design aspects of the laser system are pump chambers with homogenous excitation profile, coatings with high damage threshold and an appropriate design for the compensation of thermally induced birefringence. Side pumped transverse fundamental mode systems are sensitive to diffraction from the hard aperture of the gain material. We investigated the impact of star like serrated apertures on the beam profiles from side pumped rod amplifiers in addition.

8599-28, Session 6

Self-Q-switched Cr:LiCAF laser near 800 nm

Ersen Beyatli, Alphan Sennaroglu, Koç Univ. (Turkey); Umit Demirbas, Uluslararasi Antalya Univ. (Turkey)

Self-Q-switched (SQS) operation of lasers enable the generation of Q-switched pulses from simple laser cavities without using any additional saturable absorbers or active modulators. Earlier studies have reported SQS in ruby, Nd:YAG and Cr:LiSAF lasers. However, these systems were mostly flaslamp pumped and required cooling of the crystal and/or misalignment of the laser cavity for the observation of SQS. In this presentation, for the first time to our knowledge, we report SQS operation of a Cr:LiCAF laser. SQS was achieved in an astigmatically compensated x-cavity containing only a Cr:LiCAF crystal that was end-pumped with a 140-mW continuous-wave (cw) diode at 660 nm. During regular cw operation, the laser produced a diffraction-limited beam with 50 mW of output power and had a spectral width of 0.5 nm near 795 nm. SQS operation could be initiated by fine adjustment of the separation between the curved mirrors of the cavity. and was observed at several mirror separations within the stability range of the resonator. During SQS, the laser generated saw-tooth-shaped pulses with 20-30 microsecond duration in the 780-800 nm wavelength range, at repetition rates between 10 and 30 kHz. SQS operation was further accompanied with a decrease in the output power to the 30-45 mW range. In this regime, the output beam became multimode and spectral broadening up to 8 nm (FWHM) was observed. Detailed experimental data describing the temporal, spectral, and spatial characteristics of the SQS Cr:LiCAF laser, as well as the effect of curved mirror seperation on SQS will be presented.

8599-29, Session 6

Multi-output Q-switched solid-state laser using an intra-cavity MEMS micromirror array

Ralf Bauer, Walter Lubeigt, Univ. of Strathclyde (United Kingdom); Caspar C. Clark, Euan J. McBrearty, Helia Photonics Ltd. (United Kingdom); Deepak G. Uttamchandani, Univ. of Strathclyde (United Kingdom)

A Microelectromechanical system (MEMS) scanning micromirror array was used to actively Q-switch a diode side-pumped Nd:YAG laser. Through the 2x2 array configuration, multiple individually controllable laser output beams were simultaneously generated using a single gain medium. The small footprint size and high fill factors of the array enabled multiple Q-switched outputs over the 3mm diameter cross section of the laser rod.

The MEMS array consisted of four resonant, electrostatic comb-drive actuated 25?m thick single-crystal silicon micromirrors with a diameter of 700?m, fabricated using a commercial multi-user silicon-on-insulator process. The micromirror mechanical resonant frequencies were around 8kHz, with optical scan angles of up to 78°. A post fabrication 240nm-thick gold layer coating was applied to the mirror surfaces leading to a reflectivity of R=96% at 1064nm, therefore enabling their intra-cavity use.

A 2-mirror cavity was built around a diode side-pumped Nd:YAG crystal using the MEMS micromirror array as cavity end-mirror and a T=20% output coupler. Simultaneous separate actuation of two neighbouring micromirrors led to dual Q-switched laser output beams with a combined average power of 125mW and pulse durations of 28ns and 34ns at pulse repetition frequencies of 8.7kHz and 7.9kHz for each output respectively. The output power was limited by thermal deformation of the mirror surfaces due to laser light absorption in the gold coating. Further power-scaling will be obtained by using low stress, high reflectivity (R>99%) dielectric coatings on the thin mirror structures and will be presented as well as coupling schemes of the array outputs.

8599-30, Session 6

Diode-pumped 300-mJ, 100-Hz, single-mode laser

George J. Doster, Faming Xu, Northrop Grumman Cutting Edge Optronics (United States)

Northrop Grumman Cutting Edge Optronics has developed a diode-pumped single-mode laser capable of producing 300mJ/pulse at repetition rates exceeding 100Hz. The diode-pumped design minimizes the thermal load on the rod compared to flashlamp-pumped designs, thereby reducing the effects of thermal lensing and stress birefringence. This allows the system to be operated at higher repetition rates than flashlamp-pumped systems, which are typically limited to 50Hz.

The laser utilizes an unstable resonator design with a graded reflectivity mirror, a large-aperture electro-optic Q-switch and birefringence compensation. The end result is a system with large TEM00 mode volumes, high energy output, and good beam quality. Design details and limitations are discussed with a special emphasis on requirements of laser amplifier. Additional information on further amplification to several Joules, operation at higher repetition rates, and harmonic conversion is provided.

8599-31, Session 6

High peak power Yb,Er:glass lasers

Scott J. Hamlin, MegaWatt Lasers, Inc. (United States)

The Ytterbium, Erbium co-doped glass laser was invented by E. Snitzer and R. Woodcock at the American Optical Company in 1965. Although invented shortly after the first laser demonstration, it was not until the

late 1980's and early 1990's when Yb,Er:glass lasers were produced in quantity. The first and largest production run was as rangefinder transmitters for the US Army's Mini Eyesafe Laser Infrared Observation Set (MELIOS). Yb, Er:glass lasers have several desirable attributes including the direct generation of laser radiation at 1535 nm (so-called Eyesafe wavelength) and very long fluorescent life. The challenges imposed by Yb,Er:glass, including: three level lasing, low thermal conductivity, and low emission cross-section, require more engineering and modeling than most other solid-state lasers. This paper will summarize our efforts in manufacturing high peak power Yb,Er:glass microlasers, and the development of Yb, Er:glass MOPA configurations for higher energy (100's of mJ and Joule level) applications. In particular, we will discuss the modeling and present results of recent single-pass, multiple-pass, and regenerative Yb,Er:glass amplifiers using flashlamp, diode, and VCSEL pump sources.

8599-32, Session 6

DPSS amplifiers for high-energy, high-repetition-rate applications

George J. Doster, Faming Xu, Ryan Feeler, Northrop Grumman Cutting Edge Optronics (United States)

Northrop Grumman Cutting Edge Optronics has developed a line of commercial off the shelf amplifiers to enable high-energy, high-repetition-rate amplification applications. These amplifiers are based on symmetric diode pumping of laser rods with rod diameters ranging from 2-25mm. Stored energy values in excess of 2.5J are available in these amplifiers, with small signal gain values approaching 300 in various models. These parameters make diode-pumped amplifiers a suitable replacement for flashlamp-based systems in many industrial and scientific applications. Amplifiers are available with Nd:YAG, Nd:YLF, Nd:Glass, and other laser materials.

Example data from a variety of amplifiers is presented in this paper. Gain, depolarization loss, and beam profile images are presented as a function of repetition rate and diode pumping current. Repetition rates ranging from 1Hz to several hundred Hz are investigated.

In addition, several recent examples of industrial and scientific applications are cited. These include spectroscopy, image amplification, laser shot peening, MHz and GHz pulse-train amplification, and a variety of others.

8599-33, Session 6

Flash lamp failure modes and lifetime estimation techniques

Ryand J. F. Tucker, Nicholas Cochran, Gregg L. Morelli, Honeywell Federal Manufacturing & Technologies, LLC (United States)

Solid state pulsed laser systems are of interest for military applications. Flash lamps are an effective method for pumping solid state pulsed laser systems. Flash lamp lifetime is hard to quantify past the specification provided by the manufacture and is of concern for military applications that are not used or tested on a frequent basis. The flash lamp lifetime can be shortened by three main failure modes: manufacturing quality escapes, shipping and handling damage, and shelf life. Manufacturing and shipping failure modes will be the focus of this research. Manufacturing and shipping failure modes are hard to detect, beyond the obvious non-functioning flash lamp, without testing to failure, which is not a feasible option.

A method is being proposed that can estimate the lifetime of flash lamps as well as other key characteristics of the lamp while a relatively low number of shots are taken with the flash lamp. Fill pressure and fill gas will be determined by monitoring the input voltage, current, and output spectrum with comparison to the arc length, bore diameter, wall thickness and electrode configuration. Flash lamp lifetime estimations will be determined by monitoring the current, wavelength shift, and output intensity. Experimental results will be discussed focusing on the characteristics and lifetime estimations of flash lamps.

8599-34, Session 7

Simulation of solid-state lasers with composite and ceramic crystals

Zhabiz Rahimi, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany) and ASLD GmbH (Germany); Christoph Pflaum, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany)

Composite, core-doped, and ceramic crystals are used to reduce the thermal lensing effect in laser crystals. An accurate simulation of laser resonators is needed to find optimal doping structures for a required laser. Also simulation helps apply these crystals efficiently. In this work, results of simulations performed on resonators containing core-doped Nd:YAG ceramic crystals with radial dependent doping concentration, and composite crystals with different layers of doping concentration are presented. The absorbed pump light in crystals is simulated using the ray tracing algorithm. The thermal lensing effect has been computed by the finite element analysis of the temperature and deformation. The dynamic mode analysis (DMA) was used to compute the laser beam quality and output power. The DMA solves rate equations separately for each Gauss mode. It also calculates population inversion by solving rate equations on finite volume grids. This approach yields a few thousands of rate equations for population inversion on the finite volume grid. The advantage of this method for both mentioned crystals is that different decay rates can be associated to regions with different doping concentration.

Simulation results have shown that sophisticated laser crystals are able to reduce thermal lensing effect and increase beam quality.

8599-35, Session 7

Thermo-optic quality assessment of doped optical-ceramics

Christina C. C. Willis, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

The application of optical-quality doped ceramic materials as laser gain media is rapidly expanding in terms of the range of laser architectures and variety of host materials. However, it is clear that a wide variation of quality exists in ceramic materials from one source to the next, and even between batches made in the same laboratory. Material and phase impurities can increase undesirable absorption and/or increase scattering, thereby increasing thermal distortions under load. As such diagnostics for assessing the quality of ceramic samples are pivotal for optimizing fabrication techniques and practices. And our experiments indicated that high transmission in the visible does not necessarily indicate superior thermal performance. By using Shack-Hartmann wavefront sensing (SHWFS) to measure thermally-induced distortions in ceramic material, we have developed a new method for direct comparison of ceramic (and crystalline) sample quality. In these experiments we examine Yb^{3+} doped YAG ceramic material from a variety of sources in order to rank and compare their quality. Both thermally induced focal length and phase delay are measured using SHWFS, as well as their transmission from 200 to 2200 nm. All samples measured are circularly symmetric. During measurement the samples are mounted in a water cooled heat sink designed to maintain the sample edges at a consistent temperature without inducing mechanical stress. A 940 nm fiber coupled diode is used to induce distortions at incident powers of up to 50 W. We believe this thermal distortion diagnostic will be a useful to improve the quality of ceramic laser media.

8599-36, Session 7

To be announced

Saurabh Sharma, Naval Air Warfare Ctr. Aircraft Div. (United States)

No Abstract Available

8599-37, Session 7

Optical properties and oscillator strength calculations in Ytterbium-doped YAG

Nicholas D. Haynes, Air Force Research Lab. (United States) and Univ. of Dayton (United States); David E. Zelmon, Air Force Research Lab. (United States)

The refractive indices and thermo-optic coefficients of Yb:YAG crystals for 0, 1, 3, 5, 7, and 10 at. % Yb were measured from 0.4-5.2 microns at temperatures ranging from room temperature to 225 C. The coefficients for the Sellmeier fit and the values for dn/dT at constant strain are reported. The absorption at room temperature was measured from .185-3.3 microns. Using the index and spectroscopic data, a Judd-Ofelt analysis was performed to determine the oscillator strengths of 4f transitions in Yb:YAG and the dependence of these oscillator strengths on Yb concentration.

8599-38, Session 7

Quasi-single-mode random lasing within a ZnO nanoparticle film

Hideki Fujiwara, Ryo Niyuki, Hokkaido Univ. (Japan); Yoshie Ishikawa, Kagawa Univ. (Japan); Naoto Koshizaki, National Institute of Advanced Industrial Science and Technology (Japan); Takeshi Tsuji, Kyushu Univ. (Japan); Keiji Sasaki, Hokkaido Univ. (Japan)

Random lasers have attracted much attention over the past decade because of their unique phenomena without a clear cavity structure. These lasers are typically composed of randomly distributed scatterers and gain materials, and the interference effects of recurrent multiple scattered light provide optical feedback in the structure, which can be expected to be utilized for easily fabricated and low-cost applications such as surface-emitting devices. However, considering the potential applications, these properties should raise issues of lasing mode controllability such as wavelength, location, and number of lasing modes, due to the randomness. For this issue, we have proposed a simple structure for manipulating resonant conditions in the random structure, in which a “defect” region is deliberately made. Because the average transmittance of the ensemble of size-monodispersed scatterers exhibits sharp dips in the transmitted intensity spectra due to the modal coupling of Mie resonances, it can be work as mirrors or filters and, therefore, intended long-lived modes in the defect surrounded by the random structure can be expected. In the presentation, as a first step toward experimental verification of our proposed method, we examined the characteristics of random lasers by introducing polymer nanoparticles as point defects in a size-monodispersed ZnO nanoparticle film. Comparing the results with those of typical random lasers, we found that the random lasing properties were markedly modified at the defect, in that the threshold decreased and the number of lasing modes suppressed. These results suggest the possibility that tunable single-mode random lasers could be realized by optimizing their structural parameters.

8599-40, Session 8

High energy ultrafast diode-pumped laser operating at 1053-nm based on Yb:CaF2

Antoine Courjaud, Vincent Clet, Amplitude Systèmes (France); Patrice Camy, Jean-Louis Doualan, Richard Moncorgé, Ecole Nationale Supérieure d’Ingenieurs de Caen et Ctr. de Recherche (France); Eric P. Mottay, Amplitude Systèmes (France)

Several laser developments aim to achieve the petawatt level using flash pumped Nd:glass technology [1,2], at a central wavelength of 1053nm. For these developments, damage threshold measurements are necessary to control and validate critical optical components. Ultrafast laser sources are therefore required at this specific wavelength, with high reliability and stability, and able to operate at high repetition rates for long-term cumulative tests. Ultrafast diode pumped technology is well established in industry, and well known for its compacity and performances, however the emission wavelength is usually around 1030nm, which is not compatible with Nd:glass components.

Recently, we demonstrated the broad tunability of Yb:CaF2 at room temperature from 1030 to 1065nm in Q-switched regime [3]. We report here on an ultrafast laser based on an Yb:CaF2 regenerative amplifier operating in the millijoule regime at a central wavelength of 1053nm.

The laser consists in an ultrafast fiber oscillator delivering pulses at a central wavelength of 1053nm, a grating based stretcher, a regenerative amplifier based on a Yb:CaF2 crystal pumped by a CW 15W fiber-coupled laserdiode, and a grating based compressor.

The regenerative amplifier delivers 3mJ pulses at a central wavelength of 1050nm at 100Hz repetition rate, with a pulse-to-pulse stability of 0,3% rms. The injected spectrum is shaped in the stretcher in order to achieve a central wavelength of 1053nm, with a bandwidth of 3,5nm. The amplified pulses are subsequently compressed to a pulse duration of 600fs, with a pulse energy of 2mJ and an excellent beam quality.

8599-41, Session 8

Energy scaling of a multipass-cavity mode-locked femtosecond bulk laser with a carbon nanotube saturable absorber

I?insu Baylam, Koç Univ. (Turkey); Sarper Ozharar, Bahçesehir Univ. (Turkey); Huseyin Cankaya, Koç Univ. (Turkey); Sun Y. Choi, Kihong Kim, Fabian Rotermund, Ajou Univ. (Korea, Republic of); Uwe Griebner, Valentin P. Petrov, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany); Alphan Sennaroglu, Koç Univ. (Turkey)

In mode locking applications, single-walled carbon nanotube saturable absorbers (SWCNT-SAs) have emerged as important alternatives to semiconductor saturable absorber mirrors due to their favorable optical characteristics, low cost, and relatively simple fabrication scheme. Therefore, it is of great interest to explore the limits of energy scaling in lasers mode-locked using SWCNT-SAs. Due to its appropriate wavelength range for biomedical applications, a room-temperature Cr4+:forsterite laser operating near 1.3 ?m was used in the mode-locking experiments. The laser was end-pumped with a continuous-wave Yb-fiber laser at 1064 nm. Furthermore, a q-preserving multipass-cavity was added to extend the resonator length resulting in a reduced pulse repetition rate of 4.51 MHz and to scale up the output pulse energy at low average power. The SWCNT-SA was fabricated based on SWCNTs synthesized by the high-pressure CO conversion (HiPCO) technique. With dispersion compensation optics, the net group delay dispersion of the resonator was estimated to be around -4440 fs2. When mode-locked with the SWCNT-SA, the resonator produced 10-nJ, 121-fs pulses at 1247 nm with a spectral bandwidth of 16 nm, corresponding to a time-bandwidth product of 0.37. To our knowledge, this represents the highest peak power (84 kW) generated to date from a bulk femtosecond solid-state laser, mode locked by using a SWCNT-SA. The results also show

that the peak power achieved in our experiments was limited only by self-focusing in the Cr4+:forsterite gain medium. The presented concept of output energy scaling should be applicable to other gain media mode-locked using SWCNT-SAs.

8599-42, Session 8

200-W fs INNOSLAB amplifier with 100-µJ pulse energy for industrial applications

Torsten G. Mans, Jan Dolkemeyer, Claus Schnitzler, AMPHOS GmbH (Germany); Clemens Höenninger, Eric P. Mottay, Amplitude Systèmes (France)

Femtosecond laser sources are ideally suited for machining applications requiring high precision or dealing with delicate materials or material compositions. The outstanding machining results and properties are made possible by the unique combination of ultrashort pulse duration and extreme high peak power. The high energy concentrated in ultrashort pulses enables the variety of applications. However, in order to ensure the necessary throughput and productivity, large scale industrial applications require ultrafast lasers of high average power.

We have realized a powerful industrial femtosecond Yb:YAG Innoslab laser amplifier providing all ingredients necessary for large scale economical applications with unprecedented precision and quality. A compact and robust femtosecond seed laser producing µJ-level pulses of ~350 fs pulses is directly injected and amplified in an optimized Innoslab amplifier configuration to a pulse energy level exceeding 100 µJ and an average power of more than 200 W. The ultrashort pulse duration is essentially maintained during the amplification process, resulting in a laser source of unique parameters: <1ps pulse duration, >100 µJ pulse energy, >200 W average output power. This parameter set is obtained in a simple and robust power amplifier configuration without the need of chirped pulse amplification.

This laser source is ideally suited for large scale applications requiring high throughput and productivity.

8599-43, Session 8

1-Watt femtosecond mid-IR Cr:ZnS laser

Evgeni Sorokin, Technische Univ. Wien (Austria); Nikolai Tolstik, Irina T. Sorokina, Norwegian Univ. of Science and Technology (Norway)

We report a high-power Kerr-Lens modelocked Cr:ZnS laser generating 1 W of average power at 2.3-2.5 µm with less than 70 fs pulse duration, corresponding to only eight optical cycles. This is the first high-power and high-energy femtosecond oscillator in this very attractive for applications “molecular fingerprint” wavelength range, representing a high-power alternative to previously demonstrated Cr:ZnSe laser. In this paper we present results on this novel femtosecond laser operating in soliton- as well as in chirped-pulse regimes, and compare it with the existing femtosecond Cr-ZnSe oscillators.

The laser operates at room-temperature and open-air conditions. The output power is limited by the available 5W commercial Er:fiber laser and corresponds to 20% of absolute optical-optical efficiency. The dispersion control is realized by a compact and environmentally stable combination of negative-dispersion material and chirped mirrors. The output pulse energy reached 5.6 nJ at 105-157 MHz repetition rates and is limited by the onset of pulse break-up. Further pulse energy increase is possible using the demonstrated chirped-pulse oscillator, with compressable 0.8-2 ps pulse durations, allowing us to scale pulse energy over 10 nJ. For environmentally-protected delivery we suggest and realize duration-preserving soliton propagation in a ZBLAN fiber.

At this power and energy level, this mid-IR oscillator is now capable of direct nonlinear-optical applications, such as supercontinum generation, pumping of mid-IR and THz sources, as well as applications in molecular spectroscopy and trace gas sensing. We shall discuss the already demonstrated applications ranging from fast high-resolution molecular spectroscopy and high-sensitivity intracavity spectroscopy to subharmonic OPO pumping. Further bandwidth increase is demonstrated by a 2.0-2.8 supercontinuum generation in a chalcogenide fiber.

Summarizing, we present the first robust and reliable room-temperature high-power mid-IR oscillator, producing few-cycle pulses at up to 1 W average power levels – a superior performance to an alternative Cr:ZnSe laser. Supercontinuum generation and the demonstrated applications of this source for high resolution spectroscopy, together with the realized ZBLAN fiber delivery makes this source a future “working horse” of the mid-IR femtosecond technology and applications.

8599-44, Session 8

900-fs pulses at 1040 nm from a passively Q-switched Nd:YVO4 microchip laser system

Reinhold Lehneis, Alexander Steinmetz, Jens Limpert, Friedrich-Schiller-Univ. Jena (Germany); Andreas Tünnermann, Friedrich-Schiller-Univ. Jena (Germany) and Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

We present a novel concept for an ultrashort pulse source from a passively Q-switched Nd:YVO4 microchip laser system reaching the sub-ps domain with a tunable emission wavelength from 1030nm to 1050nm. This technique comprises two stages: one that carries out the nonlinear compression of the Q-switched microchip pulses and a subsequent stage, in which these pulses are coupled into a further waveguide for secondary spectral broadening through self-phase modulation (SPM) followed by a band-pass filter. The high peak power and the short pulse duration of the compressed pulses result in wide SPM spectra with a nearly un-chirped region at the spectral edges, which is used for this concept. Therefore, the pulses can be filtered far away from the original wavelength, which leads in addition to further temporal pulse shortening and shaping to an adjustable wavelength shift.

The setup of a proof-of-principle experiment consists of a fiber-amplified Nd:YVO4 microchip laser which emits SPM-broadened 80ps pulses followed by a grating compressor leading to pulse durations of 3.5ps at 1064nm. Afterwards the compressed pulses are coupled into a passive single-mode fiber (0.25m long, 10µm core diameter) in which SPM broadens the spectrum to a bandwidth of ~50nm. The used band-pass filter has a spectral transmission window of 4nm with a tunable central wavelength. Subsequent filtering at the edge of the pulse spectrum results in pedestal-free pulses with 900fs duration. At the same time the filtered pulses have been shifted to 1040nm, which is very advantageous for subsequent power amplification in Yb-doped materials.

8599-45, Session 8

High repetition rate titanium sapphire PetaWatt laser system

Francois Lureau, Sébastien Laux, Olivier Casagrande, Christophe Radier, Olivier Chalus, Frederic Caradec, Christophe Derycke, Gilles Brousse, Paul Jougla, Christophe Simon-Boisson, Thales Optronique S.A.S. (France)

Ultra high intensity laser pulses are required for a growing number of applications. Some of them like laser plasma acceleration require significantly higher repetition rates than available today in order to acquire enough statistics in a reasonable time. This is the reason why a 1.3 PetaWatt laser operating at 1 Hz has been built by Thales Optronique for the BELLA project of Lawrence Berkeley National Laboratory aiming to accelerate electrons up to 10 GeV.

This 1 Hz 1.3 PetaWatt laser is based on a double CPA configuration with a XPW filter for temporal contrast enhancement. The two final amplifiers are pumped by 12 new high energy flashlamp-pumped Nd:YAG lasers (GAIA HP) delivering stable flat-top green pulses of 14 J each at 1 Hz.. Disabling of ASE and transverse lasing at full energy has been successfully verified.

The laser system has been now entirely built, and is currently in the process of final commissioning at Berkeley. An energy per pulse of 62 J has been measured at the output of the final Ti:Sa amplifier stage. The energy of the compressed beam has been directly measured at 42 J with a power meter while a FROG measurement has been performed over the entire pupil of the beam compressed at full energy leading to a measured pulse duration of 40 fs. Therefore we have demonstrated for the first time ever the operation at a repetition rate of 1 Hz of a laser system delivering pulses with a peak power exceeding 1 PetaWatt

8599-46, Session 8

Petawatt scale ultrashort laser system with diffraction-limited focus and transform-limited pulse duration

Cheng Liu, Sudeep Banerjee, Jun Zhang, Shouyuan Chen, Kevin Brown, Jared B. Mills, Nathan Powers, Baozhen Zhao, Donald P. Umstadter, Univ. of Nebraska-Lincoln (United States)

A high spatial and temporal quality petawatt (PW, 1015 W) scale Ti: Sapphire laser system is demonstrated. Two beamlines with independent compression stages (100 TW, 10 Hz), and (1 PW, 0.1 Hz) were built for high-field experiments. The on-target pulse energy is 3.5J (30 J) for 100 TW (1PW) operation. The on-target pulse duration is ~30 fs by proper management of dispersion for the whole system. A Dazzler/Wizzler closed loop was used to get the Fourier-transform limited pulse as well as good temporal contrast on the time scale of hundreds of femtoseconds. The wave-front distortion of the laser beam is compensated by the wave-front sensor and deformable mirror close–loop. The Strehl ratio is enhanced to 0.9. The beam can be focused to 18?18 μm, 8 ? 8 μm, and 2?2 μm by F13.3, F4.4, and F2 off-axis parabolic mirrors, respectively. The beam pointing stability both in air and vacuum is monitored and can be corrected. The energy and pointing stability is 1% and 3%. The nanosecond and picosecond contrast ratio are 1.0 ? 10-8 and 3.3 ? 10-7, respectively. All the laser parameters are fully characterized and monitored to meet the experimental requirements. Quasi mono-energetic electrons and high brightness Thomson scattered gamma-rays were generated by using this high quality laser facility.

8599-47, Session 9

Cryogenic Yb-doped lasers for efficient nanosecond, picosecond, and femtosecond sources *(Invited Paper)*

Darren A. Rand, Daniel E. Miller, Tso Yee Fan, MIT Lincoln Lab. (United States)

Operation of lasers at cryogenic temperatures has been used since the very earliest days of laser development.

Generally, operation at low temperatures has been viewed as an undesirable and impractical means to improve laser performance. However, many of the fundamental laser materials properties (thermal conductivity, thermal expansion, dn/dT, saturation intensity and fluence) improve significantly as the temperature decreases.

Additionally, many rare-earth-ion-doped solid-state lasers that are quasi-three-level lasers at room temperature become 4-level lasers at cryogenic temperature, leading to more efficient laser operation. The overhead associated with cryogenic cooling has been mitigated over time as cryogenics have become increasingly ubiquitous.

Recent laser demonstrations have taken advantage of the improved properties to scale the power of relatively simple end-pumped lasers to hundreds of Watts of output power and provide performance that is not possible with conventional room-temperature lasers. The improved performance is of particular interest for laser systems that need both high average and high peak powers simultaneously. We provide an overview of cryogenic solidstate lasers, discuss recent demonstrations, and give a perspective on the future of this technology.

8599-48, Session 9

5-kW Yb:YAG thin disk laser with good beam quality

Yuan Han Peng, Yu Xian Lim, James Cheng, Yunn Boon Tan, Wei-Pin E. Lau, Kin Seng Lai, DSO National Labs. (Singapore)

A stable laser resonator with a single Yb:YAG thin disk module has been designed and demonstrated to produce 5kW CW laser output at 1030nm with an M-square factor of 7. Pumped with 940nm diodes, the optical-to-optical efficiency was >50% at full power. A simple V-shaped resonator consisting of only three optical elements was implemented, with a flat output coupling mirror (R=96%), a concave high reflectivity mirror, and with the 16mm diameter Yb doped thin disk acting as an active mirror. No additional adaptive optics for aberration or mode control was used; instead the results were achieved with a laser cavity design that takes into account the changing radius of curvature of the pumped thin disk. The design ensured the laser always operated well within the stable cavity zone and with an optimised and relatively large fundamental laser mode size on the thin disk. The low optical aberrations and effective thermal management of the thin disk, mounted on a diamond cooled heat sink, together with the above cavity design approach, enabled the realization of such a high power and good beam quality thin disk laser in a simple single disk laser oscillator.

8599-49, Session 9

100-W Tm:YLF INNOSLAB laser at 2 micron

Ansgar Meissner, Fraunhofer-Institut für Lasertechnik (Germany); Jing Li, Suhui Yang, Beijing Institute of Technology (China); Marco Höefer, Hans-Dieter Hoffmann, Fraunhofer-Institut für Lasertechnik (Germany)

Laser radiation with wavelengths of around 2 μm is useful for remote sensing, LIDAR and processing VIS-transparent materials. Due to its superior thermal properties, the ILT-proprietary INNOSLAB laser platform is most suitable for generating high power or high pulse energy laser emission at diffraction limited beam quality.

In this work, the INNOSLAB laser platform is applied to a Tm:YLF laser crystal, which is doped with 2.5 at % and fabricated by Beijing Opto-Electronics Technology from China. The crystal is partially end-pumped with a 6-bar diode-laser stack at 792 nm from each side in a line focus with an effective height of about 800 μm in fast axis. In slow axis, the laser crystal is fully pumped with a Top-Hat-like profile.

At an absorbed pump power of 420 W, an output power of 100 W and a slope efficiency of 37 % are measured. With an intracavity Brewster plate, the output polarization and, thus, the wavelength are switched between parallel (1888 nm) and perpendicular (1908 nm) with respect to the crystal's c-axis. The laser resonator is spherical and produces a strongly elliptical output beam with a Gaussian shape along the semi-minor axis (w ~ 500 μm, M? < 5) and a Top-Hat-like beam shape along the semi-major axis (w ~ 5 mm, M? < 650).

Further work is aimed towards efficiency scaling by changing the pump height and the doping level and toward using the output beam for pumping a Ho:YLF INNOSLAB amplifier for ps-pulses.

8599-50, Session 10

Wavelength dependence of the optical axis in double tungstate crystals

Romain Cattoor, Institut Franco-Allemand de Recherches de Saint-Louis (France) and Univ. Bordeaux 1 (France); Inka B.

Manek-Hönninger, Marc Tondusson, Univ. Bordeaux 1 (France); Todor Kirilov, Conerefringent optics SL (Spain); Daniel Rytz, FEE GmbH (Germany); Lionel S. Canioni, Univ. Bordeaux 1 (France); Marc Eichhorn, Institut Franco-Allemand de Recherches de Saint-Louis (France)

Recently, the interest in a phenomenon called conical refraction has increased. Potential applications of this effect in beam shaping or the use as laser material have already been investigated by some groups. The conical refraction occurs only in biaxial crystals, which have a complex index ellipsoid. This effect is only observed for light beam propagation exactly along the optical axis. In order to predict the orientation of the optical axis for different wavelengths the refractive index must be known very accurately. We demonstrate experimental results of the angular dependence of the optical axis for different wavelengths from the blue (430 nm) up to the infrared (1580 nm). Using the biaxial materials pure KGW and Neodymium doped KGW. The crystals are around 1 cm long and have a section of 3x3 mm? and 4x3 mm?, respectively. All samples are cut along one optical axis allowing the observation of conical refraction. The measurements have been performed by observing the ring shaped beam formed by conical refraction allowing for the correct alignment of the crystals over the whole wavelength range. The variation of the angle is about 2.3° between the blue and the infrared. The measurements show that the currently available accuracy on refractive index data is not enough for precise prediction of the optical axis orientation. Over the investigated spectral domain, we do also not observe a rotation of the index ellipsoid along the crystallographic b-axis, which means the variation occurs only in one plane. Moreover, no significant influence of doping of the crystal was observed.

8599-51, Session 10

Single-frequency Nd:YAG laser with LG01 donut mode output

Di Lin, Jae M. Daniel, W. Andrew Clarkson, Univ. of Southampton (United Kingdom)

Laguerre-Gaussian (LG0n) laser beams with a donut-shaped profile are attracting growing interest due to a wealth of applications in areas such as optical manipulation of particles, trapping and guiding of atoms, laser drilling and writing and super-resolution microscopy. Here we report a diode-end-pumped single-frequency Nd:YAG laser using a novel fiber-based pump beam conditioning element to achieve lasing on the lowest order donut (LG01) mode. The pump conditioning element was fabricated from a capillary (hollow-core) silica fiber with a 200 µm outer diameter and a 105 µm diameter inner air hole. The fiber was tapered and spliced to a fiber-coupled laser diode with a maximum output power of 4 W at 808 nm. The capillary fiber yielded ~3.5 W of output in a beam with a ring-shaped near-field profile. The latter was imaged into a Nd:YAG rod in a two-mirror plano-concave resonator to selectively excite the LG01 mode. The laser produced up to 1.71 W of multi-axial-mode output at 1064 nm for 3.5 W of incident pump power. The corresponding slope efficiency was 57%. Single-axial-mode operation was achieved by inserting quarter-wave plates at both ends of the Nd:YAG rod to suppress spatial-hole-burning together with an intracavity etalon. Using this set-up, we obtained 810 mW of single-frequency LG01 mode output with a well-defined sense of spiral phase for ~3.1 W of incident pump power. The beam propagation factor (M2) was measured to be ~2.09 and hence in close agreement with the theory. The prospects for further improvement in performance will be discussed.

8599-52, Session 10

Nd-doped PTR glass DBR laser

Leonid B. Glebov, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); Aleksandr Ryasnyanskiy, OptiGrate Corp. (United States); Nikolai Vorobiev, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); Vadim Smirnov, OptiGrate Corp. (United States); Julien Lumeau, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); Larissa Glebova, Oleksiy Mokhun, Christine P. Spiegelberg, OptiGrate Corp. (United States); Michael A. Krainak, NASA Goddard Space Flight Ctr. (United States)

The need of compact, narrow line laser sources stimulated the development of hybrid devices such as distributed feedback (DFB) lasers and distributed Bragg reflector (DBR) laser.

Recent development in recording of volume holographic elements in PTR glass has led to the production of high efficiency volume Bragg gratings (VBGs), which allow narrowband filters in both spectral and angular spaces. On the other hand, co-doping of PTR glass with luminescent ions and recording VBGs inside the glass paves a way for creation of compact monolithic DFB and DBR volume solid state lasers.

We report on the first Distributed Bragg Reflector solid state laser recorded in Nd-doped PTR glass. An emitting at 808-nm laser diode with maximum power of 40 W was used as a pump source. In order to prevent heating, the pumping was in pulsed regime with pulse duration of 1 ms and repetition rate of 50 Hz. The DBR element (2% Nd-doped PTR glass) with an aperture of 2?6 mm2 and thickness of 11 mm was kept in a copper housing mounted on the TEC for temperature control.

The telescope type laser cavity was formed by a broadband mirror, focusing lens and DBR element which was acting as an active element (Nd-doped PTR glass) and output coupler (VBG with diffraction efficiency ~99%). The DBR laser produced 3W narrow line (~30 pm) radiation around 1060 nm. The laser was operating in a single transverse mode and no signature of saturation caused by a thermal lens effect was observed.

8599-53, Session 10

Resonant optical devices for IR lasers

Eric G. Johnson, Menelaos K. Poutous, Yuan Li, Indumathi Raghu Srimathi, Aaron J. Pung, Clemson Univ. (United States); Martin Richardson, Larry Shaw, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); Ramesh Shori, Naval Air Warfare Ctr. Weapons Div. (United States); Robert Magnusson, The Univ. of Texas at Arlington (United States)

This talk will highlight recent developments in resonant optical devices for IR and MidIR lasers. Both solid state and fiber based systems will be discussed and the design and fabrication of such devices will be summarized.

8599-54, Session 10

879-nm pump diode stack and single Nd:YAG rod design to achieve 20-W to 300-W adjustable laser output power at 532 nm and 38% optical to optical conversion efficiency

Jason R. Xuan, Mike Scott, Xirong Yang, American Medical Systems (United States)

The goal of this research was to design a cost effective, high efficient diode-pumped and Q-switched 532nm laser with large laser output power range and fast laser output power switching from 0W to any user defined operating power by adjusting the pump diode current. It is well known that pump diodes used in the solid-state Nd:YAG lasers have center wavelength around 808nm or 885nm and will shift their center wavelength while changing its pump current. The shift of those pump diode wavelength could be big enough so it's outside of the laser gain medium absorption band and causes lower pump absorption efficiency which results in lower overall system optical to optical conversion

efficiency for some portion of the laser output power range. A few typical ways to minimize this wavelength-shift-caused lower pump absorption effect with their trade-offs have been discussed. We reported the special pump wavelength and single Nd:YAG rod design without those trade-offs for the laser system. The laser had 38% optical to optical conversion efficiency with adjustable laser output power from 20W to 300W. We reported the unique pump diode wavelength of 879nm and single Nd:YAG rod design for this laser system that can adjust the pump current to switch the laser output power from 0W to any other output powers between 20W to 300W within 2 seconds without causing Nd:YAG rod damage and maintain the high efficiency at any laser output power levels.

8599-55, Session 11

High power high repetition rate VCSEL array side-pumped pulsed blue laser

Robert Van Leeuwen, Pu Zhao, Tong Chen, Bing Xu, Laurence S. Watkins, Jean-Francois Seurin, Guoyang Xu, Alexander Miglo, Qing Wang, Chuni L. Ghosh, Princeton Optronics, Inc. (United States)

Recently we developed high power, kW-class, 808 nm pump modules based on the vertical-cavity surface-emitting laser (VCSEL) technology for side-pumping of solid-state lasers. The pump modules comprise twelve VCSEL arrays arranged in a 6 x 2 layout. Each VCSEL array has a 2.7 mm x 2.7 mm emitting area that contains a few thousand small aperture elements that emit in a low-order circularly symmetric mode. The VCSEL arrays were operated in a quasi-CW mode with a pulse length comparable to the fluorescence lifetime of the Nd:YAG gain medium. With 100 ?s 240 A current pulses 1.2 kW peak output power was obtained for repetition rates up to 500 Hz. A 5% peak power drop was observed when the repetition rate was ramped to 1 kHz (10% duty cycle). With 250 ?s pulses more than 1.0 kW peak output power was obtained for repetition rates up to 400 Hz (10% duty cycle). Two high power VCSEL pump modules were implemented in a dual side-pumped Nd:YAG laser operating at 946 nm. The laser was actively Q-switched using an acousto-optic modulator and the output was externally frequency doubled in a BBO crystal to produce 10 mJ blue laser pulses at high repetition rates.

8599-56, Session 11

0.9-W compact UV pulsed lasers using high-power VCSEL array side-pumping

Tong Chen, Bing Xu, Robert Van Leeuwen, Pu Zhao, Jean-Francois Seurin, Guoyang Xu, Alexander Miglo, Qing Wang, Chuni Ghosh, Princeton Optronics, Inc. (United States)

Diode-pumped solid state lasers (DPSSLs) are traditionally pumped by edge-emitting diode bars. Recently, advances in the development of high-power two-dimensional arrays of vertical-cavity surface-emitting lasers (VCSELs) have made them attractive alternative pumping source for DPSSLs. Here we reported a compact UV pulsed laser pumped by high-power VCSEL arrays. kW-class 808 nm VCSEL pump modules were implemented to side-pump a Nd:YAG crystal laser operating at 1064 nm. The laser was passively Q-switched with the insertion of Cr:YAG crystals. The output pulses were frequency-doubled outside the laser cavity to 532 nm and quadrupled to 266 nm using KTP and BBO crystals respectively. With quasi-continuous-wave (QCW) VCSEL pumping at 1.3 kHz repetition rate, 8.2 W average Q-switched IR power, 4.2 W average green power and 0.9 W UV power were obtained respectively with IR to UV conversion efficiency of 11%. The UV pulse energy is 0.68 mJ and the pulse duration is 10 ns. This VCSEL pumped high power UV laser source provides a reliable, low-cost and low-profile solution for military and commercial applications including remote sensing, laser processing and spectroscopy. We will also discuss the merits of VCSEL array side-pumping of high power miniature solid-state lasers.

8599-57, Session 11

Laser and phosphor hybrid source for projection display

Fei Hu, Yi Li, Appotronics Corp. (China)

Laser and phosphor hybrid light source proved to be a promising technology for the next generation projection display industry. One compact light source architecture, based on a blue laser diode and a transmissive phosphor wheel, is targeted at applications such as pico-projectors. A 0.3 inch single DLP projector engine is used to integrate with the light source module. 183 lumens (ANSI test) are achieved on the screen, while the power consumption of the light source is only 11.5 W. The lumen efficacy is 15.9 lumen/W, which more than doubles the lumen efficacy of the RGB LED projector we made. The ultra thin design of the light source module achieved a thickness of 16.3 mm. Including heatsink, the size of this module is 53.4 mmx 34.8 mm. The red, green, blue and yellow four segment phosphor wheel provides the color sequence. The color gamut of such a pico-projector fulfills Rec. 709. The red lumen ratio over white lumen (red content) is over 5%. Reliability test data were collected for 1500 hours. The extrapolated lifetime of the light source module is longer than 20,000 hours. Such a light source module has the potential to be widely used in Pico-projectors.

8599-58, Session 11

Wide temperature operation of a VCSEL pumped 355nm frequency tripled Nd:YAG laser

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

We will describe a compact VCSEL pumped Nd:YAG laser with an emphasis on maintaining optimized performance over an extended temperature range. VSCEL pumping has a particular advantage of providing a spatially uniform emission and a low temperature dependent wavelength shift of only 0.07 nm/oC, which is ~4x less than edge emitters. This reduced wavelength shift allows for a reduction in resonator length while maintaining efficiency over temperature.

VCSEL pumped Nd:YAG lasers were used as sources to generate third harmonic pulses at 355nm. We developed compact passively Q-switched lasers that generated 15mJ 1064nm pulses with a duration of 2-3 ns. Low beam divergence and beam pointing stability over temperature were achieved using unstable resonators with an optimized graded reflectivity mirror (GRM) output coupler. Using this laser as a source for third harmonic generation, a variety of non-linear crystal combinations were explored, with the type and length optimized to yield >1mJ at 355nm over a wide temperature range.

8599-59, Session 12

Cr:ZnSe thin disk cw lasers

Günther Renz, Jochen Speiser, Adolf Giesen, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); Irina T. Sorokina, Norwegian Univ. of Science and Technology (Norway); Evgeni Sorokin, Technische Univ. Wien (Austria)

A Thulium fiber laser pumped or diode laser stack pumped Cr:ZnSe thin disk cw multimode laser at 2.4 µm with an output power of 5 and 4 W, respectively, and with optical-to-optical efficiencies of 10% will be presented. An experimentally verified and numerically simulated thermal lensing induced and cyclic instability in the laser system will be shown. As a consequence, in order to prevent the lasing conditions in the resonator to be unstable, power scaling of a Cr:ZnSe thin disk laser is possible by enlarging the pump spot and reducing thereby the thermal lensing condition. Therefore, the instability is not initiated. As a conclusion, the investigated instability will show up in any laser active

material which has a strong absorption of the pump beam, for instance in transition metal ion laser material systems in connection with any laser concept, like for instance in thin disk, bulk or slab designs.

8599-60, Session 12

High-power Kerr-lens mode-locked Yb:YAG thin-disk oscillator in the negative and positive dispersion regimes

Oleg Pronin, Max-Planck-Institut für Quantenoptik (Germany) and Ludwig-Maximilians-Univ. München (Germany); Jonathan Brons, Max-Planck-Institut für Quantenoptik (Germany); Fabian Lücking, Ludwig-Maximilians-Univ. München (Germany); Christian Grasse, Walter Schottky Institut (Germany); Vladimir Pervak, Ludwig-Maximilians-Univ. München (Germany); Gerhard Boehm, Markus C. Amann, Walter Schottky Institut (Germany); Alexander A. Apolonskiy, Ludwig-Maximilians-Univ. München (Germany); Vladimir L. Kalashnikov, Technische Univ. Wien (Austria); Ferenc Krausz, Max-Planck-Institut für Quantenoptik (Germany) and Ludwig-Maximilians-Univ. München (Germany)

By using a Yb:YAG thin-disk laser with a cavity configuration which we previously mode-locked in the regime of negative intracavity group delay dispersion (GDD) via pure Kerr-lens mode locking (KLM) as well as pure SESAM techniques, we realize stable self-starting mode-locking with positive intracavity GDD. This allows direct experimental and theoretical comparison of different mode-locking techniques and energy scaling laws. We demonstrate 0.4-µJ pulses with an average power of 17W and a pulse duration of 190fs (Fourier limit: 150fs). This result is realized with nearly one order smaller GDD in comparison to the negative GDD regime. Increase of the pulse energy with GDD (at increased pump power) and output coupling up to 30W is demonstrated, however, approaching GDD levels similar to the negative dispersion regime. Inability to start the oscillator at an increased GDD levels is found to be the limiting factor in further energy scaling. An additional starting mechanism such as regenerative mode-locking or SESAM with an increased modulation depth offers the potential for scaling the pulse energy and the power of KLM disk lasers to unprecedented values.

Additionally we characterize the carrier envelope phase (CEP) of the oscillator running in negative dispersion regime at 1.1µJ pulse energy and 45W average power. We find that the main contributions to CEP jitter are originating from the thin-disk active water cooling and the noise of pump diodes. The attempts to stabilize CEP with a feed-forward method and a feedback control of pump diodes were experimentally verified and give promising results.

8599-61, Session 12

Erbium-based edge-pumped disk laser

John Vetrovec, Drew A. Copeland, Amardeep S. Litt, Aqwest, LLC (United States); Detao Du, General Atomics Aeronautical Systems, Inc. (United States)

We report on a composite edge-pumped disk laser operating at a wavelength of 1.5 ?m. The composite laser disk is made of a central Er:Yb doped glass portion and a perimetral undoped glass portions. The doped center is pumped by 940-nm diodes and lases at 1.5 ?m. Edge pumping beneficially offers a long absorption path for the pump radiation which allows for low doping of the central portion. As a result, the edge-pumped disk can operate at a much reduced waste heat density and lasing threshold. In addition, reduced doping conveniently allows for resonant operation. Our previous work on a Yb:YAG edge-pumped disk shows that edge-pumped devices can be remarkably compact. This paper discusses laser energetics, test setup, and test results. Concurrent developments of an Er:Yb:YAG disk and a resonantly-pumped Er laser disk are also included.

8599-62, Session 12

Amplified spontaneous emission (ASE) models and approximations for thin-disk laser modeling

Drew A. Copeland, General Atomics Aeronautical Systems, Inc. (United States)

It is well–known that amplified spontaneous emission (ASE) can be a major source of upper laser level loss in high gain pulsed or steady–state solid state lasers. This paper briefly reviews the theory of ASE and, using a simple rate equation model of the upper laser level, a radiative transport equation to describe the ASE intensity, and the perturbbation method of multiple time scales, demonstrates that the loss rate of the upper laser level due to ASE adiabatically follows the spontaneous emission source term. This result which includes gain saturation is applicable to both quasi–three level and four level lasers and rigorously justifies formally using the steady–state expression derived heuristically by Lowenthal and Eggleston [1] to model ASE loss in pulsed laser media. Then, it is shown that the frequency integral occurring in the ASE loss term can be evaluated analytically for both a broad “flat–top” and a Lorentzian stimulated emission lineshape but must be evaluated numerically or using an approximation due to Tommasini and Balmer [2] or a Gaussian stimulated emission lineshape. It is shown that at high gain loss due to ASE is mitigated by ASE line narrowing. For a thin disk laser an approximate expression for the rate of ASE loss (or ASE lifetime) can be obtained by evaluating the remaining volume integral using either the method of Speiser [3] or of Vretenar et al [4]. A new approximate expression for the ASE loss rate is obtained which, unlike Speiser’s [3] expression, accounts for ASE line narrowing and, unlike Vretenar et al’s [4] expression, correctly scales with the cylindrical volume of the disk. Application to both 1D and 3D laser modeling is briefly discussed.

References:

[1] D. D. Lowenthal and J. M. Eggleston, “ASE effects in Small Aspect Ratio Laser Oscillators and Amplifiers with Non-Saturable Losses, IEEE JQE Vol. QE-22, No. 8, Aug 1986, pages 1165–1173.

[2] R. Tommasini and J. E. Balmer, “Amplified Spontaneous Emission and Maximum Gain–Length Product Re-vised for General Line Shapes,” JOSA B, Vol. 16, No. 4, Apr 1999, pages 538–545.

[3] J. Speiser, “Scaling of Thin–Disk Lasers, Influence of Amplified Spontaneous Emission,” JOSA B, Vol. 26, No. 1, January 2009, pages 26–35.

[4] N. Vretenar, T. Carson, T. C. Newell, T. Lucas, W. P. Latham, and P. Peterson, “YB:YAG Thin–Disk Laser Performance at Room and Cryogenic Temperatures,” in Solid State Lasers XXI: Technology and Devices, ed-ited by W. Andrew Clarkson and Ramesh K. Shori, Proceedings of the SPIE Volume 8235, 82350S 2012.

8599-63, Session 12

Zero-phonon-line pumped 1 kHz Yb:YAG thin-disk regenerative amplifier

Michal Chyla, Taisuke Miura, Martin Smr?, Patricie Severova, Ondrej Novak, Akira Endo, Tomas Mocek, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

High-energy, thin-disk regenerative amplifier operating in the kilohertz range is a desirable laser source for developing EUV plasma sources which are mainly applicable in science and industry. We are elaborating a 100 mJ Yb:YAG thin-disk system operating at 1 kHz repetition rate delivering 1-2 ps long pulses.

Until now few hundred millijoules output has been achieved from a thin-disk regenerative amplifier at relatively low-repetition rate, and current progress in high-repetition rate operation allows achieving only few tens of millijoules. In order to obtain the pulse energy over 100 mJ, one has to design a regenerative amplifier with a large mode diameter on the thin-disk to avoid optical damage. Since Yb:YAG is a quasi-three state laser,

the material should be pumped using high-pump intensity with large mode radius in order to have sufficient gain . These two factors, however, lead to a large thermal loading at the thin-disk which induces large OPD (optical phase distortion) causing poor mode matching, and increases both temperature and ASE (amplified spontaneous emission) causing degeneration of amplification gain.

We overcame these problems by utilizing wavelength-stabilized laser diodes as zero-phonon-line (969 nm) pumping source resulting in suppression of thermal loading. Two thin-disk laser heads are used in the regenerative amplifier's cavity to split the large thermal loading. Since twin-disk cavity requires critical cavity design, we applied a computer-assisted cavity optimization. Moreover, pulsed pumping shorter than the life time of Yb:YAG helps to reduce the ASE. Experimental results and discussion will be presented.

8599-39, Session PTue

Spectroscopic characterization and upconversion processes in Er-doped Yttria ceramics

EiEi Brown, Uwe H. Hömmerich, Hampton Univ. (United States); Althea G. Bluiett, Elizabeth City State Univ. (United States); Sudhir B. Trivedi, Brimrose Corp. of America (United States); Courtney Kucera, John Ballato, Clemson Univ. (United States)

There has been a growing interest in the development of resonantly-pumped Erbium doped solid-state laser sources operating in the eye-safe wavelength region around 1.5-1.6 µm. Resonant (in-band) pumping of Er3+ lasers with low-quantum defect allows to minimize the thermal loading of the system, which is essential to the scaling of solid state laser for high power laser application. Upon resonant laser excitation, Er3+ doped materials also exhibit visible upconversion emissions (~0.55 µm and 0.67 µm), which leave a detrimental impact on the performance of Er3+ lasers operating at 1.5 µm. Since Er3+ upconversion is non-negligible, it is essential to obtain a good understanding of the dynamics of upconversion properties in Er3+ doped materials. In this work, we report on the spectroscopic characteristics and upconversion emission in Er3+ doped Y2O3 ceramics with different Er3+ doping concentrations. Following pumping at 1.532 µm, strong green (~0.56 µm, 2H11/2, 4S3/2 --> 4I15/2) and red (~0.67 µm, 4F9/2 --> 4I15/2) emission bands were observed as well as weak near-infrared emissions at 0.8 µm (4I9/2?4I15/2) and 0.85 µm (4S3/2 --> 4I13/2) at room temperature. Pump power dependence studies indicated that a three photon upconversion process is responsible for the green and red emissions. Furthermore, the visible upconversion emissions of 0.5 at.% Er: Y2O3 ceramic were investigated for different excitation wavelengths to gain more insight into the upconversion mechanisms. More detailed studies on the temperature dependence behavior of the upconversion emission, decay analysis, as well as time-resolved spectral studies and its relevance to the 1.5 µm population dynamics will be discussed at the conference.

8599-64, Session PTue

Solid-state laser source of narrowband ultraviolet B light for skin disease care

Aleksandr A. Tarasov, Hong Chu, Laseroptek (Korea, Republic of)

Skin irradiation by ultraviolet light at 300 – 312 nm (narrowband UV-B) is common method for psoriasis and vitiligo care. At present only one type of lasers – XeCl excimer laser (308 nm) - is used in medical practice for these purposes.

The goal of our work is the development of solid-state laser source, operating in narrowband UV-B range, with parameters, required for psoriasis and vitiligo care. We based on the following parameters1: pulse energy 5 mJ, pulse repetition rate 50-100 Hz. Output wavelength was chosen as 310.7 nm, which corresponds to standard narrowband UV-B lamp.

Our source includes pulsed Ti: Sapphire laser, pumped at 532 nm, operated at 932 nm, followed by second (SHG) and third (THG) harmonic generators. Output wavelength and spectral width are determined by volume Bragg grating, which serves as a laser output coupler. The characteristics, obtained at maximum available pump energy, 60 mJ, and 50 Hz, are listed below:

Wavelength, nm	932	466	310.7	
Pulse energy, mJ	17.5	9.1	7.0	
Pulse duration, ns	55	50	45	
Overall efficiency, %		29	52	40
Spectral width, nm	< 0.03	<0.015	< 0.01	

Important result here is 40% overall efficiency of THG, which is obtained at relatively low input power level – 0.32 MW. Earlier, similar efficiency was reported2, when input power of Ti: Sapphire laser was much larger - 7.8 MW, and spectral narrowing was performed by injection seeding.

THG efficiency of nonfocused laser beam did not exceed 15%. To enhance harmonic efficiency we proposed and investigated compact optical scheme with cylinder focusing, common for the both, SHG and THG, crystals.

Nonlinear crystals are placed at opposite sites from input cylinder lens focal plane. Maximum THG efficiency was obtained independently on used crystal length (within 10 -20 mm). This allows simple optimization of harmonic generation for different criteria by the appropriate positioning of each crystal along beam direction.

References

[1] Asawanonda, P., Anderson, R. R., Chang, Y., Taylor, C. R., "308 –nm excimer laser for the treatment of psoriasis", Arch. Dermatol. 136, 619 – 624 (2000).

[2] Dergachev, A. Y., Pati, B., Moulton P. F., " Efficient third-harmonic generation with a Ti: Sapphire laser", Advanced solid-state lasers, Fejer M. M, Injeyan H., and Keller U., eds., v. 26 of OSA Trends in Optics and Photonics Series, 96-99 (1999).

8599-65, Session PTue

Power-scaling of Pr:YAlO3 laser operating in CW regime at 747 nm and 720 nm wavelengths

Martin Fibrich, Helena Jelínková, Czech Technical Univ. in Prague (Czech Republic)

Materials doped with trivalent Praseodymium ions attract a great deal of attention because they are very suitable candidates for efficient stimulated emission in the visible region of the electromagnetic spectrum. The reason for that is not only the large number of potential Pr-ion laser transitions extending throughout the whole visible range up to the near infrared, but also a significant progress made in the last year in the development of the efficient pumping sources in the blue region corresponding with Pr-absorption peaks.

An attractive laser host for Pr-ions is the yttrium-aluminum-oxide YAlO3 (YAP) because of its good thermal and mechanical properties. If compared with mostly discussed Pr-fluorides, Pr:YAP excels in higher hardness, thermal conductivity, and mechanical and chemical stability. Furthermore, Pr-oxides exhibit positive value of the temperature coefficient dn/dT enabling to design a microchip laser systems which are generally attractive light sources due to their compactness, high efficiency, good beam quality, etc.

In this contribution, following our results concerning the first realization of GaN-diode pumped Pr:YAP laser with 91 mW output power at 747 nm, and two wavelength Pr:YAP generation (747 nm and 720 nm) reached by Lyot filter tuning, power-scaled continuous-wave Pr:YAP laser systems are demonstrated. Using double-side pumping by two GaN-laser-diodes emitting at 448 nm with maximum output power of 1W each, and 5 mm long Pr(0.6 at. %):YAP crystal, laser output power amounting to 290 mW in the near-infrared spectral region is reported, as well as dual wavelength operation at 720 nm and 747 nm.

8599-66, Session PTue

A passively mode-locking Yb:YAG direct-bonding waveguide laser based on single-walled carbon nanotube saturable absorber

Ke Liu, Mei Sang, Pan Zhu, Zhaoying Wang, Tianxin Yang, Tianjin Univ. (China)

With the maturity of the Yb^(3+) doped crystal growth technology and the superior physical properties of Yb^(3+) doped crystals, Yb:YAG is becoming a kind of popular laser material to generate high power ultrafast optical pulses. Yb:YAG crystal has many good characteristics such as its suitability for laser diode(LD)pumping, high slope efficiency, high doping concentration, no excited state absorption as well as up conversion and the advantages of a long fluorescence lifetime. The gain medium in our research in a direct-bonded Yb:YAG planar waveguide crystal, with Yb:YAG as core and sapphire as cladding, making them bond directly without any glues. This structure makes it have a large step refractive index difference, a high surface to thickness ratio, which means good thermal diffusion property. In recent years, Single-walled carbon nanotubes (SWCNTs) have been extensively studied and investigated for future photonic and optoelectronic applications due to their excellent electric, optical and mechanical properties. Combine these properties, we demonstrated a passive mode-locking Yb:YAG direct bonding waveguide mode-locked laser based on single-wall carbon nanotube saturable absorber. We designed a parallel laser cavity, the length of the Yb:YAG waveguide crystal is as short as 5cm. In theory, the repetition rate of pulse is 1.6GHz. The thickness of the Yb:YAG is 0.5cm, which means a great numerical aperture and high coupling efficiency. Direct-bounded waveguide laser has the advantages of small volume and high energy density. Additionally, the configuration of planar waveguide benefits on reducing the heat-lens effects and enhance the output power of the laser. Therefore, it has great application prospects.

8599-67, Session PTue

Tunability of Yb:glass laser

Jan Sulc, Ondrej Krivosudsky, Helena Jelinkova, Czech Technical Univ. in Prague (Czech Republic); Ryszard Stepien, Institute of Electronic Materials Technology (Poland)

Ytterbium doped phosphate glass (5 mol % of Yb2O3, thickness 1 and 2 mm, uncoated), developed for fibre laser, was tested in bulk form as a laser active medium. For Yb:glass pumping fibre coupled (fibre core diameter 100 um, NA=0.22) laser diode with emission at wavelength 975 nm was used. The laser diode was operating in pulsed regime (pulse length 1.5 ms, repetition rate 5 Hz, maximum pulse energy 18 mJ) with low duty cycle to reduce a heat accumulation inside the active medium (Yb:glass was only air-cooled). Longitudinally pumped Yb:glass samples were placed inside the 145 mm long semi-hemispherical resonator formed by a flat pumping mirror (HR @ 1.0-1.1 um, HT @ 0.97 um) and by curved output coupler (r=150 mm). Set of output couplers with reflectivity 91 - 97 % @ 1.0-1.1 um was used. Tuning of the Yb:glass laser was accomplished by using a birefringent filter (single 1.5 mm thick quartz plate) placed inside the optical resonator at the Brewster angle between the output coupler (reflectivity 97 %) and laser active medium. In untuned regime energy up to 2.5 mJ was obtained at wavelength 1050 nm. Slope efficiency up to 20 % in respect to absorbed pumping was reached with the 2 mm sample. In tuned regime the smooth laser tuning curve, limited by used Lyot filter, extended from 1005 nm up to 1085 nm (FWHM 50 nm). The maximum output energy of 1.5 mJ was obtained at 1060 nm for the absorbed energy 15 mJ.

8599-68, Session PTue

Cavity length dependence of mode beating in passively Q-switched Nd-solid state lasers

Nathan D. Zameroski, Space Dynamics Lab. (United States) and Sandia National Labs. (United States); Michael Wanke, David J. Bossert, Sandia National Labs. (United States)

The temporal intensity profile of pulse(s) from passively Q-switched and passively Q-switched mode-locked (QSML) solid-state lasers are known to be dependent on cavity length. In this work, we investigate the pulse width, modulation depth, and beat frequencies of a Nd:Cr:GSGG laser using a Cr+4:YAG passive Q-switch versus cavity length. Measured temporal widths are linearly correlated with cavity length but generally 3-5ns larger than theoretical predictions. Some cavity lengths exhibit pulse profiles with no modulation while other lengths exhibit complete amplitude modulation. The observed beat frequencies at certain cavity lengths cannot be accounted for with passively QSML models in which the pulse train repetition rate is tauRT^(-1), tauRT = round-trip time. They can be explained, however, by including coupled cavity mode-locking effects. A theoretical model developed for a two section coupled cavity semiconductor laser is adapted to a solid-state laser to interpret measured beat frequencies.

We also numerically evaluate the temporal criterion required to achieve temporally smooth Q-switched pulses, versus cavity length and pump rate. We show that in flash-lamp pumped systems, the difference in buildup time between longitudinal modes is largely dependent on the pump rate. In applications where short pulse delay is important, the pumping rate may limit the ability to achieve temporally smooth pulses in passively Q-switched lasers. Simulations support trends in experimental data.

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

8599-69, Session PTue

High energy intracavity pumped eye-safe BaWO4 Raman laser

Ondrej Kitzler, Helena Jelinkova, Jan Sulc, Michal Nemec, Czech Technical Univ. in Prague (Czech Republic); Karel Nejezchleb, Vaclav Skoda, Crytur Ltd. (Czech Republic)

The goal of our research was the intracavity Raman laser emitting short pulses with high peak power in "eye-safe" region around wavelength 1.5 ?m. We use Raman self-conversion of giant pulses at wavelength 1.34 ?m in Raman active crystal BaWO4 (18 mm long, AR coated for pump and Raman radiation). Required high-peak power was reached using Nd:YAG laser (Nd:YAG rod 100 mm long, diameter 4 mm, flash lamp pumped), Q-switched by V:YAG solid-state saturable absorber (initial transmission 41% @ 1.34 ?m). V-shaped oscillator for 1.34 ?m radiation consisted of concave mirror (r = 0.5 m, HR @ 1.34 ?m, HT @ 1.06 ?m), flat polarizing intracavity mirror, and output coupler (R = 96% @ 1.3 ?m, R = 64% @ 1.5 ?m). The polarizing mirror was used to ensure stable linearly polarized laser emission and to prevent parasitic oscillations at 1.06 ?m. The Raman laser oscillator was formed by mentioned output coupler and by another intracavity mirror (HR @ 1.5 ?m, HT @ 1.3 ?m, concave r = 0.5 m), inserted in between BaWO4 and polarizing mirror. For pumping energy 20 J the stable generation of 1th Stokes radiation at 1528 nm was obtained. In a multimode operation the output energy was 15 mJ in 40 ns pulses. Single mode operation was possible to obtain by inserting a 2 mm aperture between Nd:YAG and V:YAG crystal. The output energy drops to 4 mJ and output pulse was shortened to 4 ns. The polarization of generated Raman radiation was vertical.

8599-71, Session PTue

A low jitter single frequency Q-switched laser from solid state to optical fiber configuration

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

A low jitter, single frequency Q-switched solid state laser with precisely controllable firing time was realized and developed by a new injection seeding configuration, in which the oscillator can output energy of near 100 mJ and the master oscillator power amplifier reaches the output energy of 300 mJ, with a pulse width of 10 ns and near single transversal mode. Comparing with two existing techniques, ramp-and-fire and pulse-to-pulse buildup time reduction, this report presents a way of using pulse, instead of CW, injection seeding method to precisely control the high peak energy launching time within a nanosecond jitter and achieve single frequency operation at the same time. The advantage of the realized regime is that in stable laser operation there is no need to adjust the slave cavity length to match the seeded light longitudinal mode. It is found that the slave laser frequency follows exactly to the injected seeded laser longitudinal mode which provides an effective method for frequency tuning, frequency control and locking. Furthermore, this method can be easily extended to the optical fiber laser regime. In fact, due to the easiness to obtain a long cavity length, operation in the fiber laser regime is much easier than its counterpart in solid state regime.

8599-72, Session PTue

DPSS MOPA laser system generating 250 mJ with one nanosecond pulse

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

This report presents a diode-pumped solid state (DPSS) high peak power laser with output energy of 250 mJ, operating frequency of 300 Hz and pulse width of less than one nanosecond. The laser system consists of a master oscillator power amplifier (MOPA) configuration with the output energy of one millijoule from the oscillator, the energy of 12 to 15 millijoules from the pre-amplifier and the energy of 250 mJ from the power amplifier. The transversal mode is very close to the single mode with M2 less than 1.5 and the lasing wavelength is 1064 nm. The MOPA system is well packaged in a compact footprint of 2x3 square feet.

8599-73, Session PTue

Observation of laser beam profile progression inside an extended laser cavity

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

This report presents the result of the laser beam profile progression in target-in-the-loop (TIL) system. This simulation experiment is to verify whether it is possible to form a tight hot spot similar to a single transversal mode in an extended laser cavity. Therefore, it is very important to observe the progression of the laser profile at a laser cavity mirror when a seeded high energy laser pulse is injected into the TIL system. The extended laser cavity is formed with a high reflectivity mirror on one end and an optical phase conjugated mirror as the second mirror, with potential disturbance media inside. The laser oscillation occurs only when it is triggered with a single frequency high energy laser pulse to overcome the threshold condition. With a laser cavity length of around 11 meters and a seeded laser pulse of 10 ns, we have been able to acquire and distinguish the laser beam profiles of each round-trip. Inserting a scattering media and other distortion elements can simulate atmospheric effects.

8599-74, Session PTue

Exploring optical properties of Nd-doped vanadates with intracavity self-mode locking

Hsing-Chih Liang, Jung-Chen Tung, Chia-Han Tsou, Kuan-Wei Su, Yung-Fu Chen, National Chiao Tung Univ. (Taiwan)

Phase and group refractive indices are the important properties of optical materials. The temperature dependence of refractive index is also an important physical quantity of an optical material. In solid-state lasers, it directly influences the pump power induced thermal lensing effect, which in turn limits the scaling-up of the output power, the cavity stability, the oscillation mode size, and the output beam quality. As a result, precise measurement of the temperature dependence of refractive index for laser gain media is practically important for designing high-power solid state lasers.

In this work, we develop a novel method based on intracavity self-mode locking to simultaneously measure the group refractive index and the temperature dependence of refractive index of Nd:GdVO4, Nd:YVO4 and Nd:LuVO4 crystals at the wavelength of 1064 nm and 1342 nm. The experimental results are found to agree very well with the most recent measured values. Experimental results show that GdVO4 and LuVO4 provide somewhat better thermal lensing properties at a-axis and c-axis in these materials.

8599-75, Session PTue

Cr:ZnMgSe laser pumped by 1.7 µm Er:YLF radiation

Maxim E. Doroshenko, A. M. Prokhorov General Physics Institute (Russian Federation); Helena Jelínková, Michal N?mec, Jan ?ulc, Michal Jelínek M.D., Czech Technical Univ. in Prague (Czech Republic); Vitaliy K. Komar, Andriy S. Gerasimenko, National Academy Sciences Ukraine (Ukraine); Vyacheslav M. Puzikov, Valerii V. Badikov, Kuban State Technological Univ. (Russian Federation)

The aim of the presented work is to demonstrate operation of a Cr:ZnMgSe laser pumped by a Er:YLF laser. Laser output characteristics are compared with a Cr:ZnSe laser operated under the same conditions. Pumping 1.74 um Er:YLF laser (Er:YLF rod 80 mm long, flashlamp-pumped) radiation was focused into the Cr:ZnMgSe or Cr:ZnSe crystal (thickness 4.9 mm and 2.2 mm, respectively; absorption coefficient 4.5 and 11 cm-1 @1.73um, respectively). Maximum pumping energy incident on the crystal input face was 65 mJ. The active crystal was inserted into the stable non-selective optical resonator or into the resonator with a wavelength-selective element. The 79 mm long non-selective resonator was formed by a flat dichroic pumping mirror (HT@1.74um, HR@2.4um), and a concave output coupler (R=95%@2.4um, r=500mm). The maximal output pulse energy and efficiency with respect to the incident pumping energy were 10 mJ and 20% for the Cr:ZnMgSe laser, and 16 mJ and 30% for the Cr:ZnSe laser. Central emission wavelength was 2.45 and 2.40 um for the Cr:ZnMgSe and Cr:ZnSe laser, respectively. Spectral line-width of ~60 nm was observed in both cases. The output beam spatial profile was Gaussian in both axes and the pulse duration was ~120 us. In the case of 107 mm long selective resonator the MgF2 Lyot filter was inserted between the active crystal and the output coupler. Output wavelength tuning was obtained in the range 2.34–2.55 um and 2.30-2.52 um for the Cr:ZnMgSe and Cr:ZnSe laser, respectively. Maximum output energy was ~4 mJ in both cases.

8599-76, Session PTue

Simulation of ultrashort laser pulse stretching and compression with chirped volume Bragg grating

Xiao Yuan, Jiansheng Feng, Xiang Zhang, Kuaisheng Zou, Shang Wu, Soochow Univ. (China)

Ultrashort laser pulses with high peak power and short pulse width have been widely used in various fields of science, medicine and engineering such as spectroscopy, optoelectronics, communication techniques and material processing. As one of the art technologies in high power laser facilities, chirped pulse amplification (CPA) has been the most effective approach to obtain ultrashort laser pulses. The most widely used dispersion element is the surface grating of which the laser damage threshold is not ideal, and improving the laser beam power requires the increase of the grating size. Petawatt-class systems would require surface gratings exhibiting ruled areas of approximately 1m?1m, which is quite difficult in fabrication. Chirped volume Bragg gratings (CVBGs) may be an alternative dispersion element due to the high laser damage threshold, simple configuration and easy alignment.

The beam propagation in chirped volume Bragg gratings (CVBGs) is characterized with an F-matrix method. The stretching and compression of ultrashort laser pulse with CVBGs is numerically studied. The frequency response of CVBGs is a gate-like function, and the peak diffraction efficiency grows monotonously as the increase of the grating thickness and amplitude of refractive index modulation in photothermorefractive (PTR) glasses. The group delay of CVBGs is almost linear but has fast oscillations in the passband. The well-designed CVBGs can compress a linear chirped pulse into a Fourier-Transform-Limited (FTL) one and stretch a FTL pulse into a pulse of arbitrary duration. Moreover, the bandwidth of CVBGs should be chosen as three times of the original Gaussian shaped pulse to improve the compression or stretching efficiency and the pulse distribution.

8599-77, Session PTue

Characterization of polarizing splitter optics in extreme environments

Ryand J. F. Tucker, Matthew Olson, Gregg L. Morelli, Honeywell Federal Manufacturing & Technologies, LLC (United States)

Development of laser systems capable of surviving extreme conditions experienced in military applications requires mounts and components that are able to survive these conditions. The characterization of mounted and/or bonded optical assemblies in harsh environments is critical for the development of laser and optical systems for functionality in these extreme conditions. Customized mounts, bonding assemblies and packaging strategies are utilized to develop and field reliable and robust optical subassemblies. Thin film polarizers operating at 45 deg and polarizing beam splitter cubes were chosen for initial testing based on past experiences, advancements in optical coating and construction technologies and material properties. Shock, vibration, shear strength, tensile strength and temperature testing are performed on mounted polarizing beam splitter cubes and thin film polarizers from two manufacturers.

Previous testing showed that polarizing beam splitter cubes constructed using epoxy would become damaged in the laser resonator. The cubes being tested in this report are constructed using epoxy- free direct optical contact bonding. Thin film polarizers operating at 45 deg are chosen opposed to Brewster's angle thin film polarizers to reduce the size and simplify design and construction since an optical wedge is not required. The components and mounts are each environmentally tested beyond the manufacturers' specifications for shock, vibration, and temperature. Component functionality is monitored during and after the environmental testing. Experimental results from the testing will be discussed as will the impact on future laser resonator designs.

8599-78, Session PTue

Optical extraction model including ASE loss for a CW quasi-three level thin disk laser

Drew A. Copeland, General Atomics Aeronautical Systems, Inc. (United States)

It is well–known that amplified spontaneous emission (ASE) can be a major source of upper laser level loss in high gain solid state lasers. Using the well-known, but simplified, quasi-three level kinetics model of Beach [1] and Bourdet [2] an exact analytical solution of the coupled medium and geometric, plane-wave optical propagation equations for a longitudinally or face-pumped CW thin disk laser was obtained in the absence of ASE losses by Copeland [3]. Using a new approximate expression for the rate of the upper laser level loss due to ASE [4] that model has been updated to include ASE loss. Unlike the ASE loss model of Speiser [5] it includes the effect of ASE line narrowing and unlike the model of Vretenar et al [6] it scales more correctly with disk volume. The optical extraction model, which accounts for both laser wave amplification and pump wave absorption saturation coupling, treats both one- and two-face pumping of the disk. A simple transcendental equation for the small signal laser gain as well as analytical expressions for the laser output power, the absorbed pump power, the threshold pump power, and the pump absorption, optical-to-optical, optical extraction, and slope efficiencies are obtained. Finally, a transcendental equation to determine the outcoupling which maximizes the optical-to-optical extraction efficiency as a function of mirror loss and pump power is derived. As an example the theory is applied to the Yb:YAG gain medium.

References:

[1] R. J. Beach, "Optimization of Quasi–Three Level End–Pumped Q–Switched Lasers," IEEE Journal of Quantum Elec¬tronics, Vol. 31, No. 9, September 1995, 1606–1613.

[2] G. L. Bourdet, "Theoretical Investigation of Quasi–Three–Level Longitudinally Pumped Continuous Wave Lasers," Ap¬plied Optics, Vol. 39, No. 6, 20 February 2000, pages 966–971.

[3] D. A. Copeland, "Optical Extraction Model and Optimal Outcoupling for a CW Quasi–Three Level Thin Disk Laser," in Solid State Lasers XX: Technology and Devices, edited by W. Andrew Clarkson, Norman Hodgson, Ramesh Shori, Proceedings of the SPIE Volume 7912, 79120D 1-28 2011.

[4] D. A. Copeland, "Amplified Apontaneous Emission (ASE) Models and Approximations for Thin–Disk Laser Modeling," Paper Submitted to SPIE LASE 2013, Solid State Lasers XXII: Technology and Devices, San Francisco, CA, 2013.

[5] J. Speiser, "Scaling of Thin–Disk Lasers, Influence of Amplified Spontaneous Emission," JOSA B, Vol. 26, No. 1, January 2009, pages 26–35.

[6] N. Vretenar, T. Carson, T. C. Newell, T. Lucas, W. P. Latham, and P. Peterson, "YB:YAG Thin–Disk Laser Performance at Room and Cryogenic Temperatures," in Solid State Lasers XXI: Technology and Devices, edited by W. Andrew Clarkson and Ramesh K. Shori, Proceedings of the SPIE Volume 8235, 82350S 2012.

8599-79, Session PTue

High gain coherent image amplifier

Anatoliy Khizhnyak, Vladimir B. Markov, Advanced Systems & Technologies, Inc. (United States); Douglas M. Craig, Air Force Research Lab. (United States); Shiang Liu, Advanced Systems & Technologies, Inc. (United States)

Laser illumination of remote objects allows their active imaging, tracking and ranging in low-intensity ambient light. Furthermore, coherent laser illumination enables essential information to be derived on the object of interest to allow better discrimination from the background and obtain detection parameters critical for its characterization, including its 3D state vector, velocity, spectrum of vibration, and coherent imaging. However, for long-range operation, the intensity of the backscattered signal becomes very low and requires amplification for reliable detection. The estimated gain level of such a coherent amplifier should be on the order of 100 dB or higher. This level of gain can be achieved in multi-path geometry through a single or multi-stage amplifier. The latter is preferable for coherent enhancement of the signal intensity when the amplified radiation is not diffraction-limited. The problem, however, is that maintaining a high level of amplification is non-trivial ? mainly because the amplified spontaneous emission requires special insulators between the stages of amplification. All of this makes the system very complex and causes less reliable performance.

It has been demonstrated that the solution to this problem can be achieved by applying the intracavity amplification technique. This method, however, requires precise synchronization of the spectra of the radiation to be amplified and the resonator modes – a technique that is difficult to achieve, especially when dealing with signals from a remote, fast-moving object.

This presentation will discuss the results of the theoretical analysis and experimental studies of intra-cavity image amplification based on the method of image injection, which allows successful operation without matching the spectra of the incoming (object-returned) signal and the modes of the resonator.

8599-80, Session PTue

High energy diode-pumped 5th harmonic generation of Nd: YAG laser

Xiaoyuan Peng, Enlight Technologies, Inc. (United States); Yang Yu, Chee Yuen Cheng, Yong Poo Chia, Saw Soon Yong, Ngee Ann Polytechnic (Singapore)

This paper reports a QCW high energy diode-pumped 5th harmonic generation of Nd: YAG laser system, which can generate up to 3mJ per pulse TEM00 mode output with 100 Hz repetition rate at 213 nm. A diode-pumped air-conduction cooled module is specially designed for a high efficiency and good beam quality at the fundamental wavelength 1064 nm. An air-cooled amplifier is set up out of the cavity to boost up the energy level at fundamental wavelength. In order to get high efficiency of the 5th harmonic generation, the cavity of the fundamental wavelength is EOM Q-switched which can generate very high peak power of the fundamental wavelength laser for extra cavity harmonic generations. In the harmonic generator, a non critical phase-matched LBO crystal is used for second harmonic generation, and 2 CLBO crystals are used for 2th and 5th harmonic generation. Finally, up to15% conversion efficiency from IR to UV is achieved, which is the highest efficiency reported to the best of our knowledge at 213nm in TEM00 mode (M^2~1.15). The deep UV wavelength of 213 nm is a very good substitute of 193 nm for different UV applications, the system of which is more compact, higher energy, less maintenance and better beam quality than the system of 193 nm.

8599-81, Session PTue

Experimental and simulation studies on a high-efficient, high-peak power diode pumped passive Q-switched and self Q-switched of Nd: YVO4 laser at both 1064 nm using Cr: YAG and 532 nm using KTB Crystal, respectively

Ashraf F. El-Sherif, Military Technical College (Egypt); Mahmoud M. Talaat, Military Technical Institute (Egypt)

Diode end-pumped solid-state Lasers have the potential to yield high quality Laser beams with high efficiency for Laser range finding and warning receiver applications as well as day and night military designation systems. This paper presents theoretical calculations using Advanced Dynamics Professional LASCAD software and experimental studies for a high power pigtailed fiber diode Laser module of 8 W operating at 808 nm with a specially designed high efficiency cooling system, end pumped high-efficiency Nd: YVO4 Laser of 3?3?10 mm rod and overall cavity length of 44 mm. An optical to optical slope efficiency of around 76%, the final conversion efficiency of 60% and an output Laser power of 4.1W at 1064 nm Laser were investigated with a high beam quality factor M2, and the threshold input pump power of 860mW was measured, which was in a good agreement with the theoretical calculations (710mW). A high power second harmonic Nd: YAG CW Laser at 532 nm (green Laser) was achieved with an optical to optical slope efficiency of 66% and a final conversion efficiency of 56% using a 5?5?8 mm KTP crystal inside the same 1064 nm CW Laser and water cooling systems. The green Laser output power of 3.4W at incident diode Laser power of 6 W was measured. To the best of our knowledge a self Q-switching effects was generated in Nd: YVO4 Laser by changing the cavity dimensions and the position of the intracavity KTP crystal at certain regime, in which the cavity length is reduced to be 30 mm and the distance between Nd: YVO4 rod and KTP crystal is only 1mm. Self Q-switched Laser at 532nm with high peak power of 96 W, pulse width of 8 ns at FWHM and repetition rate of 1kHz was achieved. Experimental studies of a passive Q-switched Nd: YVO4 Laser using Cr: YAG crystal with three different transmissions of 30%, 40% and 70% were investigated. Passive Q-switched Laser at 1064nm with high peak power of 250W, pulse width of 4ns at FWHM and repetition rate of 140kHz using Cr:YAG with transmission of 30% was achieved. The main application for the investigated effect is generation of an efficient and repetitive high peak power self Q-switched second harmonic Nd: YVO4 Laser system that can be realized without the need of using passive Q-switched saturable absorber mirror.

8599-82, Session PTue

Development of kW class Nd:YAG composite ceramic thin disc laser

Koichi Iyama, Osaka Univ. (Japan) and ALPROT (Japan) and Hamamatsu Photonics K.K. (Japan); Ravi Bhushan, Osaka Univ. (Japan); Hiroyuki Furukawa, Osaka Univ. (Japan) and ALPROT (Japan); Koji Tsubakimoto, Hidetsugu Yoshida, Hisanori Fujita, Osaka Univ. (Japan); Masayuki Fujita, Osaka Univ. (Japan) and ALPROT (Japan); Noriaki Miyanaga, Osaka Univ. (Japan); Yoshinori Tamaoki, Yoshinori Kato, Toshiyuki Kawashima, Osaka Univ. (Japan) and Hamamatsu Photonics K.K. (Japan)

We are developing a high-repetition and high-average-power Nd:YAG laser amplifier pumped by fiber coupled LDs in order to apply to laser machining of a carbon composite material (CFRP: Carbon Fiber Reinforced Plastic). Final target output is 1.5kW at wavelength of 1064nm by 8kW LD pumping. The amplifier is compact whose structure is several Nd:YAG composite ceramic thin discs on a non-doped ceramic YAG block. The prototype amplifier of kW-class amplifier for CFRP processing was produced. Moreover, measurement of wave-front distortion and a small-signal-gain was performed. As a result of measuring wave-front distortion, the component of wave-front distortion of the amplifier became clear, and we considered the wave-front compensation method about each component. Main component is defocus. Peak-to-Valley value is 19? at 1kW pumping. It can be compensated by lens system. Higher order components are ?2? at 1kW pumping. It can be compensated by deformable mirror. From the measurement result of the small-signal-gain, we had known that gain loss was by the temperature difference on Nd:YAG and seed laser of a broad spectrum causes. As a result of amplification test of seed laser of a narrow spectrum by 1kW LD pumping, small-signal-gain was 2.1. It agreed on the calculated value. kW-class amplifier was designed and the calculation result in which the maximum output power exceeds 1 kW was obtained. From now on, kW-class amplifier will be manufactured and an amplification test will be performed.

8600-1, Session 1

Bistable behavior of a continuous optical discharge as a laser beam propagation effect *(Invited Paper)*

Mikhail Y. Yakimov, Vladimir A. Kuznetsov, Nikolai G. Solovyov, Andrei N. Shemyakin, Vladimir P. Zimakov, A. Ishlinsky Institute for Problems in Mechanics (Russian Federation)

The results of the first experimental investigation of a continuous optical discharge sustained by radiation of CW ytterbium fiber laser at 1.07 um are presented. High temperature plasma was sustained in pure Xe contained in a quartz bulb of a standard short-arc high pressure Xe lamp. Laser radiation was focused inside the bulb and laser sustained plasma has being initiated from arc column when the laser power was increased above a certain threshold value.

The threshold value of COD sustained by 1.07 um laser was found to be on the level of tens watts - surprisingly lower than an expected theoretically estimated value of hundreds watts. The discrepancy may be explained by the contribution of bound-bound Xe atom transitions which are difficult to consider correctly only by estimations without detailed calculations.

The absorption coefficient of laser radiation found in the experiments (up to 10 cm-1) was also correspondingly higher than estimated values (of the order of 1 cm-1).

It was also found that laser beam refraction in plasma is strong and critical for the plasma stability at higher gas pressure and higher laser power.

Two stable configurations of a continuous optical discharge (COD) were observed in experiments with plasma sustained continuously in Xe at high pressure by radiation of a medium power CW ytterbium fiber laser.

One is the plasmoid of nearly spherical or ovoid shape with one temperature maximum and relatively small length and laser beam absorption of 10-30%. The other one is the plasma formation stretched along the laser beam with two or more local temperature maxima. The laser beam absorption in the second plasma configuration is increased dramatically up to 70-80% due to increased plasma length.

Both plasma shapes were obtained under close conditions, so that oscillations between the two states were possible and also have being observed.

The effect was studied and explained on the base of simplified consideration of the laser beam propagation in plasma including beam absorption and refraction.

Other experimental results on the sustaining conditions of COD and plasma properties are also presented and discussed: particularly the dependence of the threshold laser power on the gas pressure and focused beam aperture ratio.

8600-2, Session 1

Extremely high power CO2 laser beam correction *(Invited Paper)*

Ann Lylova, Alexis V. Kudryashov, Alexander Alexandrov, Vadim Samarkin, Alexey Rukosuev, Moscow State Open Univ. (Russian Federation)

No Abstract Available

8600-3, Session 1

Optimization of the intra-cavity optical flux in the unstable direction in RF excited annular CO2 laser in terms of power stability

Viktor Granson, Francisco J. Villarreal-Saucedo, Jochen Deile, Jesus F. Monjardin, Shadi S. Sumrain, TRUMPF Inc. (United States)

Modern high power industrial CO2 lasers are the result of decades of technological advancements aimed to improve laser parameters such as gain and saturation intensity to obtain the best power extraction efficiency. In this paper a resonator optimization approach will be presented that includes laser power stability as one of the criteria for selecting the best configuration. This approach is applied to a hybrid stable-unstable annular RF excited CO2 laser.

A ray tracing method is used to track the internal beam propagation as a function of the mirror geometry. The method allows to estimate the number of roundtrips for a given resonator geometry. The control of power stability is based on the assumption, that excessive internal beam path will promote residual gain amplification and result in abnormal power fluctuations. The ray tracing method allows tailoring of the internal beam path to the given boundary conditions of the laser medium, which are the small signal gain and saturation intensity.

Experimental results, where the laser output power is recorded in dependence of resonator configuration in the unstable direction, confirm the calculated data.

Gained knowledge of the upper limit of the optical gain benefits improved power stability with less than 1% power variation without compromising the high power extraction.

By optimizing the geometry of the laser active medium in the unstable direction, the overall extracted power efficiency improves by 8%. This is achieved by minimizing the RF discharge region while keeping the laser output power constant at the same time.

8600-5, Session 2

Pulse compression and beam quality improvement of a single-frequency Nd:YAG MOPA system

Oliver Lux, Hristomir Stankov, Haro Fritsche, Hans Joachim Eichler, Technische Univ. Berlin (Germany)

Stimulated Brillouin scattering phase conjugation (SBS-PC) offers the opportunity to reduce the pulse duration of high brightness solid-state lasers. This feature can be combined with the compensation of thermally induced phase distortions of the active medium if a phase conjugate mirror is employed in a double-pass amplifier arrangement. The SBS behavior of the heavy fluorocarbon liquid FC-77 was studied with a single-frequency Nd:YAG laser at 1064 nm wavelength with pulse energy of 0.25 mJ, pulse duration of 2.1 ns and repetition rate of 10 Hz. The nearly diffraction-limited output radiation (M? = 1.3) was coupled into a double-rod Nd:YAG amplifier arrangement which - in single-pass operation - increases the output energy to 5 mJ. Although the amplifier incorporates birefringence compensation, the beam quality degrades with increasing amplification level yielding M?-values of up to 1.9. The amplified laser pulse was then focused into a SBS cell filled with FC-77 realizing a double-pass through the two amplifier rods. The output pulse energy accounted for 10 mJ. Analysis of the spatial and temporal properties of the SBS-reflected radiation yielded an improvement of the beam quality compared to the single-pass configuration (M? = 1.4) as well as pulse compression to less than 800 ps. The utilization of different focusing lenses in front of the SBS cell revealed different behavior of

the compression rate with increasing pump energy. In case of strong focusing, the pulse duration is shortest for low pump energies. However, for longer focal lengths the compression rate increases with pump energy.

8600-6, Session 2

Wavefront measurement and data analysis of XUV HHG beam

Pavel Homer, Bedrich Rus, Jaroslav Nejdl, Jan Hrebicek, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

Extensive measurements of wavefront profile of the coherent XUV (eXtreme Ultra-Violet) HHG (High-order Harmonics Generation) beam at the wavelength of 30nm have been performed. The unique results have been achieved using the PDI (Point Diffraction Interferometer) technique. The basic principle of the PDI is simple – ultrathin aluminium foil with a miniature pinhole – and it benefits from the self-referencing feature which is very important due to the measured wavelength. On the other hand, a fabrication and experimental measurements are very difficult in this spectral domain. We present basic principles, experimental setup, novel alignment techniques, unique obtained data and their analysis.

8600-7, Session 2

Interaction of UV and IR filaments *(Invited Paper)*

Ladan Arissian, Jean-Claude M. Diels, The Univ. of New Mexico (United States)

No Abstract Available

8600-8, Session 2

Resonator interrogation using pulse interferometry

Amir Rosenthal, Daniel Razansky, Vasilis Ntziachristos, Helmholtz Zentrum München GmbH (Germany)

Resonator interrogation in sensing applications is mostly performed by using coherent or incoherent continuous-wave sources. Coherent techniques are usually characterized by higher sensitivity, whereas incoherent techniques enable multiplexing several resonators with a single source and offer compatibility with passive demodulation technique, leading to higher stability against environmental conditions. In this work we developed an alternative interrogation method in which pulsed lasers are used as the interrogating source. The use of coherent light leads to high sensitivities, whereas the wide spectrum can be used to multiplex numerous resonators with a single source.

The unique properties of the pulse-interferometry interrogation approach are studied theoretically and experimentally. It is found that amplified spontaneous emission is the main limiting factor on the sensitivity achieved. Methods for noise reduction in the proposed scheme are presented and experimentally demonstrated, while the overall performance is validated for broadband optical detection of ultrasonic fields using a fiber Bragg grating as the resonator. The achieved sensitivity is equivalent to the theoretical limit of a 6 MHz narrow-line width laser, which is 40 times higher than what can be achieved by incoherent interferometry for the same optical resonator.

We developed here a new optical-resonator interrogation scheme based on wideband pulse interferometry, capable of achieving high stability against environmental conditions without compromising sensitivity. Specifically, the method is compatible with passive demodulation techniques which do not require stabilization and could be resistant to shocks. Additionally, pulse interferometry may be used for multiplexing numerous resonators with a single interrogating source. The unique properties of the pulse-interferometry interrogation approach are studied theoretically and experimentally. It is found that amplified spontaneous emission is the main limiting factor on the sensitivity achieved. Methods for noise reduction in the proposed scheme are presented and experimentally demonstrated, while the overall performance is validated for broadband optical detection of ultrasonic fields using a fiber Bragg grating as the resonator. The achieved sensitivity is equivalent to the theoretical limit of a 6 MHz narrow-line width laser, which is 40 times higher than what can be usually achieved by incoherent interferometry for the same optical resonator.

In conclusion, its unique combination of properties makes pulsed interferometry an alternative to standard CW-based resonator interrogation technique and enable new sensing applications.

8600-9, Session 3

Terabit/s data transmission using frequency combs *(Invited Paper)*

Christian Koos, Jürg Leuthold, Wolfgang Freude, Karlsruher Institut für Technologie (Germany); Tobias J. Kippenberg, Ecole Polytechnique Fédérale de Lausanne (Switzerland) and Max-Planck-Institut für Quantenoptik (Germany); Joerg Pfeifle, Claudius Weimann, Karlsruher Institut für Technologie (Germany); Tobias Herr, Ecole Polytechnique Fédérale de Lausanne (Switzerland); Klaus Hartinger, Ecole Polytechnique Fédérale de Lausanne (Switzerland) and Menlo Systems GmbH (Germany); Ronald Holzwarth, Max-Planck-Institut für Quantenoptik (Germany) and Menlo Systems GmbH (Germany); David Hillerkuss, Rene Schmogrow, Karlsruher Institut für Technologie (Germany)

As data rates in world-wide communication networks and warehouse-scale datacenters continue to grow exponentially, the fundamental limits of electrical interconnects in terms of bandwidth, spatial density and power consumption become increasingly obvious. Optical interconnects are the most promising option to overcome these bottlenecks. By using highly parallel wavelength division multiplexing (WDM) schemes with tens or hundreds of channels, high aggregate transmission capacity can be provided while keeping symbol rates compliant with the electrical bandwidth of CMOS driver circuitry. Silicon photonics provides a platform for CMOS-compatible integration of the corresponding photonic-electronic interface, but scalability at the transmitter side is still limited by the lack of adequate optical sources. Hybrid integration of III-V-dies on silicon is a promising approach to realize on-chip active devices, but dense integration of tens of narrowband DFB lasers is technologically challenging and subject to thermal constraints.

In this talk, we will discuss an alternative approach to Terabit/s data transmission which relies on using frequency combs as optical sources. Frequency combs consist of a multitude of equidistant and narrowband spectral lines, each of which can be used for data transmission. In a proof-of-principle experiment, we have used a mode-locked solid-state laser and subsequent spectral broadening in a highly nonlinear fiber (HNLF) to generate a broadband comb with a line spacing of 12.5 GHz. A total number of 325 optical carriers were extracted from the comb and modulated with dual-polarization 16 QAM signals at a symbol rate of 12.5 GBd, resulting in an aggregate data stream of 32.5 Tbit/s. The data was transmitted over 227 km of standard single-mode fiber, thereby achieving a spectral efficiency of 6.4 bit/s/Hz. We are currently exploring the potential of high-Q silicon-nitride (SiN) microresonators as frequency comb generators for high-speed data transmission. In a first experiment, we have demonstrated transmission of an aggregate data rate of 170.8 Gbit/s on four channels. By systematically investigating the received data signals, we identify the occurrence of multiplet spectral lines as the main source of impairment. We expect that multiplet generation can be avoided by careful dispersion engineering and advanced pumping schemes, thereby enabling efficient Terabit/s data transmission with chip-scale frequency comb sources.

8600-10, Session 3

Four-wave-mixing parametric oscillations in dispersion-tunable micro-bubble resonators

Ming Li, Xiang Wu, Liying Liu, Lei Xu, Fudan Univ. (China)

High-Q Whispering-gallery modes (WGM) optical cavities are widely used in photonic devices including optical bio-sensors, optical filters, wavelength converters, optical switching devices and frequency comb generators [1-5] due to their ultra-high Q and small mode volume. To generate frequency comb, microcavities should be working in anomalous dispersion region which requires manipulating geometric dispersion of the cavity mode by shaping the cavity geometry.

In this work, the resonance mode dispersion of micro-bubble resonators (MBRs) is analyzed. By changing the radius and the thickness of a MBR, the geometrical dispersion and the zero-dispersion-wavelength (ZDW) of the cavity can be largely adjusted. As a result, four wave mixing parametric oscillation is experimentally realized in MBRs.

The resonant mode dispersion can be reflected in variation of FSR, which is ??n = (?n+1-?n)- (?n-?n-1), with ??n being the resonance frequency of the nth mode. The FSR variation owning to the material dispersion is given by

??≈(c^2 ?^2)/(?4π?^2 n^3 R^2) GVD?

where R and n are the radius and refractive index of the resonator, c is the speed of light in vacuum, GVD is the group velocity dispersion parameter[5]. In micro-bubbles, in addition to cavity size, bubble thickness is also a parameter that determines dispersion. We numerically calculated the resonance wavelength of micro-bubbles with different thickness (T) and outer radius (R) by Mie scattering theory. To calculate the overall dispersion of micro-resonators, both the geometrical and material dispersion should be taken into consideration. An iterative approach was chosen to add the material dispersion contribution to our calculation. Fig.1 (a) shows the calculated overall FSR variation of MBRs with different thickness at 1.55?m, and the bubble radius varies from 50 to 150 ?m. The dispersion curve of a solid microsphere is also plotted as a reference. With smaller T, the curve moves upward and the anomalous dispersion region (??>0) expands. Therefore the ZDW of MBRs can be tuned by changing the radius and the thickness of a MBR (Fig.1 (b)).

We experimentally demonstrated the effect of dispersion compensation by observing FWM parametric process in MBRs. The MBRs are fabricated by the fuse-and-blow technique. Fig2 (a) is the image of one MBR. The Q factors of the MBRs are around 6?10(7).

MBR is optically pumped via a tapered fiber. For a 110 ?m diameter MBR with the thickness around 10 ?m, only stimulated Raman scattering is observed, because phase match condition for FWM is not satisfied. FWM parametric oscillations occurs when the MBR thickness decreases to about 4 ?m (Fig.2 (b)), at which an anomalous overall dispersion appears near 1.55 ?m.

In summary, we demonstrated that the geometrical dispersion and the ZDW of MBRs can be tuned by changing the radius and the thickness of the micro-cavities. Four wave mixing parametric oscillation was observed in the dispersion compensated microcavities.

8600-11, Session 3

Microcombs and SBS lasers using wedge resonators *(Invited Paper)*

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

We describe a chemically etched ultra-high-Q resonator that attains Q factors of nearly 1 billion and is fabricated from silica on a silicon chip. Application to micro combs and narrow line width SBS lasers is also reported, as well as fabrication of low-loss delay lines

8600-12, Session 3

On phase locking phenomena in Kerr combs

Aurelien Coillet, Irina Balakireva, Remi Henriet, Laurent Larger, Yanne K. Chembo, FEMTO-ST (France)

Kerr combs have been the focus of an intense research activity in recent years. They are generated through four-wave mixing in ultra-high Q optical whispering gallery-mode resonators. For most of applications, it is critical that the excited modes in the comb remain phase-locked. For example, the phase correlation ensures a pulsed behavior in the time domain. Most importantly, if we extract the microwave signal corresponding to the free spectral range, this phase correlation ensures a high stability for the microwave intermodal frequency. However, despite its importance as far as applications are concerned, this mode-locking process is not completely understood, and the phase-correlation law between the various spectral components of the comb remains an open problem. We use a modal expansion formalism to unveil the mechanism behind Kerr comb phase-locking, and we determine the correlation law as the spectral span between the pump and the sidemodes increases. We also link the pump power and its detuning relatively to the resonance frequency to the degree of phase correlation in the comb. This work is expected to provide a quantitative insight for the integration of Kerr combs in microwave photonics technology.

8600-13, Session 4

Laser emission and thermal effects in Nd3+ doped glass microspheres, observed, and studied without coupling devices

Leopoldo L. Martin, Carla Perez Rodriguez, Univ. de La Laguna (Spain); Daniel Navarro-Urrios, Univ. de Barcelona (Spain); Inocencio J. Martin, Nestor E. Capuj, Univ. de La Laguna (Spain)

Lasers based on microcavities are extremely attractive for their compactness, low power dissipation and potential for ultrafast modulation speed. The spherical symmetry for doped glasses stands out because light is trapped internally by continuous reflections at the glass surface providing high Q and acting both as active medium and laser cavity.

Microspheres were fabricated from rapid quenching of liquid droplets of fused Barium Titanium Silicate glass doped with Nd3+ ions.

To observe laser emission, high Quality factor microspheres (selected by its sharp and narrow whispering gallery mode pattern) were pumped by the 514 nm line of an Argon laser at room temperature. The emission was collected by a microscope objective and measured in a spectrograph. In this scheme neither a pumping nor detection devices have been coupled to the sphere.

The laser emission occurs on the gain band of the Nd3+ ion, between 1060 nm and 1070 nm.

Temperature effects were studied in terms of the resonance shift (previously calibrated to be 11 pm/K) and intensity (that was previously measured on bulk samples).

Significant differences were found in the laser threshold by pumping at continuous wave or chopped pump. About this fact it has been found that is related to thermal effects that produce a quenching in the emission of the Nd3+ ions.

8600-14, Session 4

Low threshold ultraviolet lasers based on Ce:LiCaAlF6 crystal resonator *(Invited Paper)*

Nan Yu, Thanh T. Le, Jet Propulsion Lab. (United States); Steven J. Schowalter, Wade Rellergert, Justin Jeet, Univ. of California, Los Angeles (United States); Guoping Lin, Jet Propulsion Lab.

(United States); Eric Hudson, Univ. of California, Los Angeles (United States)

As high-Q devices, whispering gallery mode (WGM) optical resonators have been widely explored for laser and nonlinear optics applications. So far, most of the investigations have been limited between visible and NIR wavelengths because of material absorption properties. However, many crystalline materials have excellent transparency in the UV and VUV and can be similarly studied. The achievable high Q combined with small mode volume in WGM resonator cavities results in a significant reduction of the lasing threshold, opening the door to new laser materials. In this paper, we report results toward the first solid-state, low-threshold cw UV laser based in WGM resonators. We use WGM resonators constructed from LiCaAlF6 crystal, which is transparent down to ~110 nm and has been used as the host crystal for Ce+ doped UV lasers. We have fabricated LiCaAlF6 WGM resonators with Q = 2.6x107 at 370 nm and show that, with proper Ce+ doping concentration, it is possible to achieve the cw lasing threshold with a pump power of only 2.4 mW. Experimentally, we have demonstrated a UV laser at 290 nm with a pulsed pump laser at 266 nm, with a pump threshold of 60 nJ and slope efficiency of 38%. In the pulsed operation, we have also observed lasing delay dynamics. These results are consistent with our modeling and theoretical estimates for the experimental condition used, and pave the way for a low threshold cw UV laser using WGM resonator cavity.

8600-15, Session 4

Mid-IR WGM lasers *(Invited Paper)*

Andrey M. Monakhov, Viktor V. Sherstnev, Elena Grebenshchikova, Ioffe Physico-Technical Institute (Russian Federation); Alexei N. Baranov, Univ. Montpellier 2 (France); Yury Yakovlev, Ioffe Physico-Technical Institute (Russian Federation)

Semiconductor lasers operating in the middle-IR spectral range are of considerable interest for numerous practical applications. In particular, these lasers constitute the basis for wireless communication systems, for some medical facilities, have promising applications in various fields of biology and ecology [1]. In recent years, much attention has been focused on lasers with circular resonators (cavities) operating via the whispering-gallery modes (WGMs) [2]. The cavities of WGM-lasers have a high Q-factor that can compensate the low gain, reduce the values of threshold current in comparison with the stripe-resonator Fabry-Perot lasers.

The WGM-like modes in ring cavities and microdisks have been studied both theoretically and experimentally at shorter wave-lengths [3]. For visible and near-infrared semiconductor lasers WGM cavity is not an optimal choice, but for the MID-IR wave range, where the nonradiative recombination is high, WGM lasers seem to be a promising device [4].

Our group has fabricated and studied MIR WGM lasers operating in 2-2.5 µm wave range at room temperatures and in the 3-4 µm an the liquid nitrogen temperatures. The laser structure comprised an InAs substrate where successfully grown p-InAsSbP emitter, InAs active layer and n-InAsSb emitter. We have also fabricated a half and quarter-disk WGM lasers [5], which are quite similar to the disk ones, but have higher optical output power.

Inasmuch as a laser is a nonlinear device, a WGM laser is a good object for the exploration of nonlinear phenomena in semiconductor lasers. We have experimentally revealed and theoretically explained the effect of high tunability of WGM lasers with controlled absorber [6]. We also have revealed the self-sustained oscillation system synchronization effect in the two optically-coupled disk lasers system [7]. All this subjects will be the matter of our talk.

References:

1. A.I.Nadezhdinsky http://www.dls.gpi.ru/rus/sem/10/Nad.pdf.

2 V. V. Sherstnev, A. M. Monakhov, A. Krier, and D. A. Wright, IEEE Proc. Optoelectron. 152, 1 (2005).

3. [N.C. Frateschi, and A. F. J. Levi.: Appl. Phys. Lett., 1995, 66, pp. 2932-2934, R.P.Wang, and M.Dumitrescu: "Theory of optical modes in semiconductor microdisk lasers", J. Appl. Phys. , 1997, 81, pp. 3391 -3397. J.R.Davies, and J.T. Mendonca: "Basic physics of laser propagation in hollow waveguides", Phys. Rev. E., Stat. Nonlinear Soft Matter Phys., 2000, 62, pp. 7168 – 7180]

4. A. Krier, V. V. Sherstnev, D. A. Wright, et al., Electron. Lett. 39, 916 (2003).

5. Monakhov, AM, Sherstnev, VV, Astakhova, AP, Yakovlev, YuP, Boissier, G, Teissier, R and Baranov, AN. 2009. Experimental observation of whispering gallery modes in sector disk lasers. Applied Physics Letters. v.94 (5), p. 051102

6. A.N.Baranov, G.Boissier, R.Teissier, A.M.Monakhov, V.V.Sherstnev, M.I.Larchenkov, and Yu.P.Yakovlev, Highly tunable whispering gallery mode semiconductor lasers with controlled absorber. Appl.Phys.Lett. (USA), 100, 061112, (2012).

7. E. A. Grebenshchikova*, V. V. Sherstnev, M. I. Larchenkov, O. Yu. Serebrennikova, N. D. Il'inskaya, A. M. Monakhov, R. Teissier, A. N. Baranov, and Yu. P. Yakovlev Mid_Infrared Radiation Sources Based on Coupled Disk Cavities Technical Physics Letters, 2012, Vol. 38, No. 4, pp. 304–306.

8600-16, Session 4

High gain selective amplification in whispering gallery mode resonators: analysis by cavity ring down method *(Invited Paper)*

Patrice Féron, Ecole Nationale Supérieure des Sciences Appliquées et de Technologie (France) and Ecole Nationale Supérieure des Sciences Appliquées et de Technologie (France); Alphonse Rasoloniaina, Vincent Huet, Elodie Le Cren, Ecole Nationale Supérieure des Sciences Appliquées et de Technologie (France); Stéphane Trebaol, Ecole Polytechnique Fédérale de Lausanne (Switzerland); Gualtiero Nunzi Conti, Istituto di Fisica Applicata Nello Carrara (Italy); Hélène Serier-Brault, Ctr. National de la Recherche Scientifique (France); Michel Mortier, Ecole Nationale Supérieure de Chimie de Paris (France); Yannick Dumeige, Ecole Nationale Supérieure des Sciences Appliquées et de Technologie (France)

Whispering gallery mode 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. In this work, we have used Whispering Gallery Mode (WGM) micro lasers as very selective integrated optical amplifiers. 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. Depending on the pump power at 1480 nm launched in the resonator, a cavity ring down method allows the characteristics of the micro resonators to be measured. From these dynamical measurements, a detailed comparison with a simple numerical model allows a 20 dB amplification in stationary regime in spectral bandwidths around 330 kHz to be deduced. Those devices should be used as integrated optical delay lines or selective filters for opto-electronic applications.

8600-17, Session 5

Laser beam engineering using plasmonics and deformed resonators *(Invited Paper)*

Federico Capasso, Harvard School of Engineering and Applied Sciences (United States)

This talk reviews beam engineering of mid-infrared and terahertz quantum cascade lasers (QCLs), based on two approaches: designer plasmonic structures and deformed microcavities.1 The plasmonic structures couple laser emission into surface waves and control the laser wavefront in the nearfield, thereby greatly increasing beam collimation or introducing new functionalities to QCLs. The plasmonic designs overall preserve laser performance in terms of operating temperature and power output. The deformed microcavity QCLs operate primarily on whispering-gallery modes, which have much higher quality factors than other modes, leading to lower threshold current densities. Cavity deformations are carefully controlled to greatly enhance directionality and output power.

1. N. Yu, Q. Wang, F. Capasso; Laser & Photonics Reviews 6, 24 (2012)

8600-18, Session 5

Narrow linewidth lasers, RF oscillators, and filters with WGM resonators *(Invited Paper)*

Vladimir S. Ilchenko, David J. Seidel, Andrey B. Matsko, Anatoliy A. Savchenkov, Elijah B. Dale, Wei Liang, Jerry L. Byrd, Lute Maleki, OEwaves, Inc. (United States)

We will review recent achievements in performance of narrow-linewidth lasers, Kerr comb microwave oscillators, photonic filters and receivers being developed at as compact hybrid-integration devices based on crystalline and amorhous resonators with whispering-gallery modes.

8600-19, Session 5

High-speed modulation of optical microcavities *(Invited Paper)*

Wesley D. Sacher, Univ. of Toronto (Canada); William M. J. Green, Solomon Assefa, Tymon Barwicz, Huapu Pan, IBM Thomas J. Watson Research Ctr. (United States); Steven M. Shank, IBM Corp. (United States); Yurii A. Vlasov, IBM Thomas J. Watson Research Ctr. (United States); Joyce Poon, Univ. of Toronto (Canada)

Microcavity modulators and laser sources have attracted significant attention in recent years due to their potential to be highly compact and energy-efficient optical transmitters. Such transmitters are promising for short-distance and chip-scale optical networks envisioned for future high-performance computing systems and datacenters. However, a longstanding challenge in resonant modulation has been the trade-off between the modulation efficiency (i.e.the power consumption of the device) and modulation bandwidth, which were thought to depend oppositely on the cavity linewidth.

Here, we show that this trade-off, which depends on the intracavity optical dynamics, can be broken. By modulating the rate of the input/output coupling of the resonator rather than the intracavity index or loss/gain, the traditional trade-offs in resonant modulation can be completely circumvented. We term this mode of operation "coupling modulation." Distinct from the conventional intracavity modulation, coupling modulation works by depleting small amounts of the stored optical energy in the cavity in the transient to form output pulses that have peak powers equal to that of the continuous-wave input. The modulation is resonantly enhanced, because the intracavity field amplitude on resonance is higher than the input by a factor proportional to the cavity finesse. In other words, only a small-amplitude modulation of the coupling coefficient would be required to produce a large swing in the optical output in a high finesse cavity.

We have applied coupling modulation to microring intensity modulators, quadrature modulators, and lasers. For the modulators, we have broken the traditional cavity linewidth limitation to their operation bandwidth and induced chirp. For the lasers, we have broken the relaxation resonance frequency limit to high-speed modulation. Working with collaborators, we are implementing chip-scale versions of these devices in silicon-on-insulator (SOI) and hybrid InP-on-SOI platforms.

8600-20, Session 5

Chalcogenide glass mid-infrared integrated photonics *(Invited Paper)*

Juejun Hu, Yi Zou, Hongtao Lin, Lan Li, Okechukwu Ogbuu, Univ. of Delaware (United States); J. David Musgraves, Sylvain Danto, Kathleen Richardson, Clemson Univ. (United States) and CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

Chalcogenide glasses, namely the amorphous compounds containing sulfur, selenium, and/or tellurium, have emerged as a promising material candidate for integrated photonics given their wide infrared transparency window, almost infinite capacity for composition alloying, as well as high linear and nonlinear indices. This talk will review our recent progress on the processing and characterization of integrated photonic devices based on chalcogenide glass materials. We have shown that high optical quality glass films can be prepared using both traditional vacuum deposition as well as emerging solution derived techniques, enabling an entire array of unconventional device architectures both at the telecommunication wavelengths as well as in the 3-6 micron mid-infrared band. The examples include low-loss mid-infrared glass waveguides and resonant cavities on silicon, and robust tunable photonic devices on a flexible substrate platform. We further demonstrate that these photonic devices constitute the basic building blocks for novel ultra-sensitive chemical sensors with single molecule detection capability, and high performance thermal imagers operating at room temperature.

8600-21, Session 6

Bose-Einstein condensation of photons in a microscopic optical resonator *(Invited Paper)*

Martin Weitz, Rheinische Friedrich-Wilhelms-Univ. Bonn (Germany)

Bose-Einstein condensation has in the last two decades been observed in cold atomic gases and in solid-state physics quasiparticles, exciton-polaritons and magnons, respectively. The perhaps most widely known example of a bosonic gas, photons in blackbody radiation, however exhibits no Bose-Einstein condensation, because the particle number is not conserved and at low temperatures the photons disappear in the system's walls instead of massively occupying the cavity ground mode. This is not the case in a small optical cavity, with a low-frequency cutoff imprinting a spectrum of photon energies restricted to well above the thermal energy.

In this talk, an experiment observing Bose-Einstein condensation of photons in a microscopic optical cavity filled with dye solution is reported [1]. The cavity mirrors provide both a confining potential and a non-vanishing effective photon mass, which makes the system formally equivalent to a two-dimensional gas of trapped, massive bosons. By multiple absorption-reemission processes, the photons thermalize to the temperature of the dye solution. Signatures for a BEC upon increased photon density include a spectral distribution that shows Bose-Einstein distributed photon energies with a macroscopically populated peak on top of a thermal wing, the observed threshold of the phase transition showing the predicted absolute value and scaling with resonator geometry, and condensation at the trap center even for a spatially displaced pump spot.

Recently, we have furthermore started to investigate the number statistics of photon Bose-Einstein condensates. The current experimental status will be reported.

[1] J.Klaers, J.Schmitt, F.Vewinger, and M.Weitz, Nature 468, 545 (2010).

8600-22, Session 6

Bright squeezed light under conditions of second harmonic generation in a whispering-gallery mode resonator

Matt T. Simons, Irina Novikova, The College of William & Mary (United States)

High quality factor whispering-gallery mode resonators have been used to demonstrate efficient nonlinear optical processes, in particular second harmonic generation, optical parametric oscillation, and squeezed vacuum generation. Second harmonic generation has been shown to reduce the noise in both the fundamental and second harmonic fields below the quantum limit (squeezed light). We anticipate that a high quality factor cavity (a whispering-gallery mode resonator) can improve the level of squeezing.

In this presentation, we theoretically and experimentally examine the possibility of generating bright squeezed light by second harmonic generation using a whispering-gallery mode resonator. We use a crystalline lithium niobate whispering-gallery mode resonator disk to frequency-double a CW 1064 nm laser, through natural (temperature) phase-matching. Analyzing the noise spectrum of the transmitted light using a quantum mechanical input/output model, we ideally predict up to 10 dB of squeezing in the fundamental field for a resonator with a quality factor of 10^8.

8600-23, Session 6

Observation of spontaneous Brillouin cooling *(Invited Paper)*

Gaurav Bahl, Univ. of Illinois at Urbana-Champaign (United States); Matthew Tomes, Univ. of Michigan (United States)

No Abstract Available

8600-25, Session 6

High Q BBO whispering gallery mode resonators

Guoping Lin, Jet Propulsion Lab. (United States); Josef U. Fürst, Jet Propulsion Lab. (United States) and Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany); Dmitry V. Strekalov, Ivan S. Grudinin, Nan Yu, Jet Propulsion Lab. (United States)

Optical crystalline whispering gallery mode (WGM) resonators confine light along their circumference by continuous total internal reflections. They offer high quality (Q) factors and small mode volumes. These features have drawn strong interest in nonlinear optics applications. So far, only lithium niobate and lithium tantalate have been used for second-order nonlinear optics in high Q WGM resonators. However, these crystals are not suited in the ultraviolet (UV) range due to poor UV transparency and strong photorefractivity. Motivated by exploring various types of phase matching in diverse nonlinear crystals, we fabricate and investigate WGM resonators made from angle-cut beta barium borate (BBO) crystals. BBO is an important nonlinear crystal used in the visible and UV wavelength range. In this paper, we report the first WGM resonator made from BBO crystals and high Q WGMs in the UV region. A Q factor of 1.5?10^8 was demonstrated at 370 nm. New upper bounds for the absorption coefficients of BBO at 1560, 980 and 370 nm are obtained from the Q factor measurements. Moreover, interesting polarization rotation of WGMs in angle-cut birefringent resonators have been observed and investigated. We also found only one polarization mode family in these angle-cut BBO resonators. This work lays a foundation for further investigation of WGM properties of non-z cut birefringent resonators and their significance in nonlinear optics applications.

8600-26, Session 6

Towards room temperature quantum optomechanics with whispering gallery mode resonators and nanostrings

George Brawley, Robin M. Cole, James Bennett, The Univ. of Queensland (Australia); Silvan Schmid, Anja Boisen, Technical Univ. of Denmark (Denmark); Warwick Bowen, The Univ. of Queensland (Australia)

An important prerequisite for the production of non-classical mechanical states is the strong interaction between the mechanical elements of a system and light. In this context, the optomechanical cooperativity provides a key criterion for the strength of the linearized optomechanical interaction. A cooperativity greater than the thermal phonon occupancy of the mechanics is required for the observation of a variety effects, such as ground state cooling; measurement induced mechanical squeezing; and quantum radiation pressure noise. Since the cooperativity is defined to be proportional to the square of the vacuum coupling rate, and inversely proportional to the optical and mechanical decay rates, systems with low mechanical mass and low decay rates are desired.

Our system allows the independent tuning of these quantities, and thereby optimization of the cooperativity, by appropriate selection of the optical cavity and nanostring. Our mechanical element, a 150 nm x 3?m x 1mm silicon nitride nanostring was positioned within the evanescent field of a ~70?m diameter microsphere WGM resonator. A 780 nm laser was coupled via tapered fiber to the microsphere, which exhibited an intrinsic optical decay rate of 2MHz. Although optomechanical coupling rates as high as 100MHz/nm were seen, linewidth broadening limited practical coupling rates to ~10MHz/nm. Even with this lower coupling rate, the exceptionally low mechanical linewidth of our nanostrings (some as low as ~30mHz) ensure that the cooperativity may exceed the room temperature thermal phonon occupancy with as little as 350uW of optical power.

Hence, our results provide a route towards room temperature quantum optomechanics in truly macroscopic mechanical oscillators.

8600-51, Session 6

RF induced optical properties of a whispering gallery mode resonator made with strontium barium niobate

Andrey B. Matsko, Anatoliy A. Savchenkov, Vladimir S. Ilchenko, Iouri V. Solomatine, David J. Seidel, Lute Maleki, OEwaves, Inc. (United States)

We report on fabrication of a high-Q whispering gallery (WGM) mode resonator out of as-grown enriched SBN crystal (Sr0:75Ba0:25Nb2O6). The resonator was optically coupled with 80 percent efficiency and had optical Q-factor and finesse exceeded Q ? 7 ? 10^7 and F ? 7000 at 1550 nm, correspondingly. The measured optical attenuation coefficient of the material approached 4.4 ? 10^-3 cm^-1, which is the lowest detected attenuation value for SBN, up to our knowledge. Applying RF field to the resonator, we demonstrated electro-optical modulation effect. Tracking Q factor and frequencies of the WGMs we monitored changes in attenuation as well as refractive index of the resonator host material and shown that low power high-frequency RF field induces significant modification of SBN optical properties.

8600-27, Session 7

Compact laser beam analyzer with polarization independent optics and wide dynamic range of neutral density adjustment

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

An all passive optical design laser beam waist analyzer has been developed which can analyze in real time a focused beam waist independent upon its polarization state and facilitates a wide dynamic range of neutral density adjustment for optimizing the intensity on the sensor in an extremely compact size. The technique is applicable from the UV to the far infrared and tests in the visible and the far infrared are presented.

At the core of the design is a short Fabry-Perot resonator which produces spatial time slices of a focused laser beam and post the resonator is a pair of wire grid polarizers. The Fabry-Perot resonator optics provides a ~ 4.0 optical density for the incoming laser beam. As the intensity of the light following the Fabry-Perot resonator is sufficiently low, a very efficient and compact arrangement of a pair of wire gird polarizers are introduced to provide a wider dynamic range of focus intensity at the sensor plane without the need to add additional neutral density filters. This simple, but unique combination of optics, makes for a very compact and efficient means to evaluate focused laser beams from the ultra violet to the far infrared.

8600-30, Session 7

Recent advances in coupled laser cavity design *(Invited Paper)*

James R. Leger, Univ. of Minnesota, Twin Cities (United States)

External cavity coherent beam combining represents a path forward to higher fiber laser radiance, with several groups demonstrating scalable approaches. In this paper, we review recent advances in coupled laser cavity design. In particular, we will compare various designs and describe the pros and cons of each with regard to mode shape, allowed number of supermodes, and sensitivity to path length errors. The losses due to optical path length errors will be calculated both to the optical cavity itself and to the Strehl ratio of the output beam. Experimental measurements using a specially designed laser test bed will demonstrate the modal loss and mode shape from a variety of architectures.

A second area of new investigation is concerned with Q-switch suppression in coupled laser cavities. The increased cavity loss that accompanies path length errors in the laser arms can suppress lasing, causing a build-up in energy in the laser inversion. When the path length errors change back to a low cavity loss state, the stored energy can be released in a manner analogous to Q-switching, creating a giant laser pulse. Since the peak power of this pulse can be many orders of magnitude larger than the cw power, the high instantaneous intensity can do irreparable damage to the optics. We investigate systems that are designed to suppress this unwanted Q-switching by allowing alternative lasing paths to clamp the gain.

8600-31, Session 7

Concept for coupling of a laser diode beam in a fiber with 40 micron diameter and numeric aperture 0.1

Matthias Falk, Markus Lipp, Martin Forrer, FISBA OPTIK AG (Switzerland)

Multi-mode laser diodes are a reliable and inexpensive source of high power laser light. However, the diodes are suffering from rather low beam quality in their slow axis. In order to couple their light into a fiber with 40 micron diameter only and a Numeric Aperture of 0.1, the beam quality of the emitter has to be improved. We will present a concept study that makes use of narrow, low multi-mode emitters. Their emitter width is reduced compared to standard multi-mode diodes, but still larger than the emitter width of single-mode laser diodes. These emitters seek a compromise between the high output powers of broad area multi-mode diodes and high beam quality single-mode laser diodes. This laser diode runs on a few simultaneous modes only. Experimental results of such laser diodes will be shown and the fiber coupling conditions will be discussed. An external cavity setup is realized in order to demonstrate wavelength tuning of the output light. Possible ways to scale the power by polarization coupling, wavelength coupling, and spatial coupling are investigated.

Provision of the laser diodes by the Ferdinand-Braun Institute (FBH) is gratefully acknowledged.

8600-32, Session 8

Unraveling light with digital holograms *(Invited Paper)*

Andrew Forbes, CSIR National Laser Ctr. (South Africa) and Stellenbosch Univ. (South Africa) and Univ. of KwaZulu-Natal (South Africa)

Modal decomposition of optical fields as a concept has been in existence for many decades, yet despite its clear applications to laser beam analysis it has nevertheless remained a seldom used tool. With the commercialization of liquid crystal devices, digital holography as an enabling tool has become accessible to all, and with it modal decomposition has come of age. In this talk we will outline the basic principles of modal decomposition of laser beams with digital holograms, and review recent results on the modal decomposition of arbitrary optical fields. We will show how to use the information to infer the intensity, phase, wavefront, poynting vector and orbital angular momentum density of the light. In particular, we will show how to achieve optimal modal decomposition even in the absence of key information about the field, such as its scale and wavefront. We will demonstrate the techniques on optical fields from fibres, diode-pumped solid-state lasers, and structured light by laser beam shaping.

8600-33, Session 8

Modeling of semiconductor saturable absorber mirrors using dynamic mode analysis

Christoph Pflaum, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany); Zhabiz Rahimi, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany) and ASLD GmbH (Germany)

Semiconductor Saturable Absorber Mirrors (SESAM's) are used to produce passively Q-switched ultrashort pulse solid-state lasers. Numerical modeling of physical effects of SESAM is required to effectively design these lasers. For this purpose, simulations are performed to study the dynamic behaviour of Gauss modes, the gain of modes, and saturation of the saturable absorber mirror. The beam quality of laser has to be good enough in order to avoid chaotic laser behaviour. We extended our dynamic mode analysis (DMA) algorithm in order to calculate laser beam quality. This simulation technique is based on rate equations for a set of Gauss modes and population inversions. Gain of each mode can be calculated separately by solving the corresponding set of rate equations. We have assumed that the reflectivity of the mirror is spatially invariant in the SESAM's model. An additional rate equation is required to include the saturation of SESAM. This equation considers parameters such as modulation depth, saturation fluence and relaxation time. Simulation results show that our model can predict pulse energy and non-chaotic behaviour of the laser.

8600-34, Session 8

Large deformable mirrors for beam control of high brightness lasers

Nicolas A. Lefaudeux, Xavier Levecq, Guillaume Dovillaire, Imagine Optic SA (France); Lionnel Escolano, Sebastien Theis, ISP System (France)

Adaptive Optics is now a standard feature to control the laser beam quality of the high power lasers facilities. The development of the next generation of high power and high brightness laser facilities comes along with the increase of the energy of the laser pulses. In these lasers, the size of the optical elements used at the end of the chain must be increased in order to withstand the higher energy of the laser pulses. Laser adaptive optics systems are based on the use of deformable mirrors and are usually located at the end of the laser chain. Therefore, along with the other optics, the size of the deformable mirror must be increased in order to withstand the energy of the laser.

Mechanical deformable mirror technology is compatible with all the standard high power dielectric coatings and is easily scalable. Large mechanical deformable mirrors able to withstand high pulse energies can be manufactured without technological obstacle. We present characterization and beam shaping results obtained with two large mechanical deformable mirrors. One mirror has a 180mm circular clear aperture. The other is an elliptical deformable mirror with 270 x 190mm clear aperture and is used as a fold mirror at 45° incidence. These large deformable mirrors can withstand pulse energies around 10 kilojoules for chirped pulses. They are compatible with the needs of beam shaping and beam control of the next generation of high power and high brightness laser facilities.

8600-35, Session 8

Free space propagation without free space

Christian Schulze, Daniel Flamm, Michael Duparré, Friedrich-Schiller-Univ. Jena (Germany); Andrew Forbes, Council for Scientific and Industrial Research (South Africa)

We present a fast and easy measurement technique for measuring the beam quality factor M2 of laser beams using a spatial light modulator (SLM). Two different measurement procedures are presented, that both base on digitally simulating the free space propagation of the beam, hence getting rid of the traditional scan in propagation direction and avoiding any moving components. The first approach uses the SLM as a variable lens, yielding differently focused beams in a fixed plane, in which the beam diameter can be measured with a static CCD camera. An analytical formula is derived for the beam diameter as a function of the changing focal length of the digital lens, enabling to fit the measured beam diameter change and to extract the M2 value accordingly. The second approach makes use of the principles of the angular spectrum method, after which the propagated (near) field is obtained after multiplication with a transfer function of free space in the far field and back transformation to the near field. In experiment this is easily achieved by transforming the field by a simple lens onto the SLM, displaying the mentioned transfer function on the SLM, and transforming back to a fixed plane, in which the changing beam diameter can be measured with a CCD camera. To test both techniques, Laguerre-Gaussian modes of known M2 value have been generated and the beam quality measured. The comparison with the theoretical predictions reveals excellent agreement and proves the fidelity with which the M2 can be measured.

8600-36, Session 8

Selective excitation of higher-order modes in diode-pumped solid-state laser resonators

Andrew Forbes, CSIR National Laser Ctr. (South Africa) and Stellenbosch Univ. (South Africa)

In this paper we experimentally demonstrate the intra-cavity generation of selected higher-order Laguerre-Gaussian modes using a simple absorbing ring. First, we show selection of modes of variable radial order, from zero to five, with zero azimuthal order. Second, we select super-positions of azimuthal modes of zero radial order but high azimuthal index, up to eleven. In all cases we demonstrate high mode purity and a gain volume proportional to the order of the mode. Our results suggest a possible route to high-brightness diode-pumped solid-state laser sources.

8600-37, Session 9

Brilliant green laser lines for surface processing

Mikhail M. Ivanenko, Wyacheslav Grimm, Lisa Kleinschmidt, Aliaksei Krasnaberski, Lutz Aschke, Vitalij N. Lissotschenko, LIMO Lissotschenko Mikrooptik GmbH (Germany)

A continuous diversification of the laser thin-film processing technologies involves development of novel beam-shaping systems with green DPSS lasers. Such unlike applications like Si crystallization for AMOLED or CMOS, laser annealing of functional layers, advanced photovoltaic cells, or lift-off processes in the production of flexible displays need very different line-focus geometry with the length between few and several hundreds of mm, and width, which is only few µm for the Si crystallization and about 100 µm for annealing processes. Furthermore, the approach to the optical design depends on the required energy density, depth of the focus, number and beam quality of the lasers used.

We review fundamentals of the line shaping optics for green DPSS lasers and report exemplary on two optical systems. Both the systems provide similar line focus lengths of 200 mm, with inhomogeneity below 2.5%, and working distance of 60 mm. However, the optical technique is very different, because the first system uses two lasers and shapes a line with of only 8-µm width, while the other one couples 8 lasers in a line of 100-µm width. In the first case a micro-optical anisotropic beam transformation technique is applied to reach the strong focusing and simultaneously keep a required long depth of the focus. The second system meets the challenge of the coupling of a large number of the fibre delivered beams, and of stable handling of a multi-kW laser power.

8600-38, Session 9

Refractive beam shapers for material processing with high power single mode and multimode lasers

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

The high power multimode fiber-coupled laser sources, like solid state lasers or laser diodes as well as single mode and multimode fiber lasers, are now widely used in various industrial laser material processing technologies like metal or plastics welding, cladding, hardening, brazing, annealing. Performance of these technologies can be essentially improved by varying the intensity profile of a laser beam with using beam shaping optics, for example, the field mapping refractive beam shapers like piShaper. Operational principle of these devices presumes transformation of laser beam intensity distribution from Gaussian to flattop, super-Gauss, or inverse-Gauss profile with high flatness of output wave front, conserving of beam consistency, providing collimated output beam of low divergence, high transmittance, extended depth of field. Important feature of piShaper is in capability to operate with TEM00 and multimode lasers, the beam shapers can be implemented not only as telescopic optics but also as collimating systems, which can be connected directly to fiber-coupled lasers or fiber lasers, thus combining functions of beam collimation and irradiance transformation.

This paper will describe some features of beam shaping of high-power laser sources, including multimode fiber coupled lasers, and ways of

adaptation of beam shaping optical systems design to meet requirements of modern laser technologies. Examples of real implementations will be presented as well.

8600-39, Session 9

New monolithic Gauss-Tophat converter with integrated Fourier function and Gauss-Tophat beam splitter

Aliaksei Krasnaberski, Lisa Kleinschmidt, Mikhail M. Ivanenko, LIMO Lissotschenko Mikrooptik GmbH (Germany)

Optical Gauss-to-Tophat converters (g2T) that converts a Gaussian intensity distribution into a top-hat profile find growing applications in different laser processing technologies. Usually, such refractive or diffraction g2T converters comprise of two or more optical components. For example, one aspherical component to form a tophat angle distribution following by a Fourier lens that transforms it in desired tophat intensity distribution in a focal plane.

Here we report an optical design, which combines both the optical functions in a single monolithic component. The component is designed and manufactured by LIMO as a free-form profile, providing the square tophat of 100-µm width at the distance of 125 mm. Compared to the traditional g2T-converters it is much more compact, easy to adjust, and less sensitive to alignment errors.

In many industrial applications not a single but multiple tophat foci are desirable for a fast parallel processing. For such applications we have developed a Gauss-to-Tophat beam splitter. The beam splitting is done by a refractive-diffractive high-order grating with a smooth continuous pitch profile. Thanks to the smooth profile such a Gauss-to-Tophat beam splitter demonstrates very high efficiency of above 95% and high homogeneity between the diffraction orders.

8600-40, Session 9

Beam shaping for a high power laser diode bar with a wavelength of 940-980nm

Hansruedi Moser, Dzelal Kura, Hans Forrer, Martin Forrer, FISBA OPTIK AG (Switzerland)

Broad area high power laser diodes emit in fast axis and slow axis direction very different beam profiles. In fast axis direction a nearly diffraction limited Gaussian beam, but in the slow axis direction a multi-mode beam profile. We present two solutions for individual beam shaping using micro optical components for a standard high power laser diode bar with a wavelength of 950 nm. The compact design allows the individual beam shaping in a very small space. The quality of the beam shaping depends mainly on the precision of the micro optics and the advanced assembly process. These solutions enable the development of laser diode modules with individual and application specific beam shapes and small dimensions.

8600-29, Session PTue

Compact ultra-broadband polarization generator/analyzer for supercontinuum light source

Chun-Jen Weng, Instrument Technology Research Ctr. (Taiwan) and National Chiao Tung Univ. (Taiwan); Da-Ren Liu, Instrument Technology Research Ctr. (Taiwan); Ken-Yuh Hsu, Yung-Fu Chen, National Chiao Tung Univ. (Taiwan)

Supercontinuum light sources are generated from potonic cryrystal fiber by ultrafast fiber laser pumping. The light sources are unique optical sources that offer a variety of advantages, especially for ultra-broadband linewidth, high spectral brightness, low divergence angle and excellent beam quality. Therefore, the supercontinuum light sources are suitable for polarimetric spectroscopy and multi-wavelength polarization imaging applications. However, ultra-broadband polarization generators/analyzers are needed in the above applications. In general, bandwidth of polarization optics is limited by the dispersion of material. We proposed a compact ultra-broadband polarization state generator (PSG) with a high precision electrical motor control for supercontinuum light source. The bandwidth of this apparatus is in the range from 600nm to 2300nm while the supercontinnum light source is almost the same bandwidth. The configuration is composed of a broadband polarizer and a super-achromatic zero-order waveplate. By rotating polarization optics inside the motor, this apparatus can produce any arbitrary polarization state such as horizontal, vertical, left-handed circular, right-handed circular and other elliptical polarization state. It can be used as polarization state analyzer (PSA) by changing the direction of incident light source. This apparatus can be used to monitor and change the polarization state for supercontinnum light source. A PSA and a PSG based on this apparatus can be used in the ultra-broadband polarimeter or ellipsometers applications.

8600-70, Session PTue

High pressure tuning of whispering gallery mode resonances on neodymium doped glass microspheres

Carla Perez Rodriguez, Leopoldo L. Martin, Sergio Leon Luis, Inocencio J. Martin, Victor Lavin, Univ. de La Laguna (Spain); Daniel Navarro-Urrios, Univ. de Barcelona (Spain); Nestor E. Capuj, Univ. de La Laguna (Spain)

The Whispering Gallery Modes (WGM) also known as morphology dependent resonances of micro-resonators such as microspheres have been widely proposed for sensing applications because their sensibility to changes of refractive indices and geometry. While the use of micro-resonators as temperature sensors is well researched, their sensitivity to changes in pressure has not been reported in the range of high pressures (several GPa). Commonly micro-resonators made of non doped glasses are fabricated attached to coupling devices in order to observe the resonances. Inside the diamond cell, needed to reach the GPa range, the employ of coupling devices attached to the resonator is impossible. So, to enable the measurements, a non coupling scheme was employed. Nd^{3+} doped glass microspheres located inside the pressure cell where excited by focusing a 532 nm DPSS laser with a microscope objective. The Nd^{3+} ions emission is partially coupled into the microsphere resonances and the fluorescent light emitted by the microsphere is collected and focused into the entrance slit of a CCD spectrograph. The media pressure inside of the chamber was monitored from the R1 line of several ruby spheroids introduced in the cell.

In this work it is shown a blue shift of the wavelength resonances while increasing the pressure of the microsphere inside the cell. This shift has been measured to be reversible in the studied range from ambient pressure to 5 GPa, when decreasing the pressure to the initial one the resonances returns to their initial values as well as the FWHM of the resonances.

8600-72, Session PTue

Enhancing the radiation efficiency of dye doped microresonator using coupling effects with a suspended core microstructured optical fiber

Alexandre Francois, Shahraam V. Afshar, Kristopher J. Rowland, Matthew Henderson, Tanya M. Monro, The Univ. of Adelaide (Australia)

Recently we demonstrated that a dye-doped microresonator positioned onto the tip of a suspended core Microstructured Optical Fiber can be used as a dip sensor. In this architecture, the resonator is located on an air hole next to the fiber core, enabling a significant portion of the sphere to overlap with the guided light emerging from the fiber tip. When the resonator is excited through the suspended core fiber it exhibits an unusually high radiative efficiency, which was initially attributed to a higher excitation efficiency.

Here we demonstrate that it is possible to enhance the radiative emission of the microresonator attached to the suspended core fiber tip by changing the size of the resonator and how it is positioned on the fiber tip. In particular, we have found that the way in which the sphere interacts with the air hole cavity of the suspended core fiber significantly changes its emission characteristics. We found that the enhancement was dependent upon the interaction between the modes of the resonator with the confined geometry of the suspended core fiber rather than a higher excitation efficiency. We also evaluate the impact of the radiative enhancement on the WGM lasing threshold in different configurations.

8600-73, Session PTue

Temporal dynamics of Kerr frequency combs in WGM resonators

Aurelien Coillet, Irina Balakireva, Remi Henriet, Laurent Larger, Yanne K. Chembo, FEMTO-ST (France)

Optical frequency combs are equally spaced spectral lines with promising characteristics for the generation of ultra-stable GHz signals. While they were usually generated with mode-locked lasers, these combs can be created in high-Q whispering gallery modes (WGM) resonators thanks to the Kerr effect and four-wave mixing. In the past few years, several experimental demonstrations were achieved, and a few models were developed to describe these combs. However, the nonlinear dynamics involved in the process of populating the modes of the combs is rich and complex, and further studies are required. In this work, we focus on the temporal behavior of the combs, while different parameters are modified, namely the linear detuning of the pump laser and the exciting pump power. A variety of characteristic behaviors are observed, ranging from the transition to stable side modes for low excitations to the building of regular oscillations, and even toward a chaotic behavior of the frequency lines at high power. In particular, the establishment of these different regimes is found to be in the millisecond time span, much higher than the resonator's characteristic timescales. The analysis of these regimes and their conditions of appearance give us valuable insight on the nonlinear interactions at stake in the resonator.

8600-74, Session PTue

Microtaper fiber excitation effects in bottle microresonators

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

Recently, extensive work has been carried out on bottle microresonators (BMR). In contrast with near-perfect microspheres, in BMRs the azimuthal-mode degeneracy is broken and the strong overlap of different mode families results in very dense and complex transmission spectra. We have carried out a systematic study of the effect of microtaper diameter on the spectral characteristics of BMRs with dimensions of length=360µm, bulge-diameter=180µm and stem-diameter=125µm. By increasing the microtaper-diameter (Dt) from 2µm to 10µm results in progressively cleaner and simpler spectra. The transmission depth at resonance varies from ~15dB (@Dt=2µm) to >3dB (@Dt=10µm). The loaded Q factors were measured to be >10E+6 in all cases. However, with microtaper Dt=10µm clearly-resolved single resonance peaks could be observed and free-spectral-ranges could be easily identified. In the case of Dt=4µm and 2µm, due to dense spectra and simultaneous excitation of multiple (three-four) WGMs, the observed resonances were broader (with composite Qs 2-3 times smaller).

The observed microtaper diameter spectral dependencies are believed to be due to the fact that smaller microtaper diameters show smaller effective indices and therefore phase-match higher-radial-order BMR WGMs. Due to strong modal-family overlaps, the density of modes becomes progressively larger as the radial order increases, resulting in more complex and denser transmission spectra. This study shows that larger excitation-microtaper diameters (>6µm) provide cleaner spectra, easily identifiable FSRs and they will be beneficial in BMR potential sensor applications. These results are in contrast with near-perfect microspheres, where microtaper diameters of ~2-4µm are considered optimum.

8600-76, Session PTue

Experimental demonstration of continuous-wave index-antiguided slab waveguide lasers

Adam S. Dittli, Hossein Alisafaee, Tsing-Hua Her, Lee W. Casperson, Univ. of North Carolina at Charlotte (United States)

In this work we present, to the best of our knowledge, the first experimental demonstration of continuous-wave operation of index-antiguided lasers. The gain medium is a 200-um-thick 1% Nd-doped YAG (refractive index = 1.820), sandwiched by 2 pieces of Terbium Gallium Garnet, or TGG as cladding (refractive index 1.954) using fusion bonding. The laser cavity is composed of a HR mirror and a 95% output coupler, and is faced pump by a continuous-wave pump diode at 808 nm focused down to 500 um. The laser is index-antiguided along the confined direction and purely gain guided along the unbounded direction.

The laser has a threshold pump power nearly 5 W. At pump power of 6W, the laser output is single mode with a mode size (full width at half maximum) equal to 150 um and 300 um, respectively, along the confined and unconfined directions. As pump power increases, the laser remains single mode along the IAG direction and becomes higher order mode with increasing mode order. The highest laser power we obtained is nearly 1.6 W at pump power of 18 W, which is pump-limited with no sign of saturation. The slope efficiency is 12% which is highest reported to date for IAG laser. More experimental results and mode analysis will be presented.

8600-77, Session PTue

Two matrix algorithms of eignmodes of a Bessel-Gauss resonator

Dongxiong Ling, Dongguan Univ. of Technology (China)

A Bessel-Gauss resonator (BGR) was proposed to produce the Bessel Gauss beams. In this paper transverse profiles and their corresponding losses of the BGR are computed by use of the entrie matrix formalism and the transfer matrix method, and the computation results from two algorithms are compared. The computation results show that for the BGR there is no inconsistences in the mode fields yielded by two methods, and the tranfer marix methods are more accurate in the mode losses than the entire matrix formalism, which lead to a believable conclusion that the BGR easily produces the fundamental Bessel-Gauss mode of good quality.

8600-78, Session PTue

Spatially coherent top-hat beam output from a large mode area microstructured single-mode fiber

Pierre Calvet, Commissariat à l'Énergie Atomique (France) and Univ. des Sciences et Technologies de Lille (France); Constance Valentin, Yves Quiquempois, Géraud Bouwmans, Quentin Coulombier, Laurent Bigot, Marc Douay, Arnaud Mussot, Univ. des Sciences et Technologies de Lille (France); Emmanuel Hugonnot, Commissariat à l'Énergie Atomique (France)

Fibre technology has a great potential to improve the compactness, stability and versatility of laser systems. Fibre lasers are now able to deliver high power beams and high energies pulses for industrial needs (laser marking, welding,…), for laser-biological tissues interactions inside the body, for fundamental studies in laser-matter interaction processes or for seeding large-scale Nd:glass laser facilities. Most of these applications need a spatially coherent beam with a good quality and therefore single-mode fibres are used to deliver the beam. Nevertheless the intensity profile of theses fibres usually has a Gaussian shape. As a result, the intensity flow that reaches the target is not uniform transversally and the treatment leads to irregularity. The Gaussian profile must then be transformed to exhibit a 'top-hat' intensity profile. Different techniques already exist to get such a profile as beam-aperturing, field mapping or beam integrators (as multimode fibres) but with strong inconvenient, respectively: losses, alignment difficulties or incoherence. To overcome these difficulties, an elegant and efficient solution is to achieve a single-mode fibre which directly delivers a spatially coherent 'top-hat' beam. In fact, microstructured optical fiber technology provides a powerful means to develop large-mode-area fibers with controlled refractive index profile and top-hat fundamental mode profile. Accordingly, as it will be presented in the conference, we have designed, realized and characterized a low losses large mode area microstructured single-mode fibre able to deliver a M2=1.2 top-hat beam.

8600-79, Session PTue

Process-optimized beam profiles for laser micromachining

Christian Bischoff, Ulrich Raedel, TOPAG Lasertechnik GmbH (Germany)

The raw Gaussian laser beam profile is for many applications in laser micromachining not optimal adapted. Therefore process optimized beam profiles with e.g. Top-Hat or ring shape are required to improve process quality. Other applications require multiple beam-lets for a parallel processing to increase the process efficiency. The new diffractive FBS (Fundamental Beam-Mode-Shaper) concept of TOPAG allows the generation of e.g. square, round or line Top-Hat profiles with near diffraction limited width for smallest possible patterning or spot sizes with just a few micrometers. FBS elements can be placed at nearly any position within the beam path and do not substitute the focusing system (objective) but work together with the existing optics. Furthermore the FBS beam shapers feature very homogeneous beam profiles (+/- 2.5%), a high efficiency (> 95%) and a simplified handling. In combination with diffractive beam splitters the quality and the throughput of the laser process can be improved as a result of several optimized beams with just one beam source. TOPAG presents also application results using of FBS shapers and diffractive beam splitters for solar cell and OLED scribing.

8600-42, Session 11

Coherent perfect absorption in linear and nonlinear optics *(Invited Paper)*

Wenjie Wan, Yuanlin Zheng, Xianfeng Chen, Shanghai Jiao Tong Univ. (China)

In the time-reversed process to laser emission [Chong, PRL 105,053901(2010)], incident coherent optical fields are perfectly absorbed within a resonator which contains a loss medium, instead of a gain medium. The incident fields and frequency must coincide with those of the corresponding laser with gain. This new device was termed a "coherent perfect absorber" (CPA). In linear regime, we demonstrate this effect for a silicon cavity in the case of two counter-propagating incident fields, showing that absorption can be enhanced by two orders of magnitude [WAN Science 331,889(2011)]. A unique feature of the two-channel case is also demonstrated, that by varying the relative phase of the incident fields, absorption can be suppressed substantially as well. In nonlinear regime, such time-reversed process can also be extended to nonlinear wave generation [Longhi, PRL 107,033901(2011)], including optical parametric oscillation (OPO) and second harmonic generation (SHG). We realize coherent absorption in time-reversed schemes for both OPO and SHG, showing coherent control of absorption by phase varying. By adjusting the relative phase of two inputs, we can annihilate light at the harmonic frequency of the pump beam in time-reversed SHG, also actively control the amplification and absorption in time-reversed OPO. To our knowledge, this is the first experimental demonstration of coherent absorption processes in nonlinear optics regime.

8600-43, Session 11

Fabrication and modelling of truncated oblate and prolate microresonators *(Invited Paper)*

Michalis N. Zervas, The Univ. of Southampton (United Kingdom)

We have recently demonstrated different versions of softening and micromorphing techniques applicable to amorphous and crystalline materials for the fabrication of high quality non-spherical, predominantly oblate or prolate, microresonators. Firstly, a "soften-and-compress" technique has been developed for the fabrication of bottle microresonators (BMRs) from standard fibers or capillaries using a splicer. This has resulted in solid or hollow BMRs with Qs in excess of 10+6. Also, a "soften-and-squash" technique has been demonstrated for the fabrication of microdiscus resonators by squashing microspheres between two glassy-carbon plates in an oven. Compared to the starting microspheres, this technique results in superior microresonators, with better control of the resonant modes and two-orders of magnitude increase in Q. Finally, a controlled softening process has been developed for turning crystalline microstructures into predominantly oblate microresonators with significantly improved surface roughness while maintaining their crystalline nature.

We have also developed an efficient numerical method, based on a transfer-matrix formulation and counter-propagating waves in cylindrical structures, for calculating the resonant frequencies and field distributions in general non-spherical truncated oblate and prolate structures. The technique can be applied to structures with arbitrary cylindrical shapes where analytic expressions cannot be used. We have applied the method to analyse the resonant characteristics and match experimental data obtained with the newly developed microresonators.

8600-44, Session 11

Focused ion beam engineered disc resonators

David C. Aveline, Jet Propulsion Lab. (United States); Lukas M. Baumgartel, Jet Propulsion Lab. (United States) and The Univ. of Southern California (United States); Byungmin Ahn, The Univ. of Southern California (United States); Nan Yu, Jet Propulsion Lab. (United States)

A typical whispering gallery mode (WGM) resonator is a closed system, where the full mode intensity is not accessible. Only a small portion of the mode volume, the evanescent field just outside the dielectric boundary, is exposed for external coupling (optomechanical, atomic and molecular sensing applications). In this paper, we report our effort to apply focused ion beam (FIB) microfabrication to macro-scale mechanically-polished crystalline disc resonators in order to achieve unique high-Q resonator structures. We show that the FIB technique can create features with optical smoothness better than 10 nm, and therefore minimize additional scattering losses to preserve high Q. We have created FIB engineered disc (FIBED) resonators with open structure, i.e. a milled notch creates a free space gap within the mode volume. The gap provides complete access to the internal fields of the resonator and therefore the full mode intensity. We have demonstrated that the modified resonator structure supports high quality optical modes, exhibiting Q-factor exceeding one million. With the open structure, for example, we can directly measure the spatial profile of the modes inside the open cavity and selectively suppress specific modes. This novel system facilitates interaction of external mechanisms, atoms, or molecules with the full extent of the resonant light field. The FIBED approach also opens the door for other functional features to be formed into WGM structures, such as designs for spectral engineering and free space optical coupling.

8600-45, Session 11

SNAP devices with ideal and lossy coupling to waveguides: theory vs. experiment

Misha Sumetsky, OFS Labs. (United States)

A SNAP (Surface Nanoscale Axial Photonics) device consists of an optical fiber with specially introduced nanoscale radius variation and N transverse input/output waveguides coupled to this fiber. The input waveguides excite whispering gallery modes circulating near the fiber surface and slowly propagating along the fiber axis. It is shown that the lossy coupling to the waveguides is fully described by N(N+5) real constants. This number is reduced to 2N in the case of ideal (lossless) coupling. The transmission amplitudes of a SNAP device are expressed through these constants and the effective fiber radius variation and analyzed for simplest models (ideal and lossy coupling of one and two waveguides to a localized state of a bottle microresonator and to a uniform fiber). Excellent agreement between the developed theory and the experiment for a SNAP bottle microresonator with lossy coupling is demonstrated. Solution of the inverse problem, which restores the nanoscale radius variation of a SNAP device from its experimental resonant spectra, is presented.

8600-101,

Laser-Based Particle Acceleration and the Path to TeV Physics and Compact X-ray and Gamma Ray Sources

Wim P. Leemans, Lawrence Berkeley National Lab. (United States)

We will discuss acceleration of electrons using intense laser pulses that excite multi-gigavolt fields in plasmas and the path forward to practical machines. This will include experiments with the new high repetition rate (1Hz) Petawatt BELLA laser aimed at reaching 10 GeV in less than a meter long accelerator. The potential impact of this work ranges from providing the capability of producing high energy, ultra-short electron bunches and associated radiation pulses for forefront science in a small laboratory setting, to medical and homeland security applications, to the development of high energy particle colliders for fundamental science into the origin of matter and energy.

8600-102,

Three-Dimensional Metamaterials Made By Direct Laser Writing

Martin Wegener, Karlsruher Institut für Technologie (Germany)

Three-dimensional (3D) direct laser writing (DLW) has become a commercially available workhorse and can be seen as the 3D counterpart of planar electron-beam lithography. However, DLW was previously subject to seemingly fundamental limitations regarding (i) spatial resolution due to the Abbe diffraction barrier, (ii) accessible sample heights due to finite microscope-lens working distances, and (iii) writing speed. This talk gives an introduction and presents the state-of-the-art. (i) Stimulated-emission-depletion (STED) 3D DLW has recently broken the diffraction barrier. For example, this has enabled the first 3D visible-frequency polarization-independent invisibility cloak and the first visible-frequency 3D complete-photonic-band-gap material. (ii) 3D “dip-in” DLW has enabled the first 3D pentamode mechanical metamaterial.

8600-103,

Remote Laser Welding for Automotive Seat Production

Geert G. Verhaeghe, TWI Ltd. (United Kingdom)

No Abstract Available

8600-24, Session 12

Whispering gallery states of neutrons and anti-hydrogen atoms and their applications to fundamental and surface physics *(Invited Paper)*

Valery 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. It consists of wave localization near a curved reflecting surface and is expected for waves of various natures, for instance, for (anti)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 first observation of quantum whispering-gallery effect for cold neutrons [1-2]. 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 [3]. These two phenomena provide a direct demonstration of the weak equivalence principle for a massive particle in a quantum state. Deeply bound long-living states are weakly sensitive to surface potential; highly excited short-living states are 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. Analogous phenomenon could be measured with atoms and anti-atoms [4].

[1] V.V.N. et al, “Neutron whispering gallery”, Nature Phys. 6(2010)114; [2] V.V.N. et al, “The whispering gallery effect in neutron scattering”, New J.

Phys. 12(2010)113050; [3] V.V.N. et al, "Quantum states of neutrons in the Earth's gravitational field", Nature 415(2002)297; [4] A.Yu.Voronin et al, "Whispering-gallery states of antihydrogen near a curved surface", Phys. Rev. A 85(2012)014902.

8600-49, Session 12

Complex polarization states of off-axis uniaxial whispering gallery mode resonators *(Invited Paper)*

Florian Sedlmeir, Josef U. Fürst, Dmitry V. Strekalov, Max Planck Institute for the Science of Light (Germany); Harald G. Schwefel, Gerd Leuchs, Max Planck Institute for the Science of Light (Germany) and Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany)

Long photon confinement and high optical fields require good optical resonators. Some of the best optical resonators with a small footprint are whispering gallery mode (WGM) resonators. Their principle is based on continued total internal reflection at the interface of a round dielectric. Currently most WGM resonators are fabricated fully symmetric to their rotational axis. In WGM resonators fabricated from uniaxial crystals this symmetry axis usually coincides with the optic axis, such that the modes are either parallel or perpendicular polarized. If the optic axis is however tilted with respect to the symmetry axis the polarization of the modes changes dramatically. We report on high Q resonances in a slightly uniaxial MgF2 WGM resonator, cut at an angle of 20° with respect to the optic axis. A novel mode is observed that can be fully coupled (decoupled) with a right (left) circular polarized mode. Furthermore, the polarization properties at different outcoupling positions, determined via full Stokes measurements, are recorded and show interesting properties, with a continuous complex change in ellipticity. We will present the experimental results and a first theoretical analysis. Understanding the polarization behavior in an off-axis, birefringent WGM resonator may offer a new way for phase-matching in non-linear ?(2) materials.

8600-50, Session 12

Nanowire architectures for next-generation solar cells and photonic devices *(Invited Paper)*

Thomas Kempa, Massachusetts Institute of Technology (United States); James F. Cahoon, The Univ. of North Carolina at Chapel Hill (United States); Sun-Kyung Kim, Robert Day, Harvard Univ. (United States); Hong-Gyu Park, Korea Univ. (Korea, Republic of); Charles M. Lieber, Harvard Univ. (United States)

Core-shell nanowires are a versatile photovoltaic platform. Their electronic and optical properties can be synthetically tuned and are well suited to test or enable new concepts for next-generation solar cells. We report in situ synthesis of silicon core-shell nanowires with highly crystalline shells and well defined diode geometries. Optimized devices yield open-circuit voltages as high as 0.50 V and fill-factors greater than 72%, even for nanowires with diameters as small as 200 nm. Notably, single nanowire devices exhibit current densities double the expectation for equivalent bulk films and 1-sun power conversion efficiencies up to 6%. Furthermore, wavelength-dependent single nanowire photocurrent spectra reveal tunable optical resonances within the nanowires and quantitative analyses show that absolute external quantum efficiencies approach values equal to or greater than unity. Simulations and measurements further suggest a unique approach for enhancing efficiency through assembly of designed nanowire elements. We demonstrate directed assembly and parallel interconnection of nanowires in planar geometries and vertical stacks, and show that this can yield cells with efficiencies in excess of 8%. Simulations and experiments further suggest that sub-micron thick assemblies of single nanowire elements can achieve efficiencies in excess of those obtained in thin-film solar cells. Together, these results suggest a new paradigm for development of next-generation, ultra-thin solar cells.

8600-52, Session 13

On-chip ultrahigh-Q microcavities for highly unidirectional emission *(Invited Paper)*

Yun-Feng Xiao, Xue-Feng Jiang, Peking Univ. (China); Chang-Ling Zou, Univ. of Science and Technology of China (China); Lan Yang, Washington Univ. in St. Louis (United States); Qihuang Gong, Peking Univ. (China)

Confinement and manipulation of photons using microcavities have triggered intense research interest for more than one decade. Prominent examples are whispering gallery mode (WGM) microcavities which confine photons by means of continuous total internal reflection along a curved and smooth surface. The high Q factors, strong field confinement and in-plane emission characteristics make them promising candidates for novel light sources and biochemical sensors with the ability of detecting single nanoparticles. The principal disadvantage of circular WGM microcavities is their intrinsic isotropy of emission due to their rotational symmetry. One of vital solutions is to use deformed microcavities by breaking the rotational symmetry, which can provide not only the directional emission but also the efficient and robust excitation of WGMs by a free-space optical beam. Deformed microcavities fabricated on a chip are particularly desired for high-density optoelectronic integration, but they suffer from low Q factors in experiments. The Q factors are typically around or even smaller than ten thousand limited by the large scattering losses from the involuntary surface roughness. The high Q factor is of great importance in fundamental studies and on-chip photonic applications. Here, with a pattern transfer technique and a reflow process ensuring a nearly atomic-scale microcavity surface, we demonstrate experimentally on-chip undoped silica deformed microcavities which support both nearly unidirectional emission and ultrahigh Q factors exceeding 100 million. Consequently, low-threshold, unidirectional microlasing in such a microcavity with Q factor about 3 million is realized by erbium doping and a convenient free-space excitation.

8600-53, Session 13

Resonance-based CMOS-compatible reconfigurable nanophotonic structures in hybrid material platforms *(Invited Paper)*

Ali 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 orders-of-magnitude reduction in the size of functional integrated photonic structures. Among existing substrates, silicon on isolator (SOI) has been used the most because of the availability of efficient tuning/modulation techniques (e.g., free carrier dispersion and thermo-optic effect) and compatibility with existing CMOS-based fabrication facilities. However, despite impressing progress in resonator-based reconfigurable integrated photonics in silicon (Si), there are still several challenges in the development of practical Si-photonic devices. Silicon suffers from high nonlinear effects (e.g., two–photon-absorption and Kerr-effect) that considerably limit the input power of the photonic devices. Furthermore, the quality-factor of compact Si resonators is limited by the surface absorption and surface scattering. As an alternative, silicon nitride (SiN)

material platform has one order-of-magnitude lower loss and lower nonlinearity (compared to Si), but lacks an efficient tuning mechanism. To address this challenge, we have developed a hybrid material platform based on vertical integration of different Si and SiN layers that combines the ultra-low-loss and high power handling in SiN with efficient and fast modulation and reconfigurability in Si. Furthermore, we have developed more efficient modulation and reconfiguration techniques based on multi-layer Si platforms.

8600-54, Session 13

Silicon-based monolithically integrated whispering-gallery mode resonators *(Invited Paper)*

Mher Ghulinyan, Fondazione Bruno Kessler (Italy); Fernando Ramirez Manzano, Nikola Prtljaga, Univ. degli Studi di Trento (Italy); Georg Pucker, Fondazione Bruno Kessler (Italy); Lorenzo Pavesi, Univ. degli Studi di Trento (Italy)

We report on the realization and characterization of a silicon-based integrated optical platform which implements a vertical coupling scheme between a Whispering-gallery type microresonator and a buried dielectric waveguide. The vertical coupling allows for the separation of the resonator and the waveguide into different planes, which enables one to realize the optical components in different materials/thicknesses. The high optical quality of these cavity micro-optical system follows from the accurate planarization of the waveguide topography, which is achieved by multiple depositions-and-reflows of a borophosphosilicate glass over strip waveguides. Importantly, we demonstrate the feasibility of our approach for wafer-scale mass fabrication of freestanding planar resonators suspended in air and coupled to integrated bus waveguides. This opens the door for the realization of stable all-integrated resonator systems for optomechanical and metrological applications and has the potential to substitute today's complicated fiber-taper coupling schemes

8600-55, Session 13

Metal-graphene-metal photodetectors *(Invited Paper)*

Thomas Mueller, Alexander Urich, Marco Furchi, Andreas Pospischil, Technische Univ. Wien (Austria)

Graphene – a two-dimensional electron system comprised of a single layer of carbon atoms – exhibits extraordinary physical properties and has therefore attracted much attention from both universities and the electronics industry. In this talk I will demonstrate that graphene shows a surprisingly strong photocurrent response and discuss its possible application as a photodetector. Specifically, I will present photoconductivity studies of graphene, I will discuss the origin of its photoconductive behavior, and present ultrafast photocurrent measurements. Based on these findings we developed several concepts for graphene-based photodetectors. One of these concepts involves depositing on graphene interdigitated metal electrodes to realize an ultrafast metal-graphene-metal photodetector. We used this device to demonstrate the faithful detection of data streams at rates of 10 gigabits per second. Another concept relies on the monolithic integrating of graphene with a Fabry-Pérot microcavity. These devices benefit from the large increase of the optical field inside a resonant cavity, giving rise to increased absorption. We demonstrate that the optical absorption can be 26-fold enhanced as compared to “conventional” devices. Finally, I will present ultrafast photocurrent measurements. Using an optical correlation technique with femtosecond laser pulses, we obtain a response time of 2.1 ps. This time translates into a photodetection bandwidth of 260 GHz.

8600-56, Session 13

Far-field pattern simulation and measurement for unidirectional-emission circular microlasers *(Invited Paper)*

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

Semiconductor microdisk lasers supported by a pedestal to form vertical waveguide of semiconductor/air can realize perfect optical confinement in the vertical direction. However, microcircular lasers with vertical optical confinement of different semiconductor materials will greatly improve thermal conductivity and current injection efficiency. The whispering-gallery modes (WGMs) in the 3D circular resonators with the vertical waveguide of semiconductor materials were simulated by the finite-difference time-domain (FDTD) technique. The vertical radiation loss is greatly affected by the structure parameters of the resonator, especially as the radius of the circular is only several micrometers. In addition, we have found that transverse magnetic (TM) WGMs have much less vertical radiation loss than transverse electric (TE) WGMs. Furthermore, The vertical radiation loss can be reduced due to the destructive interference between vertical leakage modes for TE WGMs in the circular microresonators. However, the vertical mode field patterns of the WGMs are different from that of the slab waveguide with the multiple-layer structure, which will greatly affected the far-field patterns.

In this paper, the mode field distributions are simulated by 3D FDTD technique for a circular microresonator and that with an output waveguide, and then the far-field patterns are calculated based on the near-field distributions and compared with measured far-field patterns of the fabricated circular microlasers. For the circular microlasers connected with a 2?m wide output waveguide, the far-field patterns are usually over 180°in the horizontal plane because a high order guided mode is excited in the output waveguide. Furthermore, the vertical far-field patterns influenced by the vertical leakage mode are observed experimentally.

8600-57, Session 14

Impulse response of microresonators with a dual frequency comb probe

Claudine N. Allen, Hugo Bergeron, Jean-Raphaël Carrier, Vincent Michaud-Belleau, Julien Roy, Simon Potvin, Maxime Charlebois, Jérôme E. Genest, Univ. Laval (Canada)

Label-free microsphere resonators were shown to be sensitive optical biosensors thanks to the very high quality factor up to Q~10E9 of their whispering gallery modes (WGMs). The spectral shift of a single mode of a single microsphere is the most common detection signal, but several resonances are available to probe the analyte frequency response in polarizability. However, the full spectrum of WGMs for an elliptical resonator is complicated, warranting further measures and optimizations of light propagation in this system. Our high resolution interferometric studies of a silica microresonator with a dual frequency comb provide both its impulse response in the time domain with 80 fs resolution and its transmission spectrum in the frequency domain with 125 MHz resolution, i.e. at the picometer level. We observe that a light pulse is periodically outcoupling from a ~156 ?m microsphere after round trips of ~2 ps as can be expected from the group velocity. However, the structure of the full impulse response is much more rich, for example showing clusters of pulses separated by roughly ~50 ps. This reveals the light pulse is not outcoupling from the slightly elliptical microresonator at each round trip because its trajectory is precessing. Finally, we see that a refractive index change at the resonator surface, be it isotropic or a local perturbation, causes a phase delay in the impulse response corresponding to the well-know WGM frequency shifts in the transmission spectrum.

8600-58, Session 14

Ultra-compact and high-Q micro-ring

resonators based on metal cladding polymer waveguides and their applications in high-frequency ultrasonic imaging

Tao Ling, Sung-Liang Chen, Cheng Zhang, L. Jay Guo, Univ. of Michigan (United States)

High-frequency (> 20 MHz) ultrasonic imaging is considered to be the next frontier in medical imaging. Ultrasonic detectors with small element size and wideband response play an important role in high-frequency imaging. Besides, detector arrays enable fast imaging, facilitating clinical applications. Optical detection of ultrasound has potential to realize such arrays. Previously we have demonstrated high-quality (Q) factor polymer micro-rings with a radius (R) of 30 um. However, such microrings are not sufficient to support efforts to develop a dense array for high-frequency imaging. For example, in phased array ultrasound imaging applications, such microring arrays, if developed, can only be operated at a central frequency less than 15 MHz. Further reducing device's radius is needed. Due to polymer material's relative low refractive index, it is difficult to fabricate an ultra-compact device (R < 10 um) without sacrificing high-Q factor. In this work, we successfully overcome the issue by introducing a novel metal-hybridized polymer waveguide. We fabricated polymer micro-rings (R = 10 um) on a thin metal film substrate with a buffer layer in between. Such a hybrid bottom cladding layer greatly increased the mode confinement and reduced the leakage loss to the substrate. The device's Q factor was measured to be as high as 2x10^5 in air and 4 ? 10^4 in water. Such an ultra-compact and high-Q device can be developed as arrays for phased array ultrasound imaging at more than 35 MHz. The device also greatly benefits other ultrasound-related imaging.

8600-59, Session 14

Cavity enhanced Raman spectroscopy

Perry S. Edwards, Corey Janisch, The Pennsylvania State Univ. (United States); Bo Peng, Washington Univ. at St. Louis (United States); Lan Yang, Washington Univ. in St. Louis (United States); Zhiwen Liu, The Pennsylvania State Univ. (United States)

Resonator-based sensing has garnered significant interest in recent years, in particular, highly sensitive particle detection for applications in biomedicine, pollution sensing, and national security. Resonators have shown promise for sensitive single particle and molecule detection by exploiting interaction with the strong, circulating resonator modes. Several resonator-based sensing techniques have demonstrated capability for extremely sensitive, label-free biochemical sensing. However, they rely on indirect observations of changes in the resonant cavity mode due to interactions with the particle. Here, we explore cavity enhanced Raman spectroscopy as a new paradigm for resonator-based particle detection that utilizes Raman scattering to provide intrinsic molecular specific detection. In this work, scattered Raman signal was collected from particles adhered to a ring-cavity resonantly pumped by a tunable laser and spectroscopic analysis was performed. The circulating pump photons within the cavity allows for significantly enhanced interaction with the adhered particle leading to an increase in the collected Raman signal. This enhancement was observed when the pump laser was locked to the resonant mode of the cavity. Raman spectroscopy results from particles adhered to an all-fiber ring-cavity and high-Q microtoroid cavities will be shown.

8600-60, Session 14

Ultrahigh sensitive label-free coupled capillary optofluidic ring laser biosensors *(Invited Paper)*

Xiang Wu, Liqiang Ren, Ming Li, Liying Liu, Lei Xu, Fudan Univ. (China)

Optofluidic sensors are very important sensitive and miniature label-free biosensors [1]. Up to now, most optofluidic sensors are passive sensors that need sophisticated working scheme, and most importantly, they have theoretical sensing limit. In this talk, we will introduce a new conceptual COFRL sensor, which can break the sensing limit and realize ultrahigh sensitivity. After careful investigation both theoretically and experimentally, we clearly explained the mechanism of the response of the sensor to the refractive index change of aqueous solutions.

The sensor consists of an active cylindrical ring resonator (ACRR) and a passive thin-walled capillary-based optofluidic ring resonator (OFRR) as shown in Fig. 1. Based on the Vernier Effect, the lasing spectrum of the COFRL is strongly modulated [2]. By monitoring the modulated spectral envelope shift, the sensitivity can be amplified by orders of magnitude. Theoretical results show that the bulk refractive index sensitivity (BRIS) over 10000 nm/RIU is possible.An ultrahigh BRIS of 2510 nm/RIU in aqueous solution and the magnification factor M as high as 355 are obtained experimentally. The noise equivalent detection limit (NEDL) is 1.6x10^(-5) RIU. The corresponding surface mass detection limit (SMDL) is measured to be about 6.9 pg/mm2 for small protein molecules such as BSA.

We will also discuss about the dual-optofluidic-channel structure for the COFRL and its application in biosensing. By using the new structure, higher BRIS (>5000 nm/RIU) and lower SMDL (~1pg/mm^2 or less) can be realized experimentally.

References

1. X. Fan and I. M. White, Nat. Photonics, 5, 591-597 (2011).

2. X. Zhang, L. Ren, X. Wu, H. Li, L. Liu, and L. Xu, Opt. Express 19, 22242-22247 (2011).

8600-61, Session 14

Hybrid organic/inorganic resonators for sensing and telecommunications applications *(Invited Paper)*

Andrea M. Armani, Nishita Deka, Audrey Harker, Ashley J. Maker, Simin Mehrabani Zeinabad, The Univ. of Southern California (United States)

Historically, integrated photonic devices have been fabricated from inorganic material systems, such as silicon, silicon nitride, silica and gallium arsenide. As a result of their inherently low material loss and compatibility with nanofabrication tools, high performance waveguides and resonant cavities have been demonstrated. However, to achieve many of the desired performance metrics, it is necessary to implement active stabilization systems. For example, as a result of the thermo-optic effect, the resonant wavelength of a microcavity will change with temperature, resulting in an unpredictable resonant wavelength without temperature stabilization. Therefore, new materials and material systems are desired.

One approach is to combine the inorganic materials conventionally used in telecommunications with organic polymeric materials. These hybrid systems offer the ability to tune the optical and mechanical properties of the inorganic materials, achieving athermal or temperature-independent performance. Additionally, given the wide range of polymeric material available, new material systems with previously unrealized behavior are possible; for example, materials which mechanically respond to UV, humidity and specific chemicals.

Using silica toroidal whispering gallery mode resonant cavities as the device platform, a series of hybrid organic/inorganic resonators were fabricated. Several different types of organic layers were studied, varying both the specific polymeric material and the deposition method. For example, polyisobutylene was coated on the devices using either a spin-coating method or a surface initiated cationic polymerization process. With the wide range of possible organic materials, many different devices have been fabricated, including athermal devices, humidity and bio/chemical sensors, and microlasers.

8600-62, Session 15

Whispering gallery mode microresonators: results on aptasensors and on a new sensing approach *(Invited Paper)*

Gualtiero Nunzi Conti, Francesco Baldini, Simone Berneschi, Daniele Farnesi, Ambra Giannetti, Silvia Soria, Cosimo Trono, Istituto di Fisica Applicata Nello Carrara (Italy); Lorenzo Lunelli, Laura Pasquardini, Cecilia Pederzolli, Fondazione Bruno Kessler (Italy)

We present results on the implementation of Whispering Gallery Modes biosensors and on the demonstration of a new detection method for WGM based sensors. We first shortly describe the implementation of an immunosensor (IgG and anti-IgG) where a homogeneous polymeric thin layer has been used as functionalizing agent on silica microspheres. Then we present a functionalization procedure based on the DNA-aptamer sequence immobilization on WGM resonators, able to recognize specifically thrombin or vascular endothelial growth factor (VEGF) proteins. The protein binding was optically characterized in terms of specificity in buffer solution or in 10% diluted human serum. The aptasensor was also chemically regenerated and tested again, demonstrating the reusability of our system.

When performing the above measurements we have used the typical detection scheme for WGM based resonators, which relies on tracking the resonance shift ? by scanning with a tunable laser ? when a change of the refractive index in the region probed by the WGM takes place. In the second part of the presentation we propose a new sensing approach based instead on monitoring the position of the laser line of a fiber ring laser having a WGM microsphere in its loop. We demonstrate that the induced shift is the same for the ring laser line and for the microsphere resonance. The proposed method requires simpler and cheaper equipment and may also improve the sensor resolution because the ring laser line is narrower than the microsphere WGM resonance.

8600-63, Session 15

Microcavity single virus detection and sizing with molecular sensitivity

Venkata R. Dantham, Polytechnic Institute of New York Univ. (United States); Stephene Holler, Fordham Univ. (United States); Vasily Kolchenko, New York City College of Technology (United States); Zhenmao Wan, Hunter College (United States); Stephen Arnold, Polytechnic Institute of New York Univ. (United States)

The label-free detection of individual aqueous borne virus is an important goal in the bio-sensing field. So far microspherical Whispering Gallery Mode (WGM) resonators have succeeded in detecting individual InfluenzaA virions and quantifying their size and mass (512 ag). The signal/noise (S/N) ratio in those experiments of 3 would have precluded the detection of single viruses such as polio (14 ag) or the smallest RNA virus MS2 with a mass (6 ag) only ~1% of InfluenzaA. Herein we report the label-free detection and sizing by a microcavity of MS2. Although, adsorption of individual MS2 virus at the equator of the bare resonator produces a theoretical shift ~ 0.25 fm, which is well below our r.m.s. background noise of 2 fm, it was accomplished with ease (S/N = 8) using a WGM-hybrid (WGM-h) composed of a spherical dielectric microcavity with a nanoplasmonic receptor at the equator. The maximum wavelength shift observed in the presence of MS2 viruses was ~ 17 fm, providing an enhancement in wavelength shift of ~70x, in agreement with the calculations based on Finite Element Method. Unique wavelength shift statistics are recorded for this ultra-uniform genetically-programmed substance. Analytical expressions based on the “reactive sensing principle” are developed to extract the radius of the virus from the measured signal which agrees with neutron diffraction data. Estimated limit of detection for these experiments was ~0.4 ag or 240kDa, below the size of all known viruses and largest globular protein.

8600-64, Session 15

Flow cytometer system for single-shot biosensing based on whispering gallery modes of fluorescent microspheres

Reno Lessard, Olivier Rousseau-Cyr, Alex Paquet, Maxime Charlebois, Karel Boissinot, Maurice Boissinot, Michel G. Bergeron, Claudine N. Allen, Univ. Laval (Canada)

We report an innovative label-free biosensor based on statistical analysis of several WGM spectral shifts in polystyrene fluorescent microspheres using a custom microflow cytometer. WGM analysis enables detection of nanometer-sized analytes showing promising possibilities for virus, bacteria and molecular detection. To demonstrate this, fluorophore-doped microspheres of the appropriate size parameter are mixed with Bacillus globigii spores in aqueous solution. Then, a syringe pump pushes the solution through a fiber optic flow cell where a laser beam illuminates the analysis area to excite the microspheres and their fluorescence is collected. This device provides a low-cost and user friendly solution to enhance spectrum acquisition rates up to 5 spectra per second thanks to the considerable amount of microspheres flowing through the excitation area per unit time. Finally, the WGM spectra are statistically investigated using an algorithm to determine a reliable value for the refractive index since the exact radius of the microsphere scanned is unknown. This refractive index becomes an effective value for the local perturbation caused by B. globigii spores on the microsphere surface and hence, determines whether or not bacteria are adsorbed by comparing to a control sample. Combining a flow cell with our detection algorithm, we can achieve a limit of detection of 1.9E9 spores/mL for a 500 uL vial within one hour.

8600-65, Session 15

Beam-coupled micro-sphere optical resonator for high-resolution electric field detection

Tindaro Ioppolo, Amir Ali, M. Volkan Otugen, Southern Methodist Univ. (United States)

In this paper we present a beam-coupled micro-optical sensor for high-resolution electric field detection. The main components of the sensor are a microsphere optical resonator and a dielectric micro-beam (or plate). The dielectric beam is placed inside the evanescent field of the sphere. The electrostriction force exerted by the electric field on the beam induces a change in the gap between sphere and beam perturbing the evanescent field of the sphere. This in turn induces a shift in the whispering gallery modes of the sphere resonator. The resonator is made of silica while the beam is made of polydimethylsiloxane (PDMS). Different beam and sphere sizes are studied to optimize the proposed sensor’s electric field resolution and bandwidth. The optical modes of the sphere are exited using a tapered single mode optical fiber that is coupled to a distributed feedback laser. The transmission spectrum through the fiber is monitored to detect WGM shifts.

8600-66, Session 15

Optimization of resonator radial dimensions for quartz enhanced photoacoustic spectroscopy systems

Samara L. Firebaugh, U.S. Naval Academy (United States); Eugene A. Terray, Woods Hole Oceanographic Institute (United States)

Quartz Enhanced Photoacoustic Spectroscopy is an absorption spectroscopy technique in which absorption is detected as sound using

a quartz tuning fork. It allows for compact, rugged sensors for trace gas sensing. The addition of acoustic resonator tubes about the tuning fork significantly increases the signal to noise ratio in these systems. Other groups have examined the optimization of the length for these resonator tubes empirically and using the model of an orifice ended tube.

This work examines the optimization of the radial dimensions for the tube, using both transmission line models as well as finite element modeling. In the absence of loss terms, the ideal diameter for the resonator tube would be the laser beam waist, but experimentally the optimum diameter has been found to be much greater. This work establishes that the difference is explained by including thermal and viscous losses in the model of the resonator structure, which become more significant as the tube radius decreases.

This work builds on a COMSOL model, which has been described elsewhere. The key development in this work described here is the inclusion of the loss terms along the inner resonator tube walls. This loss is incorporated into a COMSOL Multiphysics model for the system through the use of an equivalent impedance along the tube wall. The resulting model has good agreement against published data. Further refinements in the fork boundary conditions should improve this model further. The importance of these tube wall loss terms has also been confirmed through the use of an acoustic circuit analogy in which the loss terms are incorporated into the transmission lines representing the tubes.

With the inclusion of these tools, the model then becomes a design tool that could be used to determine the optimal resonator radial design, as well as a tool for examining other geometries.

8600-67, Session 16

Integrated force and displacement sensors using cavity optomechanics *(Invited Paper)*

Kartik Srinivasan, National Institute of Standards and Technology (United States); Houxun Miao, Yuxiang Liu, National Institute of Standards and Technology (United States) and Univ. of Maryland, College Park (United States); Vladimir A. Aksyuk, National Institute of Standards and Technology (United States)

Micromechanical transducers are common in nanoscale metrology and inertial sensors, where a force drives the transducer and its resulting motion is determined through methods like capacitive or optical readout. Optical readout is advantageous due to low noise and large bandwidth, but in applications like atomic force microscopy (AFM), it is usually separated from the transducer. We are developing mechanical transducers with integrated optical readout to produce compact, stable, self-aligned devices in the silicon-on-insulator platform. High-sensitivity readout is enabled by cavity optomechanics, where the transducer's motion is evanescently coupled to the mode of a high quality factor cavity. Two specific device geometries are presented. In the first, a specially-designed AFM probe, consisting of a semicircular nanoscale cantilever supporting a sharp tip at its midpoint, is laterally coupled to a microdisk cavity. We demonstrate sub-fm/Hz^1/2 displacement sensitivity readout for a variety of cantilever geometries, in which the stiffness and resonant mechanical frequency range between 0.01 N/m-300 N/m and 250 kHz – 100 MHz, respectively, suggesting potential in a number of AFM applications. In the second system, a silicon nitride ring attached to an electrostatically-actuated silicon cantilever is coupled to the near-field above the microdisk. Adjusting the ring-disk separation by applying a DC voltage to the actuator tunes the cavity's optical modes by ?5 nm, while applying an AC voltage enables feedback cooling of the cantilever motion by three orders of magnitude. Readout sensitivity near the standard quantum limit is achieved in both systems, and prospects for application in areas like AFM are discussed.

8600-68, Session 16

Photonic crystal split-beam nanocavities for torsional optomechanics

Marcelo Wu, Univ. of Calgary (Canada); Aaron C. Hryciw, National Institute for Nanotechnology (Canada); Behzad Khanaliloo, Christopher J. Healey, Paul E. Barclay, Univ. of Calgary (Canada); John Davis, Mark R. Freeman, Univ. of Alberta (Canada)

A novel type of photonic crystal nanocavity tailored to sensitively measure torques is experimentally investigated. Suspended low-mass elements (< pg) in the nanomechanical resonator are sensitive to environmental stimuli, such as a magnetic field from external sources or from embedded nanomagnetic systems. The torsional mechanical motion of these elements directly influences the optical field concentrated inside the optical nanocavity, resulting in a strong cavity optomechanical coupling rate in the GHz/nm range. The actuation of the mechanical resonator is readout with high sensitivity using evanescent coupling between the photonic crystal nanocavity and an optical fiber taper. Our designs take into consideration the nature of torsional mechanical modes and the requirement of linear optomechanical coupling. A 50 nm physical air gap in the middle of the nanobeam cavity allows torsional mechanical degrees of freedom as well as strong optical field confinement in a small mode volume. Numerical simulations suggest high-Q (up to 3x10^6) optical cavities with a gap are possible. Current fabricated devices exhibit quality factors up to 5x10^3, limited by fabrication imperfections. Potential applications incorporating these devices include sensitive magnetometry and probing the quantum properties of nanomagnetic systems.

8600-69, Session 16

Cavity optomechanics on a microfluidic resonator *(Invited Paper)*

Tal Carmon, Univ. of Michigan (United States)

Light pressure is known to excite1-3 or cool4-10 vibrations in microresonators for sensing quantum-optomechanical effects9-12 and we now show that it can be explored for investigations with liquids. Currently, optical resonances are utilized to detect analytes in liquids13,14. However, optomechanical oscillations have never been excited when devices were immersed in liquid. This is because replacing the surrounding air with water inherently increases the acoustical impedance and the associated acoustical-radiation losses. Here we fabricate a hollow optomechanical bubble resonator with water inside, and use light pressure to excite 8 MHz - 140 MHz vibrations with 1 mW optical-threshold power and >2000 mechanical Q, constituting the first time that any microfluidic15 system is optomechanically actuated. Bridging between optomechanics and microfluidics15-17 will enable recently developed capillaries18-21 and on-chip22 bubbles to vibrate via optical excitation; and allow optomechanics with non-solid material phases15 including bio-analytes16, superfluids, and quantum condensates23,24.

Monday - Thursday 4 –7 February 2013

Part of Proceedings of SPIE Vol. 8601 Fiber Lasers X: Technology, Systems, and Applications

8601-1, Session 1

Progress on kW-class narrow linewidth fiber lasers and amplifiers *(Invited Paper)*

Imtiaz Majid, Nufern (United States)

Narrow line-width, monolithic, single mode fiber lasers/amplifiers undergoing beam combination (spectral or coherent) have been demonstrated to be attractive for scaling up to very high power levels (50-100kW's). The primary limitation in achieving narrow line-widths in high power fiber lasers/amplifiers is Stimulated Brillouin Scattering (SBS). Recent results on the latest generation of Yb-doped LMA fiber amplifiers (operating at ~1um) have demonstrated narrow ~ 5-20 GHz line-widths at the ≥ 2kW power level with excellent beam quality (M2 ~ 1.2); these results were achieved by pumping the amplifier in a co-pumped configuration. Other amplifier architectures (counter and bi-directionally pumped) that exhibit higher SBS thresholds than a co-pumped system may also be used; advantages and disadvantages associated with the use of alternate architectures are discussed in this work. Recent results in both PM and non-PM, fiber based high power lasers/amplifiers also indicate the existence of "mode instabilities" (M-I) that appear to inhibit power scaling in diffraction limited single mode beams. The origin and mitigation of such higher order mode instabilities is currently an area of great interest. We present results demonstrating the onset of M-I, and discuss these results in light of recently proposed theories on the origin and elimination of M-I in fiber based laser/amplifier systems. Finally, we discuss novel packaging configurations for these amplifiers, that are especially suitable for applications requiring lightweight designs and remote power delivery schemes; these designs facilitate multiplexing of a large number of amplifiers during power scaling via beam combination techniques.

8601-2, Session 1

58 mJ burst containing ultra-short pulses with a homogenous energy level from an Yb-doped fiber amplifier

Sven Breitkopf, Friedrich-Schiller-Univ. Jena (Germany); Arno Klenke, Friedrich-Schiller-Univ. Jena (Germany) and Helmholtz-Institut Jena (Germany); Thomas Gottschall, Hans-Jürgen Otto, Friedrich-Schiller-Univ. Jena (Germany); Jens Limpert, Andreas Tünnermann, Friedrich-Schiller-Univ. Jena (Germany) and Helmholtz-Institut Jena (Germany) and Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

There is a great interest in obtaining laser pulses with a high average power as well as high pulse energies. Continuously pulsed systems face many problems to satisfy those requirements, independent on the amplifier concept. While many applications such as electron beam characterization and free-electron-laser seeding need high pulse energies at high repetition rates, they only need those laser pulses for a certain amount of time. Therefore, it is not necessary to run a laser system with continuous pulses at those parameters and a so-called burst mode might be sufficient and even essential in such cases.

We report on a CPA-laser system, based on a large pitch fiber as a main-amplifier delivering bursts containing ultra-short, highly-energetic pulses. The burst rate is set to 20Hz, while each burst contains 2000 pulses at a pulse-repetition-rate of 10MHz and with a pulse-duration of 700fs. Hence the duty cycle D is 0.4%. To achieve a homogeneous pulse energy level between 27µJ and 31µJ after the compression, the main amplifier is pumped with a very high power of 1.6kW in a bursted mode (D=10%). By using an acousto-optical modulator (AOM) after the main-amp fiber, the residual output before and after the burst is removed to suppress ASE and any underground-pulses around the amplified burst.

The limitations that could be observed during this experiment were mainly due to mode instabilities, which were detectable even on a very short time scale of a few hundred µs using a high speed camera.

8601-3, Session 1

Higher-order mode erbium-doped fiber amplifier with output reconversion to the fundamental mode

Jeffrey W. Nicholson, John M. Fini, Anthony M. DeSantolo, Xiaoming Liu, Kenneth S. Feder, V. R. Supradeepa, Paul Westbrook, Eric M. Monberg, Frank V. DiMarcello, Clifford Headley III, David J. DiGiovanni, OFS Labs. (United States)

Nonlinearities in high-power fiber lasers can be mitigated by increasing the mode effective area (Aeff). Among the approaches investigated for scaling of large-mode area (LMA) fibers are rod-type fibers , chirally coupled fibers, leakage channel fibers, and helically coiled cores. Fibers operating in the fundamental mode however suffer from bend induced reductions in Aeff, and this effect becomes more pronounced as the mode size is increased. Another approach to increasing Aeff is to use a fiber specifically designed to operate in a higher-order mode. Large effective-area, higher-order modes are robust to bend-induced area reductions as well as distributed scattering to nearest neighbor modes. Amplification has previously been demonstrated in a cladding-pumped, Yb-doped HOM fiber at 1 um. In addition, core pumping of a CW Er-doped HOM fiber in the LP0,10 with an effective area of 2700 um^2 has been demonstrated. The HOM-Er amplifier is unique in that it is a core-pumped amplifier with both pump (a high power 1480 nm cascaded Raman fiber laser) and signal propagating in the same higher order mode, allowing for maximum pump-signal overlap and thus short lengths of amplifier fiber. Nanosecond pulse amplification in an HOM-Er fiber has been demonstrated in the LP0,9 mode with an effective area of 2440 um^2 and the nonlinear properties of this amplifier compared to a conventional Er-doped LMA fiber with 800 um^2 Aeff. The nonlinearity of the HOM amplifier was found to be significantly lower than a conventional LMA amplifier, decreasing in proportion to the increase in Aeff. More recently, the effective area of the HOM-Er fiber was further scaled to 6000 um^2 in the LP0,14 mode, and nanosecond pulses were amplified, generating up to 226 uJ pulses with 226 kW peak power in this fiber. In this work, we demonstrate for the first time an Er-doped fiber amplifier where amplification occurs in the higher-order mode with 6000 um^2 Aeff and an output mode converter re-converts the signal to the fundamental mode.

8601-4, Session 1

Mode-converters for rectangular-core fiber amplifiers to achieve diffraction-limited power scaling

Arun K. Sridharan, Paul H. Pax, Derrek R. Drachenberg, John E. Heebner, Jay W. Dawson, Lawrence Livermore National Lab. (United States)

Ytterbium doped fiber lasers and amplifiers at 1 um (based on circularly-symmetric waveguides) that routinely output ~ 10 kWs with diffraction-limited beam quality are approaching fundamental limits. By moving to ribbon-like rectangular-core fiber waveguides, the single aperture power limit of circular core fiber lasers is increased. The ribbon fiber waveguide has a rectangular cross-sectional core with a high width-to-thickness aspect ratio. In such a structure the thin dimension (y) is coiled and single-moded and the wide dimension (x) is multi-moded. Since higher-order-modes (HOM) are less susceptible to bend loss and mode mixing

we propose ribbon fiber amplifiers in which we launch a particular HOM (in the x direction). Mode-converters are therefore required before and after the ribbon-amplifier fiber.

We present the first design and experimental results of a mode-converter system that converts a single higher-order-mode (HOM) of a ribbon-geometry-based amplifier fiber to a diffraction-limited TEM00 mode. Our design utilizes two phase plates - placed in two conjugate Fourier planes of the laser's output face) and has nearly 100% theoretical conversion efficiency. Experimentally, we have achieved conversion efficiencies in the 80-85% regime. The first phase reshapes the ribbon fiber's multi-lobed HOM amplitude profile to a Gaussian profile in the plane of the second plate. The second phase plate corrects the phase and outputs the required TEM00 mode. We also present designs on how to apply this scheme to improve the beam quality of a circular-core fiber that outputs radiation in a single HOM.

8601-5, Session 1

High efficiency cascaded Raman fiber laser with output power of 204 W at 1480 nm

V. R. Supradeepa, Jeffrey W. Nicholson, Clifford Headley III, OFS Labs. (United States); Bera Palsdottir, Dan P. Jakobsen, OFS (Denmark)

Cascaded Raman fiber lasers provide a high power, single-mode source of wavelengths for which rare-earth gain is not available. Raman lasers in the 1.5micron region are particularly attractive as high brightness, low quantum defect pump sources for Erbium-doped media (both fiber and solid-state) and as eye-safe alternatives for material processing applications. Power scaling of Raman fiber lasers is a subject of current interest, and recently, a record 104 W was demonstrated from a 1480 nm cascaded Raman fiber laser. However the optical–to-optical conversion efficiency from Yb fiber laser pump to 1480 nm Raman output was only ~48%, far below the quantum efficiency limit of 75%.

The primary sources responsible for the enhanced loss in a conventional cascaded Raman laser architecture are excess losses associated with Raman cavity assembly. Here we demonstrate an architecture which eliminates the Raman cavity and hence most of the excess loss. We perform the required Raman conversion of multiple wavelength shifts in a single pass through simultaneous seeding at all intermediate Stokes wavelengths. A low power conventional cascaded Raman laser is an ideal seed source by simultaneously providing all the necessary intermediate wavelengths. The elimination of excess losses associated with the Raman cavity allows for significant enhancement in conversion efficiency. The cascaded Raman amplifier is made of a Raman fiber with a long wavelength cut-off (Raman filter fiber). This suppresses further Raman conversion of the output light and helps maintains efficiency at higher output powers. This architecture provides a record output power of 204W at 1480 nm while simultaneously achieving a record conversion efficiency of 65%.

8601-6, Session 2

High order ribbon fiber modes, simulations, and experiments for high power amplifiers

Derrek R. Drachenberg, Michael J. Messerly, Paul H. Pax, Arun K. Sridharan, John B. Tassano, Jay W. Dawson, Lawrence Livermore National Lab. (United States)

High average power fiber lasers from 10s of kW to greater than 100 kW are of interest to manufacturers and the defense industry. Theoretical limits on diffraction limited circular geometry fiber lasers limit the average power to 2 kW for narrowband and 10-36 kW for broadband lasers. We have proposed an alternative ribbon fiber geometry to allow scaling of fiber lasers far above these limits in which a single high order ribbon mode with a high effective area is amplified and converted back to the fundamental mode once in free space. This ribbon fiber geometry offers increased effective area to mitigate nonlinear effects, and improved thermal properties. A 10 kW, single mode, and single frequency ribbon fiber amplifier design is presented and Beam Propagation Method (BPM) simulation results verify the approach. Rectangular core, ribbon fibers are multimode in one dimension. The effective index spacing between modes increases with mode number. It is therefore advantageous to illuminate a single high order mode at the input of a ribbon fiber amplifier. Ribbon fiber modes can be illuminated by various methods including coupling by pressure induced long period gratings, fringes induced by interfering two beams at a small angle, or illumination through a binary phase plate. These methods of illuminating a novel rectangular core fiber are discussed with modeling and experimental results showing high purity illumination, > 90% , and simulations predict high stability of the ribbon mode during amplification in the presence of modal noise, and non-linear effects.

8601-7, Session 2

Mode instability thresholds of fiber amplifiers

Arlee V. Smith, Jesse J. Smith, AS-Photonics, LLC (United States)

In earlier reports we showed stimulated thermal Rayleigh scattering can account for the modal instability seen in large mode area, high power fiber amplifiers operated with a narrow signal spectrum. We showed that this mechanism leads to exponential gain of a Stokes shifted wave in mode LP11 driven by the strong light in the fundamental mode LP01. The computed high Stokes gain leads to sharp thresholds in agreement with observations. Further the computed gains predict threshold powers that are compatible with reported instability thresholds, usually in the range of a few hundred watts.

However, in our previous reports we did not discuss the source of the seed Stokes light in detail. Here we consider several possible sources and show how each can affect the threshold power according to our numerical models. Sources include quantum noise, which would give the highest possible threshold; amplitude or spectral modulation of the pump light in the sub kHz range; amplitude or phase modulation of the signal seed light in the sub kHz range. If the source of the seed Stokes light can be identified as signal or pump modulation in a laboratory amplifier, it may be possible to suppress the modulation to achieve a substantial increase in the instability threshold power.

8601-8, Session 2

Analytical time-dependent theory of thermally-induced modal instabilities in high power fiber amplifiers

I-Ning Hu, Almantas Galvanauskas, Univ. of Michigan (United States)

Starting from a wave equation we derive a pair of time-dependent nonlinear coupled-amplitude equations describing thermal modal instabilities in high power fiber amplifiers. This model accurately includes all aspects of a realistic fiber amplifier, such as spatial thermal diffusion in a fiber, longitudinal distributions of pump and signal powers, and modal loss. Most importantly, it is capable of describing temporal response of a system, including temporal modal instabilities. This theory shows that the onset of thermally-induced modal instabilities can in general be described as a stimulated scattering process, in many aspects analogical to the Stimulated Raman Scattering process. This is essentially a two-wave mixing process occurring between fundamental and higher-order modes through a thermally-induced grating resulting from the spatial beating between these modes. Numerical models presented by other groups earlier postulated that phase-matching between the modes require that this thermal grating would be moving. We show that theory predicts this movement to be a result of a finite thermal-response time of a fiber medium. Around the instability threshold fundamental mode acts as a pump for a higher-order mode, the later one being frequency-downshifted with respect to the pump mode. The magnitude of this

frequency shift is directly related to the thermal response time of the fiber, typically corresponding to kHz-frequency range.

Importance of this theory is that it fundamentally explains origin of thermal modal instabilities in high power fiber lasers and is consistent with experimental observations. Furthermore, it significantly simplifies accurate prediction of the instability threshold in various fiber structures without resorting to computationally-intensive beam-propagation simulations, thus opening a path to effective exploration of possible instability-mitigation strategies.

8601-9, Session 2

Mitigation of mode instabilities by dynamic excitation of fiber modes using an acousto-optic deflector

Hans-Jürgen Otto, Cesar Jauregui-Misas, Fabian Stutzki, Florian Jansen, Friedrich-Schiller-Univ. Jena (Germany); Tino Eidam, Jens Limpert, Friedrich-Schiller-Univ. Jena (Germany) and Helmholtz-Institute Jena (Germany); Andreas Tünnerman, Friedrich-Schiller-Univ. Jena (Germany) and Helmholtz-Institute Jena (Germany) and Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

The most limiting effect for the average-output-power scaling of high-power fiber lasers and amplifiers is the threshold-like onset of mode instabilities (MI). Hereby, a former stable beam profile becomes instable and starts to fluctuate rapidly after reaching a certain output-power level. In this work we use an acousto-optic deflector to dynamically vary the excitation conditions of the Yb-doped fiber main amplifier of a MOPA system on a millisecond time-scale. Furthermore, by feeding the information about the stability at the output of the system back into a logic circuit, it is possible to greatly mitigate the fluctuations of MI. We have investigated the response of MI to the dynamic excitation for several output powers well beyond the power threshold of our system by capturing high-speed videos and time traces. We show that with the stabilization mechanism presented herein, the average fundamental mode power content are increased from ~50% up to 90% in comparison to the free-running system. Additionally the FM's minimum relative power content is also improved from nearly 0% in the unstabilized case up to more than 66%. Consequently, the beam quality and pointing stability of the amplified signal can be improved at power levels where otherwise strong mode instabilities are observable.

8601-10, Session 3

Fiber laser market analysis *(Invited Paper)*

Timothy P. V. Mammen, IPG Photonics Corp. (United States)

The paper will present an analysis of the fiber laser market size including historical trends and growth rates. Included are estimates of market share and a review of the growth rates and trends for macro processing (high power > 1-kilowatt), micro-processing, non-metal processing, and fine-processing.

8601-11, Session 3

Medical applications of optical coherence tomography using fiber-based laser sources *(Invited Paper)*

Michalina Gora, Wellman Ctr. for Photomedicine (United States); Maciej Wojtkowski, Nicolaus Copernicus Univ. (Poland); Robert Huber, Ludwig-Maximilians-Univ. München (Germany); Brett E. Bouma, Wellman Ctr. for Photomedicine (United States) and Harvard-MIT (United States); Andrzej A. Kowalczyk, Nicolaus Copernicus Univ. (Poland); Guillermo J. Tearney M.D., Wellman Ctr. for Photomedicine (United States) and Massachusetts General Hospital (United States)

In this paper, recent advances in the development of fiber-based broadband and wavelength swept light sources for Fourier-domain optical coherence tomography (OCT) and its application in ophthalmology, cardiology and the gastrointestinal tract will be presented. Examples of different medical applications of OCT will be used to demonstrate the requirements and limitations of currently available light sources. Further development of light sources is of great importance as it can improve the capability of OCT to be used for the early diagnosis of a variety of important diseases.

8601-12, Session 3

Ultrafast laser technology, markets, and applications *(Invited Paper)*

Eric P. Mottay, Amplitude Systèmes (France)

Ultrafast lasers have moved rapidly during the last few years from advanced scientific instruments to industrial tools enabling the development of new medical and industrial applications. Their unique advantage of being able to interact with matter in an extremely precise way has been complemented by tremendous improvements in laser technology, most notably in terms of simplicity, reliability and size. We will review key ultrafast technologies available today, ultrafast fiber laser being one of the most significant. We will present selected case studies illustrating their acceptance into new applications, as well as outline future key developments.

8601-13, Session 4

Advances in power scaling of fiber lasers *(Invited Paper)*

Valentin P. Gapontsev, IPG Photonics Corp. (United States)

No Abstract Available

8601-15, Session 4

Design evolution, long term performance and application tests of extra large mode area (XLMA) fiber lasers

Andreas Langner, Mario Such, Gerhard Schötz, Heraeus Quarzglas GmbH & Co. KG (Germany); Florian Just, Martin Leich, Stephan Grimm, Matthias L. Jäger, Kay Schuster, Institut für Photonische Technologien e.V. (Germany); Hagen Zimer, Marcin Kozak, Björn Wedel, HIGHYAG Lasertechnologie GmbH (Germany); Charley Bachert, Georg Rehmann, Volker Krause, Laserline GmbH (Germany)

Yb-doped fused bulk silica produced by sintered doped granulates is now a commercially available product. The excellent performance of this material in several key areas such as refractive index and doping level homogeneity, large batch size, attenuation behavior etc. are well known and will be reviewed briefly. In addition, we will present new results comparing the homogeneity of the bulk silica and typical MCVD material.

Starting from the key parameters of the bulk silica we carried out numerical simulations to explore potential laser applications and suitable fiber designs. We simulated the influence of different core dopant compositions and concentrations on the brightness conversion factor of XLMA fibers to achieve the highest optical-to-optical efficiency and the best long-term operation without degradation. In particular, we will discuss the optimal material parameters for the Yb-Al- and Yb-Ce-Al-doped bulk silica.

Using the Yb-doped bulk silica as the core material for XLMA fiber lasers we have investigated the key performance parameters of such high power single XLMA fiber laser systems, including the beam quality and the outstanding multi-kW output power. In addition, the multi-kW long-term performance (>> 100 h) of the laser system will be compared with the alternative measurements of accelerated damage in fibers made by the same bulk silica core material. We will present these aging data for different XLMA fiber core compositions and conclude with several application tests to demonstrate the excellent performance of the XLMA fiber laser.

8601-105, Session 4

Mode instabilities: physical origin and mitigation strategies

Cesar Jauregui-Misas, Hans-Jürgen Otto, Florian Jansen, Fabian Stutzki, Tino Eidam, Jens Limpert, Friedrich-Schiller-Univ. Jena (Germany); Andreas Tünnermann, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

The onset of fluctuations in the output beam of a fiber laser (mode instabilities) once that a certain average power threshold has been reached, has quickly become the most limiting effect for a further scaling of the average power of fiber laser systems. At this point, it is important to get a detailed understanding of the physical origin of this phenomenon in order to develop efficient mitigation strategies. In this work we present a detailed analysis of the different physical processes contributing to the onset of mode instabilities and reveal that thermally-induced non-adiabatic waveguide changes taking place in high-power operation play a key role. Thus, it will be shown how the modal beating between two different transverse modes can give rise to an index grating that, at sufficiently high powers, can create non-adiabatic waveguide changes in the active fiber. This non-adiabaticity will, in turn, give rise to a phase-shift between the thermally induced index grating and the modal interference pattern, which enables energy transfer between the interfering modes. This leads to the energy being transferred from the fundamental mode into the higher order mode. Additionally, a competing process, namely the thermally induced local compression of the interference period, allows the energy to flow back from the higher-order mode into the fundamental mode. The interplay between these two processes can give rise to the complex temporal dynamics of mode instabilities. With this insight in the physical processes underlying mode instabilities, several mitigation strategies will be presented and their operating principle will be discussed.

8601-16, Session 5

Bi-doped optical fibers: a new active medium for NIR lasers and amplifiers *(Invited Paper)*

Evgeniy M. Dianov, A. M. Prokhorov General Physics Institute (Russian Federation)

Bi-doped glass optical fibers are a very promising active laser medium. Various types of Bi-doped optical fibers have been developed for the construction of Bi-doped fiber lasers and optical amplifiers. The recent results on the luminescence properties of various Bi-doped optical fibers and on the development of Bi-doped fiber lasers and optical amplifiers for the spectral region 1300-1500nm are reviewed.

8601-17, Session 5

All-glass optical fibers derived from sapphire

Peter D. Dragic, Univ. of Illinois at Urbana-Champaign (United States); Thomas W. Hawkins, Paul Foy, Stephanie Morris, Clemson Univ. Research Foundation (United States); John Ballato, Advanced Materials Ctr. (United States)

Increasing power levels and novel applications are demanding from fibers performance capabilities that have, to-date, not been realized. One such example arises from the nascent push towards the 10-kW power threshold for narrow linewidth fiber lasers designed for applications including coherently-phased laser arrays and spectroscopic lidars. It is well-known that Brillouin scattering still restricts continued power scaling in these systems, despite several recent advances in acoustic-wave Brillouin management. Accordingly, novel fibers possessing a Brillouin gain coefficient 10 dB or more less than previously demonstrated would be of great practical benefit if they comprise novel materials in simple geometries and are manufactured using industry-accepted methods. Introducing a new and effective approach to the management of Brillouin scattering, we present on all-glass optical fibers derived from silica-clad sapphire with alumina concentrations up to 55 mole percent; considerably greater than conventionally possible enabling the design of optical fiber possessing a series of essential properties. Markedly, a Brillouin gain coefficient of 3.1 ? 10^-13 m/W was measured for a fiber with an average alumina concentration of 54 mole percent. This value is nearly 100 times lower than standard commercial single-mode fiber and is likely the lowest ever specified value. This reduction in Brillouin gain is enabled by a number of key material properties of the alumina-silica system, amazingly even leading to a predicted, but not yet demonstrated, composition with zero Brillouin gain. Optical fiber materials with these and other crucial properties will be discussed in the context high energy fiber laser systems.

8601-18, Session 5

Longitudinally-graded optical fibers

John Ballato, Advanced Materials Ctr. (United States); Alex Evert, Clemson Univ. Research Foundation (United States); Thomas W. Hawkins, Clemson Univ. Research Foundation (United States); Peter D. Dragic, Univ. of Illinois at Urbana-Champaign (United States); Paul Foy, Liang Dong, Roger H. Stolen, Clemson Univ. Research Foundation (United States); Robert R. Rice, Dreamcatchers Consulting (United States)

Described in this work are optical fibers possessing significant compositional gradations along their length. MCVD-derived germanosilicate fibers were fabricated that exhibited a gradient of up to about 0.55 weight % GeO2 per meter. The refractive index difference is shown to change by about 0.001, representing a numerical aperture change of about 10%, over a fiber length of less than 20 m. The stimulated Brillouin scattering (SBS) spectrum from the fiber exhibited a 4.4 dB increase in the spectral width, and thus reduction in Brillouin gain relative to a standard commercial single mode fiber over a length of 17m. The method employed is very straight-forward and provides for a wide variety of longitudinal refractive index and acoustic velocity profiles, as well as core shapes, that could be especially valuable for SBS suppression in high energy laser systems. Next generation analogs, with longitudinally-graded compositional profiles that are very reasonable to fabricate, are shown computationally to be more effective at suppressing SBS than present alternatives, such as externally-applied temperature or strain gradients. Lastly, other applications and additional unique features of these novel fibers are also discussed.

8601-19, Session 5

Cross-correlation imaging of single mode photonic crystal rod fiber with distributed mode filtering

Marko Laurila, Technical Univ. of Denmark (Denmark); Roman Barankov, Boston Univ. (United States); Mette M. Jørgensen, Sidsel R. Petersen, Technical Univ. of Denmark (Denmark); Thomas T. Alkeskjold, Jes Broeng, NKT Photonics A/S (Denmark); Jesper Lægsgaard, Technical Univ. of Denmark (Denmark); Siddharth Ramachandran, Boston Univ. (United States)

The successful development of high-power fiber lasers and amplifiers has induced the wide spread of this novel technology in scientific and industrial markets. These high-performance fiber designs require new experimental characterization methods to evaluate their modal properties. The usual measure of the beam quality in these systems is the so-called M2-parameter but low a M2 number does not guarantee a single mode operation. Therefore, new alternative methods, which can reliably reveal the modal content of waveguides, are currently under active development.

One such method, called Spatially and Spectrally (S2) resolved imaging, relies on the spectral analysis of the interfering modes guided by the fiber. This method has proved useful in several cases, but it has several limitations. An alternative characterization method is Cross-correlated (C2) imaging, which is free of these limitations. The C2 imaging method relies on interference in the time domain between an external reference beam and each of the modes propagating in the test fiber.

We analyze the modal regimes of distributed mode filtering rod fiber having the MFD of 60 µm by the C2 imaging method in different wavelength ranges and evaluate the modal content to various in-coupling conditions. As a result, we experimentally identify the resonant coupling between the higher-order core modes and the cladding modes, tailored by microstructure of the fibers, as the key mechanism that ensures SM operation at specific wavelengths. We demonstrate a fiber design, in which the higher-order modal content is suppressed below 20 dB, even for significantly misaligned in-coupling configurations.

8601-20, Session 5

Real-time mode analysis of fiber-to-fiber coupling processes using the correlation filter method

Daniel Flamm, Philipp Gelszinnis, Christian Schulze, Friedrich-Schiller-Univ. Jena (Germany); Siegmund Schröter, Institut für Photonische Technologien e.V. (Germany); Michael Duparré, Friedrich-Schiller-Univ. Jena (Germany)

A frequent process in fiber optics is the fiber-to-fiber coupling where two fibers are aligned to efficiently transmit light from one to another waveguide. Such automated alignment processes are nowadays performed in every conventional fiber splice apparatus. However, if one of the coupling fibers is a MMF, the accuracy of the alignment process will become a crucial point, since already small deviations from perfect coupling conditions can excite a significant amount of higher order modes. The actually guided modal content, in turn, is strongly affecting essential beam properties, such as, e.g., beam-propagation ratio or beam-pointing stability. Hence, the direct measurement and control of the modal content during the coupling process results in an enhanced performance of transport fibers as well as fiber laser.

The talk will present in detail the correlation filter method (CFM) for measuring the modal power spectrum in MMF during a fiber coupling process with a single-mode fiber. The CFM is based on an optical filter performing the integral relation of correlation. This filter is realized as a computer-generated hologram (CGH) with a specifically designed transmission function based on the spatial distribution of guided modes in the investigated waveguide. The beam emerging from the MMF under test is illuminating the CGH and generating a diffraction pattern containing information about modal amplitudes and phases. We will show that a simple single-shot intensity measurement is sufficient to extract the information about modal amplitudes and phases from the diffraction pattern which result in the ability to reconstruct the optical field under test.

8601-21, Session 6

Nonlinear spatial mode imaging of hybrid photonic crystal fibers

Sidsel R. Petersen, Technical Univ. of Denmark (Denmark); Thomas T. Alkeskjold, NKT Photonics A/S (Denmark); Marko Laurila, Technical Univ. of Denmark (Denmark); Thomas V. Andersen, NKT Photonics A/S (Denmark); Jesper Lægsgaard, Technical Univ. of Denmark (Denmark)

Hybrid Photonic Crystal Fibers (PCFs) have attracted much interest, due to the novel design possibilities presented by the presence of both high- and low-index inclusions in the cladding, which gives rise to both index and bandgap guiding type mechanisms. For example, they are well-suited as gain-shaped fiber amplifiers in the long wavelength region of the Ytterbium gain spectrum, or providing form factor reduction due to novel bending properties [1, 2]. Large mode area hybrid PCFs offer some unique possibilities in high-peak power pulsed fiber systems, either as passive transport fibers or as active amplifier fibers, where the spectral response of the fiber can be widely tailored.

The nonlinear response of hybrid PCFs is different from index-guiding PCFs, due to the wavelength dependent interaction of the spatial modes with the high-index inclusions of the cladding. The hybrid fiber can suppress certain nonlinear effects, such as stimulated Raman scattering, but thorough investigation of the nonlinear processes in hybrid PCFs is important to fully understand and utilize the mechanisms.

In this work, nonlinear effects in a double-clad hybrid PCF are investigated and compared to an index-guiding PCF with similar nonlinear threshold. The spatial mode content of the hybrid PCF is spectrally imaged, which gives an insight into the spectral and spatial dependence of nonlinear processes, for the first time observed in this manner. Spatial coupling of nonlinearly generated light is observed, and we show that the spatial distribution of the light can to a large extent be controlled in hybrid PCF designs.

8601-22, Session 6

Electronically controllable mode selection in a multimode fiber oscillator

Jae M. O. Daniel, W. Andrew Clarkson, Univ. of Southampton (United Kingdom)

We present a simple technique for mode selection in a multimode fiber laser that allows electronically controllable selection of individual transverse modes and relatively fast switching between modes. Our approach exploits the different spectral responses of in-fiber Bragg gratings (FBGs) in a multimode core and an acousto-optic tunable-filter (AOTF) to simultaneously achieve wavelength selection and spatial mode selection in a simple fiber laser with an external feedback cavity architecture. This approach has been applied to a core-pumped Tm-doped silica fiber laser with a multimode core to selectively excite either the fundamental mode (LP01), the next higher order mode (LP11), or the donut-shaped hybrid LP11 mode at power levels in excess of 3 W by simply adjusting the RF drive frequency to the AOTF. Fast switching between LP01 and LP11 mode at ~kHz rates was also realized.

8601-23, Session 6

Impact of Tm ions on the photodarkening process in Yb fibers

Sylvia Jetschke, Sonja Unger, Anka Schwuchow, Martin Leich, Matthias L. Jäger, Johannes Kirchhof, Institut für Photonische Technologien e.V. (Germany)

Recently, we have shown that photodarkening (PD) in Yb/Al fibers is an intrinsic feature of this core material and not caused by unintentional contamination with Tm ions [1]. Because of the generally high PD loss in these fibers (≈ 0.4 mol% Yb_2O_3, ≈ 4 mol% Al_2O_3), an assumed effect of added Tm ions could not be detected up to concentrations of 10 ppm-mol Tm_2O_3.

Yb fibers only codoped with P are known to show very weak PD effects. Therefore, we prepared a fiber series with similar Yb concentrations but P-codoped instead of Al and variation of the Tm content. Actually, we did not detect PD loss higher than 0.5 dB/m at 633 nm (pumped with 976 nm) in fibers prepared from extremely pure raw materials; a Tm contamination of about 0.015 ppm-mol was estimated from measured absorption at 1200 nm. However, in fibers with Tm concentrations as low as 1 ppm-mol, photodarkening is not longer negligible, and with 100 ppm-mol or more, loss values similar to Yb/Al fibers with same Yb concentration were observed.

The influence of Tm codoping on Yb lifetime as well as Yb and Tm fluorescence intensities will be discussed in the context of these photodarkening results.

This work contributes to the understanding of photodarkening in Yb fibers with different codopants. Moreover, it emphasizes the importance of high purity of raw materials for the preparation of Yb laser fibers because otherwise Tm trace impurities of only some ppm-mol can seriously impair the performance of fiber types with expected very low photodarkening.

[1] S. Jetschke, M. Leich, S. Unger, A. Schwuchow, and J. Kirchhof, “Influence of Tm- or Er-codoping on the photodarkening kinetics in Yb fibers”, Optics Express 19, 14473-14478 (2011)

8601-24, Session 6

Strong excited state absorption (ESA) in Yb-doped fiber lasers: the origin of photodarkening?

Magnus Engholm, Sara Rydberg, Mid Sweden Univ. (Sweden)

Strong excited state absorption (ESA) is observed in the UV- and visible range of Yb-doped fiber lasers. The ESA reaches core absorption levels of several tens of dB/m in the 500nm range already at moderate inversion levels. This finding contributes to the understanding of the mechanisms behind photodarkening which can suggest new ways to improve the reliability of Yb-doped high power fiber lasers. Cooperative luminescence, which is commonly observed as a blue-green emission in Yb/Al-doped fiber lasers is suggested to act as an intermediate pathway for the observed photodarkening as well as photobleaching processes. An experiment is conducted where a short piece of Yb/Al fiber is subjected to 915nm pumping while co-pumping with small intensities (~50uW/um2) from a 532nm solid state laser. The results show a remarkable difference with a rapid increase in the photodarekning rate compared to just 915nm pumping. The finding suggests that cooperative luminescence in the range 480-550nm play a major part in the photodarkening as well as photobleaching processes observed in Yb/Al-doped fiber lasers.

Comparison will also be made for Yb-doped fibers co-doped with phosphorus (P) which are known for showing less cooperative luminescence in the visible range and also a higher photodarkening resistivity. The ESA in Yb/P-doped fiber are shifted to shorter wavelengths, which is consistent with the above findings and could explain the observed improved photodarkening rersistivity in Yb/P doped fibers compared to Yb/Al doped fibers.

8601-25, Session 7

SESAM designs for ultrafast lasers *(Invited Paper)*

Clara J. Saraceno, Cinia Schriber, Mario Mangold, Martin Hoffmann, Oliver H. Heckl, Cyrill R. Baer, Matthias C. Golling, ETH Zurich (Switzerland); Thomas Südmeyer, ETH Zurich (Switzerland) and Univ. of Neuchâtel (Switzerland); Ursula Keller, ETH Zurich (Switzerland)

The invention of the semiconductor saturable absorber mirror (SESAM) nearly 20 years ago was a major advancement for the development of ultrafast laser systems. Today, SESAMs have become key devices for modelocking of numerous laser types, including DPSSLs, fiber lasers, and semiconductor lasers. Semiconductors are ideally suited as saturable absorbers because they can cover a broad wavelength range and yield short recovery times, supporting the generation of picosecond to femtosecond pulse durations. The macroscopic nonlinear optical parameters for modelocking can be optimized over a wide range by the design of the mirror structure and the choice of the semiconductor absorber. Furthermore, their damage threshold can be controlled making them ideally suited for high-power levels. In this presentation, we will focus on recent advances in SESAMs for cutting-edge ultrafast lasers.

8601-26, Session 7

All-fibre high power pump stripper manufactured by CO2 laser micro-structuring

Mateusz Wysmolek, Thomas Theeg, Hakan Sayinc, Jörg Neumann, Dietmar Kracht, Laser Zentrum Hannover e.V. (Germany) and Ctr. for Quantum Engineering and Space-Time Research (Germany)

To further scale the output power of all-fibre laser systems a new line of high-power fibre-optic components is needed. To maintain the all-fibre integrity a fibre-based pump stripper is needed to out-couple the excessive pump light – firstly to isolate a high quality signal from pump light, ASE and cladding modes and secondly to protect the other components from residual pump power especially in back-end pumping fibre-optic amplifiers. The commercially available high-power pump strippers consist of a high refractive-index polymer fibre coating that strips the cladding light and is pressed with two metal blocks for heat dissipation. The main disadvantage of a polymer-based component is the reasonably low thermal stability, hence lower power handling capabilities and shorter lifetime of such a component is expected. Here we present a novel all-fibre all-glass cladding light stripper made by fibre micro-structuring with a CO2 laser. With the simple parallel stripes pattern the stripping efficiency varied from 60% up to 97% depending on the stripe angle relative to the fibre. The complete device is packaged in small footprint casing for micro-structure protection and excessive heat dissipation. Long-term tests at 25 W, 50 W and 100 W pump power directly coupled into the device through a 8x1 fibre-bundle pump combiner were carried out. To the best of our knowledge, this is the first demonstration of all-glass fibre pump stripper for high-power applications.

8601-27, Session 7

Femtosecond pulse inscription of a selective mode filter in large mode area fibers

Ria G. Krämer, Christian Voigtländer, Friedrich-Schiller-Univ. Jena (Germany); Erik Freier, Andreas Liem, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Jens U. Thomas, Daniel Richter, Friedrich-Schiller-Univ. Jena (Germany); Thomas Schreiber, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Andreas Tünnermann, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany) and Friedrich-Schiller-Univ. Jena (Germany); Stefan Nolte, Friedrich-Schiller-Univ. Jena (Germany) and Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

We present a selective mode filter inscribed with ultrashort pulses directly into a few mode LMA fiber. The mode filter consists of two refractive index modifications alongside the fiber core in the cladding. The refractive index modifications, which were of approximately the same order of magnitude as the refractive index difference between core and cladding have been inscribed by nonlinear absorption of femtosecond laser pulses (800 nm wavelength, 110 fs pulse duration). If light is guided in the core, it will interact with the inscribed modification causing modes to be coupled out of the core. In order to characterize the mode filter, we used a femtosecond inscribed fiber Bragg grating (FBG), which acts as a wavelength and therefore mode selective element in the LMA fiber. Since each mode has different Bragg reflection wavelengths, an FBG in a multimode fiber will exhibit multiple Bragg reflection peaks. In our experiments, we first inscribed the FBG using the phase mask scanning technique. Then the mode filter was inscribed. The reflection spectrum of the FBG was measured in situ during the inscription process using a supercontinuum source. The reflectivities of the LP01 and LP11 modes show a dependency on the length of the mode filter. Two stages of the filter were obtained: one, in which the LP11 mode was reduced by 60% and one where the LP01 mode was reduced by 80%. The other mode respectively showed almost no losses. In conclusion, we could selectively filter either the fundamental or higher order mode.

8601-28, Session 7

Fabrication of a high power Faraday isolator by direct bonding

Carolin Rothhardt, Miroslaw Rekas, Gerhard Kalkowski, Nicoletta Haarlammert, Ramona Eberhardt, Andreas Tünnermann, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

With increasing output power of fiber lasers, demands on components for the laser systems become challenging. Optical absorption may endanger thermal stability. We report on the fabrication of a Faraday isolator for high power laser application (P = 1 kW) at a wavelength of 1080 nm and operation at room temperature. As rotator material we chose Terbium Gallium Garnet (TGG), having the highest known Verdet constant (V = 35 rad/Tm) for that wavelength at room temperature. Finite element modeling (FEM) shows, that thermal lensing is an issue at this power level, but can be avoided, if heat transport off the TGG crystal is improved. We investigate direct bonding of TGG to sapphire disks, to benefit from the high transparency and good heat spreading properties (thermal conductivity of sapphire = 42 W/mK) of the latter. Index matching is improved by applying anti-reflective coatings on the bonding interfaces. Successful bonding was achieved by extensive cleaning of the even (flatness around lambda/4 peak to valley) and smooth (rms roughness 1 nm) surfaces prior to low pressure plasma activation. Final rinsing in water yields highly hydrophilic surfaces, which are then contacted in a vacuum environment at elevated temperature under compressive pressure. Strong bonds, which sustain heating up to 600°C were obtained. Apparently, only minor stresses are generated by the bonding process. The bonded interface has no measurable influence on transmission properties and bonded samples are found to be stable for laser output powers of at least 260 W. As compared to a single TGG substrate, wavefront aberrations were significantly decreased by bonding sapphire disks to TGG.

This work is supported by the European Union within the Project “LIFT” under grant agreement no. NMP2-LA-2009-228587.

8601-29, Session 7

Photo-recovery of modal stability in rod fiber amplifiers

Mette M. Jørgensen, Marko Laurila, Technical Univ. of Denmark (Denmark); Danny Noordegraaf, Thomas T. Alkeskjold, NKT Photonics A/S (Denmark); Jesper Lægsgaard, Technical Univ. of Denmark (Denmark)

Rare-earth doped fiber lasers and amplifiers currently undergo massive improvements concerning beam quality performance and extractable average and peak power. High pulse energies and peak powers require large effective area and new fiber designs are investigated. However, very large mode area fibers often support higher order modes at high power operation leading to mode degradation and modal instability setting the upper limit for future power scaling [1-3]. The threshold of modal instability is assumed closely related to the inversion profile increasing towards the fiber output end. Recently, experimental studies report on a fiber memory effect decreasing the threshold power level for modal instability as this threshold is reached multiple times [4]. This indicates a permanent inscription of thermally induced refractive index changes that could be related to color-center formation associated with photodarkening [5].

We identify the decrease in modal instability threshold of very large mode area photonic crystal fiber amplifiers and report on a saturated power level. Blue light bleaching of the fiber raises the modal instability threshold power level and yields a partial recovery of the fiber. Different bleaching approaches are considered and compared for recovery of modal instability threshold level.

[1] A. V. Smith and J. J. Smith, “Mode instability in high power fiber amplifiers,” Opt. Express 19, 10180-10192 (2011).

[2] T. Eidam, C. Wirth, C. Jauregui, F. Stutzki, F. Jansen, H.-J. Otto, O. Schmidt, T. Schreiber, J. Limpert, and A. Tünnermann, “Experimental observations of the threshold-like onset of mode instabilities in high power fiber amplifiers,” Opt. Express 19, 13218-13224 (2011).

[3] B. Ward, C. Robin, and I. Dajani, “Origin of thermal modal instabilities in large mode area fiber amplifiers,” Opt. Express 20, 11407-11422 (2012).

[4] M. Laurila, M. M. Jørgensen, K. R. Hansen, T. T. Alkeskjold, J. Broeng, and J. Lægsgaard, “Distributed mode filtering rod fiber amplifier delivering 292W with improved mode stability,” Opt. Express 20, 5742-5753 (2012).

[5] I. Manek-Hönninger, J. Boullet, T. Cardinal, F. Guillen, S. Ermeneux, M. Podgorski, R. Bello Doua, and F. Salin, “Photodarkening and photobleaching of an ytterbium-doped silica double-clad LMA fiber,” Opt. Express 15, 1606-1611 (2007).

8601-30, Session 8

300 W all-fiber counter-pumped single-frequency amplifier stage

Thomas Theeg, Laser Zentrum Hannover e.V. (Germany); Hakan Sayinc, Jörg Neumann, Dietmar Kracht, Laser Zentrum Hannover e.V. (Germany) and Ctr. for Quantum Engineering and Space-Time Research (Germany)

The development of monolithic high power single-frequency ytterbium-doped fiber amplifier systems for gravitational wave detection and coherent beam combination has gained much interest in the recent years. To overcome the primary limitation of stimulated Brillouin scattering (SBS), an efficient approach is the application of the counter-propagation pumping (CPP) scheme instead of co-propagation pumping. However, monolithic single-frequency amplifier systems are primarily co-propagation pumped due to the lack of reliable all-fiber combiner for CPP. Hence, we developed an all-fiber combiner satisfying the requirements for CPP. The fiber combiner consists of one or several pump fibers with core diameters of 105 µm (0.22) which were side-coupled to a double-clad fiber with a pump cladding diameter of 250 µm (NA 0.46) by using a coreless intermediate fiber. With the CPP all-fiber high power amplifier stage a maximum output power of 301 W at a wavelength of 1064 nm with a near diffraction limited beam quality (M? ~ 1.2) was achieved. During CPP it was important to protect the pump diodes against amplified signal light. With the developed all-fiber combiner an isolation of 30 dB was achieved. The power handling of the fiber combiner wasn't limited due to pump or signal power. The threshold of stimulated Brillouin scattering of the high power fiber amplifier was shifted from 175 W to 280 W by the use of an external thermal management in conjunction with the pump-induced intrinsic temperature gradient.

8601-31, Session 8

Stimulated Brillouin scattering suppression in optical fibers by hydrogen-loading technique

Fanting Kong, Liang Dong, Clemson Univ. Research Foundation (United States)

SBS is the key limit to power-scaling of single-frequency fiber lasers. Transverse-acoustic-waveguide tailoring is studied extensively in recent years. It involves complex material designs to alter acoustic waveguide without affecting optical waveguide. Experimentally, the level of SBS suppression has been limited to ~10dB, which was also recently confirmed theoretically. Longitudinal-acoustic-velocity tailoring along fibers is regularly used in the form of natural thermal gradient along high-power fiber amplifiers. The SBS peak gain can be moved by ~100MHz at reasonable temperatures, giving rise to ~3dB suppression. We are reporting, for the first time, a new technique for longitudinal-acoustic-tailoring in optical fibers, with potential for significantly improved suppression. This technique involves first to load hydrogen in fibers, which takes few days at room temperature, and second to permanently bond hydrogen to glass with a UV exposure, which takes up to few hours. The basic mechanism is based on the inverse-square-root dependence of acoustic velocity on density. The addition of hydrogen leads to high local density, resulting in lower acoustical velocity and SBS frequency shift. The UV exposure can be changed along the fiber, leading to a tailored SBS frequency profile. The local rate of change in SBS frequency can be optimized for the local power levels along an amplifier, leading to optimal suppression. We have demonstrated ~300MHz SBS frequency shift, equivalent to SBS suppression of ~7.8dB using hydrogen or ~9.3dB if using heavier deuterium. It has been shown 5-fold more deuterium can be incorporated, leading to potential SBS suppression of >16dB.

8601-32, Session 8

Coherent beam combining of sinusoidal phase modulated amplifiers at the kW level

Angel Flores, Iyad Dajani, Chunte A. Lu, Craig Robin, Air Force Research Lab. (United States)

We present experimental results of beam combining of high power sinusoidally modulated ytterbium-doped fiber amplifiers. Optical path matching was achieved through variable delay lines and was shown to be robust in the range of 200 MHz to 5 GHz. Using a single-frequency source without the benefit of phase modulation, the stimulated Brillouin scattering (SBS) threshold for our 7 meter 25/400 fiber amplifier was encountered at ~30 W. Subsequently, through sinusoidal phase modulation, a narrow linewidth pump-limited output power of greater than 200 W was achieved. In addition, the SBS enhancement factors over a broad range of modulation depths and frequencies were measured and compared to the theoretical predictions of a time-dependent SBS model; showing excellent agreement. Furthermore, we explored the additional SBS suppression through the utilization of an external thermal gradient whereby the gain fiber was divided between cold and hot spools set at 20? C and 80? C, respectively. We show that with a modulation frequency of ≥200 MHz, the full benefit of the two SBS suppressing techniques is attained. In subsequent experiments, five phase modulated amplifiers were coherently combined in a tiled aperture configuration leading to 1 kW of combined power. Finally, we discuss path length tolerances and beam combining performances of sine modulated amplifiers as well other discrete periodic modulation schemes (for example pseudo random bit sequence PRBS). Notably, we demonstrate reduced path length complexity over that encountered in a white noise source driven system.

8601-33, Session 8

Single-frequency, single-polarization holmium-doped ZBLAN fiber lasers

Xiushan Zhu, NP Photonics, Inc. (United States) and College of Optical Sciences, The Univ. of Arizona (United States); Jie Zong, Andy Miller, Kort Wiersma, NP Photonics, Inc. (United States); Robert A. Norwood, College of Optical Sciences, The Univ. of Arizona (United States); Narasimha S. Prasad, NASA Langley Research Ctr. (United States); Arturo Chavez-Pirson, NP Photonics, Inc. (United States); Nasser N. Peyghambarian, College of Optical Sciences, The Univ. of Arizona (United States)

We report a single frequency, single-polarization holmium (Ho3+)-doped ZBLAN (ZrF4-BaF2-LaF3-AlF3-NaF) fiber laser at 1200 nm, for the first time. This distributed Bragg reflector (DBR) fiber laser was developed by splicing a 22 mm long highly Ho3+-doped ZBLAN fiber to a pair of silica fiber Bragg gratings (FBG). The successful fusion splicing of silica fiber to ZBLAN fiber, with their very different melting temperatures, was accomplished by using NP Photonics proprietary splicing technique. The 3 mol% Ho3+-doped ZBLAN fiber had a core diameter of 6.5 µm and a cladding diameter of 125 µm. The threshold of this laser is seen to be about 260 mW, and when the pump power was 520 mW, the output power was about 10 mW. The efficiency of the 1200 nm single-frequency fiber laser, i.e. the ratio of the output power to the launched pump power, is about 3.8%. The linewidth of the 1200 nm single-frequency fiber laser was estimated to be about 75 kHz by comparing the measured frequency noise of the 1200 nm single-frequency fiber laser with that of 1 µm NP Photonics single-frequency fiber lasers whose linewidths have been measured to be in the 1-10 kHz range. The relative intensity noise of this DBR all-fiber laser was measured to be < 110 dB/Hz at the relaxation oscillation peak and the polarization extinction ratio was measured to be > 19 dB. Due to its low phonon energy and long radiative lifetimes, rare-earth-doped ZBLAN allows various transitions that are typically terminated in silica glass, resulting in ultraviolet, visible, and infrared rare-earth doped ZBLAN lasers. Therefore, our results highlight the exciting

prospect that accessible wavelength range of single-frequency DBR fiber lasers can be expanded significantly by using rare-earth-doped ZBLAN fibers.

8601-34, Session 8

Pseudo-random binary sequency phase modulation in high power Yb-doped fiber amplifiers

Craig Robin, Iyad Dajani, Air Force Research Lab. (United States); Clint Zeringue, ZModDynamics LLC (United States); Angel Flores, Benjamin Pulford, Ann Lanari, Shadi A. Naderi, Air Force Research Lab. (United States)

We present experimental and theoretical studies on the stimulated Brillouin scattering (SBS) threshold in fiber amplifiers seeded with a spectrally broadened single-frequency laser source. An electro-optic phase modulator is driven with various pseudo-random binary sequence (PRBS) patterns to highlight the unique characteristics of this linewidth broadening technique and its facility in SBS mitigation. Theoretical predictions show a specific PRBS pattern will provide a maximum SBS suppression factor regardless of modulation frequency. This prediction is experimentally validated in a high power monolithic fiber amplifier operating with near diffraction limited beam quality. We also show Rayleigh scattering and other sources of back reflected light in phase modulated signals can seed the SBS process and significantly reduce the nonlinear threshold.

8601-14, Session PTue

Thermally guiding high-power active fibers

Florian Jansen, Fabian Stutzki, Hans-Jürgen Otto, Cesar Jauregui-Misas, Jens Limpert, Friedrich-Schiller-Univ. Jena (Germany); Andreas Tünnermann, Friedrich-Schiller-Univ. Jena (Germany) and Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

The fast increase of output power of ultra-short pulse fiber laser systems seen in recent years has been enabled by the development of very large mode area fibers that mitigate nonlinear effects. However, recent studies have shown that, at mode field diameters exceeding 50µm, the formation of a thermally induced transverse index profile in the fiber core strongly affects the guiding properties of very large mode area fibers. This index gradient results in significant changes of the guided mode set. In this contribution we present experimental evidence showing that this thermally induced index profile alone is strong enough to guide a stable fundamental mode in a very large mode area fiber. The fiber under test had an Ytterbium-doped core with a refractive index slightly below that of the surrounding silica material. Thus, the index-antiguiding core had a diameter of 42µm and was surrounded by solid silica up to a 170µm-diameter-air-clad for pump guidance. Robust single-mode operation was obtained with output powers of up to 100W. In this experiment the fundamental mode shrank more severely than in comparable fibers with a guiding structure. Beyond the 100W output power, mode instabilities with radially symmetric modes occurred. It should be pointed out, however, that the mode instability threshold was significantly lower than that of an equivalent large-pitch fiber with comparable geometric dimensions and mode field diameter, clearly showing the advantageous concept of higher-order-mode delocalization. The experiments are supported by numerical simulations. Furthermore, the relation to index-antiguiding gain-guiding fibers is discussed.

8601-64, Session PTue

Robust single-mode all solid photonic bandgap fibers with core diameter of 50 micron

Liang Dong, Clemson Univ. Research Foundation (United States); Kunimasa Saitoh, Hokkaido Univ. (Japan); Fanting Kong, Thomas W. Hawkins, Devon McClane, Guancheng Gu, Clemson Univ. Research Foundation (United States)

Mode area scaling is the key for further power scaling of fiber lasers, a very important topic for a wide range of applications in medical, industry, defense and science. Here the key issue is that physics dictates more modes are likely supported once a waveguide is scaled up. There are two fundamentally different design approaches, lower effective index contrast to counter the increase of waveguide dimensions and introduction of additional losses to suppress higher order mode propagation. Lower index contrast leads to weak waveguides, resulting in fibers no longer being coil-able. Our work has been focused on all-glass designs with significant higher-order-mode suppression. In conventional waveguides based on total internal reflections, modes are increasingly guided in the center of the scaled-up waveguide, making it very hard to couple out modes to introduce loss and limiting the scalability of all designs based conventional waveguides. In all-solid photonic bandgap fibers, modes are guided due to anti-resonance of the cladding photonic crystal lattice. This leads to naturally strong mode-dependent guidance. Our theoretical simulation has shown that these fibers, when appropriately designed, provide the best higher-order-mode suppression in all known fiber designs that we have studied for the same equivalent core diameter. Recently, we have demonstrated robust single-mode operation in passive fibers with ~55micron core diameters, a record for all-solid photonic bandgap fibers and largely confirming our theoretical predictions. In this work we will report detailed characterizations of these all-solid photonic bandgap fibers and progress towards the demonstration of ytterbium-doped fibers with ~50micron core.

8601-65, Session PTue

Hyperspectral optical fiber refractive index measurement spanning 2.5 octaves

Andrew D. Yablon, Jayesh Jasapara, Interfiber Analysis (United States)

We have measured the refractive index of optical fiber samples across a wavelength range spanning 2.5 octaves, from 360 nm in the UV to 2100 nm in the SWIR, using a single phase-shifting interferometric apparatus. This spectral range is more than a factor of 2 larger than our previously reported multi-wavelength optical fiber refractive index measurements and adds several new spectral regions of critical importance. The new ultra-broad measurement range includes the pump and amplification bands of high-power Yb-doped, Er:Yb-doped, and Tm-doped fibers, as well as the entire transmission range of all telecom optical fibers. For example, to the best of our knowledge we present the first-ever measurements of any optical fiber or optical fiber preform in the 2000 nm amplification band of Tm-doped silica. Our apparatus can measure the material dispersion of an optical fiber in a spatially-resolved manner that permits more accurate prediction of the fiber's waveguide properties. While it is obviously advantageous to measure any fiber's refractive index at its operating wavelength, measurements performed at other wavelengths can also provide compelling benefits. For example, shorter wavelengths permit superior spatial resolution whereas longer wavelengths significantly reduce the incidence of interferometric phase ambiguities when measuring large diameter polarization-maintaining (PM) optical fibers. Since the measurements are performed transversely through the side of an un-cleaved optical fiber sample, the three dimensional variation of optical fiber fusion splices, physical tapers, or mode transformers can be quantified across this broad measurement band.

8601-66, Session PTue

Distinguishing dispersion from distributed scattering in S2 fiber mode analysis

Jayesh Jasapara, Andrew D. Yablon, Interfiber Analysis (United States)

We introduce a new spectrogram approach for analyzing spatially- and spectrally-resolved interferometry (S2) data that overcomes the previously overlooked ambiguity between dispersion and distributed scattering. Traditionally, S2 yields a one-dimensional spectrum of inter-modal group delays between higher-order-modes (HOMs) and the dominant fundamental mode. According to this interpretation, inter-modal group delay broadening is considered to be a location signature of HOM scattering; for example, a narrow peak in the spectrum is interpreted to be a discrete scattering event whereas a broad feature is interpreted to be distributed scattering along the fiber. Since the inter-modal dispersion is high for weakly guided HOMs, discrete scattering events will also manifest as broadened features. For the first time, we demonstrate a spectrogram approach to S2 analysis in which the spectral interference data is analyzed over small staggered wavelength windows and the inter-modal group delay is plotted as a function of wavelength. In this new two-dimensional map the wavelength dependence of the inter-modal group delay produces an inclination of streaks traversing the spectrogram. This new perspective resolves the ambiguity as to whether group delay broadening is caused by fiber dispersion or distributed scattering that is inherent to the previous one-dimensional S2 mapping. The spectrogram is a more accurate map of mode conversion along the fiber length and is essential for evaluating high power fibers and devices. Results for standard telecom single mode fiber and a large-mode-area fiber will be presented.

8601-67, Session PTue

A high-peak power nanosecond all-fiber MOPA system at high-repetition rate

Chun-Lin L. Chang, National Taiwan Univ. (Taiwan); Po-Yen Lai, National Central Univ. (Taiwan); Yen-Yin Li, National Taipei Univ. of Technology (Taiwan); Shih-Hung Chen, National Central Univ. (Taiwan); Sheng-Lung L. Huang, National Taiwan Univ. (Taiwan) and National Taiwan Univ. (Taiwan)

For all-fiber system, the utilization of large-mode-area (LMA) fibers with typical core NA of 0.07±0.01 is common for easy splice. Furthermore, to maintain the quasi-single-mode output at 1064 nm, the maximum active core diameter should be limited to 15 ?m [1] because the corresponding V number is < 3.8 to make sure only LP11 modes can exit in addition to LP01 mode (HE11). Moreover, the energy scaling of a highly-controlled nanosecond master oscillator power amplifier (MOPA) system is critical especially in high repetition rate, because its seed source is typically nano-joule level or weaker, especially in single mode. Therefore the design of preamplifier becomes significant. In this manner, the subsequent amplifiers can be seeded more to suppress the inter-pulse amplified spontaneous emission (ASE) for saving the stored energy [2], and to enhance the signal amplification for the release of fiber localized thermal load while pump power arises. In addition, forward pumping scheme is usually advantageous in all-fiber layout because the stimulated Raman scattering (SRS) is most likely to occur along the later passive delivery fiber. Besides other ideas [3], large seed energy can ease the efficiency loss caused by shortening active fibers for higher SRS threshold. We achieved the double-passed single-mode preamplifier to obtain the energy 4 times higher than single-pass one with >36-dB gain. The core-pumped scheme can shorten active fiber significantly without photo-darkening effect tested in hours. As a preliminary result, a 15-ns pulse with an energy of 110 ?J at 20 kHz was obtained at the output of a 15/130 double-clad output as shown in Fig.1.

8601-68, Session PTue

Gamma radiation induced darkening of ytterbium doped laser fiber: the role of AlOHC point defect

Thierry Deschamps, Institut des Nanotechnologies de Lyon (France) and CEA (France); Nadege Ollier, CEA-IRAMIS (France); Herve Vezin, Univ. des Sciences et Technologies de Lille (France); Cedric Gonnet, Draka (France)

Ytterbium doped silicate glasses for high power laser fiber is a promising candidate for inter-satellites telecommunication. However, ionizing radiations in space environment imply the formation of absorbing point defects which degrade the laser performance. Despite many studies on this phenomenon called radiodarkening, the colored centers responsible of the output loss has not been yet clearly identified. Using a combination of experimental techniques such as optical absorption, Raman scattering, continuous wave and pulse Electron Spin Resonance (ESR), we characterize a set of ?-irradiated Yb3+ doped silica glass preforms with different contents of Al and P. We demonstrate that when P is introduced in excess compared to Al, nearly no radiodarkening is induced by ?-rays. On the other hand, when Al>P, a large absorption band centred at 550nm with a tail in the near IR is induced by radiation. Combining optical absorption and cw-ESR, thermal annealing experiments demonstrate the correlation between the decrease of the absorption band and the decrease of the Al Oxygen Hole Center (AlOHC) paramagnetic signal. This result unambiguously demonstrated that AlOHC is mainly responsible of the darkening. HYSCORE (HYperfine Sublevel CORElation) 2 dimensional pulse-ESR experiments allow to probe the local environment of the Yb3+ ions. The 2D spectra reveal a high Al-P nuclear spin coupling when P>Al and no coupling when Al>P. This result shows that AlOHC creation is probably inhibited by Al-O-P linkages. Confronting our data with previous works, we show that the well-known photodarkening process, meaning the pump induced losses, can also be explain in this framework.

8601-69, Session PTue

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

Jianqiu Cao, Shaofeng Guo, Jinyong Leng, Xiaojun Xu, Jinbao Chen, National Univ. of Defense Technology (China)

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

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

8601-70, Session PTue

Precisely tunable L-band multi-wavelength fiber laser

Xuwei Qin, Zhaoying Wang, Cuiqin Gao, Dongfang Jia, Mei Sang, Tianxin Yang, Tianjin Univ. (China)

Multi-wavelength fiber laser has been widely used in many potential applications, such as wavelength division multiplexing systems, optical fiber sensing network, optical processing, optical coherence tomography and microwave photonics. Many efforts have been done for obtaining more output wavelengths within flat power spectrum. However, techniques of controlling multi-wavelength have also been brought up most recently. In this paper, we propose a scheme on precisely tunable L-band multi-wavelength fiber laser. This fiber laser has three main characteristics namely broad wavelength band, uniform power spectrum and precise tunability. Firstly, multi-wavelength output with 50GHz channel spacing in broad spectrum range can be obtained at room temperature by using two cascaded semiconductor optical amplifiers (SOA) as the gain medium. Secondly, the output power spectrum of multi-wavelength is flattened by a polarization independent feedback mechanism. Thirdly, precisely and repeatable tuning of multi-wavelength can be realized without affecting its quality using a single-side-band (SSB) modulator driven by electrical radio frequency (RF) signals. Experimentally, about 65 wavelengths within 1.5dB power variation with channel spacing of 50GHz are obtained. The measured optical signal noise ratio (OSNR) and line width of each wavelength channel are about 20dB and 345.5MHz respectively. Theses 65 wavelengths are able to be tuned simultaneously up or down in frequency domain with a tuning step ranging from 10 MHz to 14 GHz. The tuning resolution can potentially be as low as 1 Hz in our experiment which is determined by the resolution of the RF signal. Homogenous sideband-mode suppression ratio (SMSR) ~20dB for each wavelength after tuning is achieved.

8601-71, Session PTue

Fundamental mode evolution in long, large-core (>100 µm) adiabatic tapers

Juho Kerttula, Valery Filippov, Tampere Univ. of Technology (Finland); Yuri Chamorovskii, Vasily Ustimchik, Institute of Radio Engineering and Electronics (Russian Federation); Oleg G. Okhotnikov, Tampere Univ. of Technology (Finland)

We have experimentally studied fundamental mode propagation in several meters long adiabatic step-index tapered fibers with a high numerical aperture, core diameter up to 117 ?m (V=38) and tapering ratio up to 17. We confirmed the single fundamental mode propagation by several experiments, including depolarization and simplified S^2-measurements. Furthermore, we ensured a uniform core index profile without a central dip by using the rod-in-tube technology for preform fabrication. We performed a cut-back measurement to study the evolution of the beam characteristics during propagation through the taper (transversal mode field distribution, divergence, beam quality, polarization state, and modal composition). We found the near field distribution of the fundamental mode to evolve in the taper via a top-hat shape at ~50 ?m core diameter to an annular profile at larger diameters. Despite the solitary fundamental mode guiding, the mode deformation led to a slowly decreasing beam quality with increasing core diameter. We characterized the intrinsic mechanical stresses in the tapers and found these stresses responsible for the mode shape distortion. The robust fundamental mode propagation without mode coupling illustrates the potential of long adiabatic doped tapers particularly for traveling-wave large-mode-area amplifiers. Eliminating the intrinsic stress by careful design of core and cladding materials, doping, and fiber geometry is expected to allow single-mode scaling with diffraction-limited beam quality to very high core diameters, limited only by bending of the fiber due to coiling for practical purposes.

8601-72, Session PTue

Multiple sensor interrogation system based on Fourier domain mode-locked wavelength swept laser

Byeong Kwon Choi, Yong Seok Kwon, Ik Gon Park, Min Yong Jeon, Chungnam National Univ. (Korea, Republic of)

We demonstrate a multiple fiber Bragg grating (FBG) sensor interrogation system using Fourier domain mode-locked (FDML) wavelength swept laser. It consists of a semiconductor optical amplifier (SOA) as an optical gain medium, a 5 km-long dispersion-managed SMF-28e fiber, two optical circulators, two polarization controllers, two isolators, a fiber Fabry-Perot tunable filter (FFP-TF), two 3 dB fiber coupler, an 30 % output coupler, several FBGs. There are two paths in the laser cavity with FBG sensor array. The FDML wavelength swept laser is operational when the scanning frequency of the FFP-TF matches the fundamental frequency of the each laser cavity. Each FBG array provides a separate laser cavity for the FDML wavelength swept laser. The sensing FBGs consists of two FBGs which are arranged close enough to operate with same scanning frequency. Therefore, there are only two peaks for each scanning frequency, implying that the scanning frequency should be changed in order to monitor the sensing point in the multiple-FBG sensor interrogation system. The scanning frequency of the FDML wavelength swept laser is about 46.5 kHz without FBG array. Using the FDML wavelength swept laser, we measure the performance of the multiple FBG strain sensor system in both the time and spectral domains. We also demonstrate the dynamic response of the interrogation with several modulation strains using the FDML wavelength swept laser with different scanning frequencies.

8601-73, Session PTue

Modal instability of rod fiber amplifiers: a semi-analytic approach

Mette M. Jørgensen, Kristian R. Hansen, Marko Laurila, Technical Univ. of Denmark (Denmark); Thomas T. Alkeskjold, NKT Photonics A/S (Denmark); Jesper Lægsgaard, Technical Univ. of Denmark (Denmark)

Rare-earth doped very large mode area fiber amplifiers have gained increased attention due to high output powers with excellent beam quality and good pointing stability. High pulse energies and peak powers require large effective area and new complex fiber designs to mitigate nonlinear effects. Currently, the onset of modal instabilities [1-3] degrading the output beam quality sets the upper limit for power scaling. The modal instability sets in as the average signal power reaches a certain threshold, typically on the order of a few hundred W to 1 kW. A phase shift between a thermally induced index grating at high power levels and the signal intensity causes power transfer from the fundamental mode to a higher order mode leading to modal instability. Beam propagation codes are numerically heavy and simpler models for estimating the modal instability threshold are desired.

A semi-analytic approach [4] is extended for estimating modal instability threshold of photonic crystal fibers. Analytic considerations for thermally induced mode coupling are combined with the finite element method allowing complex micro structured fibers to be considered. This ensures low computational time on the order of minutes per wavelength (standard PC). We investigate modal instability levels of various single- and multi-mode fiber designs as well as evaluate the impact of differential gain.

[1] A. V. Smith and J. J. Smith, “Mode instability in high power fiber amplifiers,” Opt. Express 19, 10180-10192 (2011).

[2] T. Eidam, C. Wirth, C. Jauregui, F. Stutzki, F. Jansen, H.-J. Otto, O. Schmidt, T. Schreiber, J. Limpert, and A. Tünnermann, “Experimental observations of the threshold-like onset of mode instabilities in high power fiber amplifiers,” Opt. Express 19, 13218-13224 (2011).

[3] B. Ward, C. Robin, and I. Dajani, “Origin of thermal modal instabilities in large mode area fiber amplifiers,” Opt. Express 20, 11407-11422

(2012).

[4] K. R. Hansen, T. T. Alkeskjold, J. Broeng, and J. Lægsgaard, "Thermally induced mode coupling in rare-earth doped fiber amplifiers," Opt. Lett. 37, 2382-2384 (2012).

8601-74, Session PTue

Graphene thickness-dependent Er-doped Q-switched optical fiber laser

Xiaolong Wang, Mei Sang, Pan Zhu, Ke Liu, Tianxin Yang, Tianjin Univ. (China)

A stable Q-switched laser is useful in the area of remote sensing, range finding, optical imaging, material processing, and fiber communications. With its excellent linear and nonlinear optical characteristics, graphene has been proven to be an attractive material to generate nanosecond, picosecond and femtosecond laser pulses. It has a lot of advantages, such as lower saturation intensity, larger saturable-absorption modulation depth, higher damage threshold, sub-picosecond recovery time, and an ultrabroad wavelength- independent saturable-absorption range. In this paper, we demonstrate a graphene based Q-switched fiber laser. Graphene was deposited on the fiber interface by the optically driven deposition method. The thickness of the graphene can be controlled by changing depositing time. The compact Q-switched erbium-doped fiber laser based on graphene operated stably, and got Q-switched pulse sequences output with the repetition rate of 19KHz and the average power of 1.4mW when pump power is 40mW. Higher peak power, shorter pulse duration, and higher repetition rate could be achieved by adjusting the thickness of the graphene layer appropriately. Besides, the pulse duration and output power is proved to be a function of the pump power. The repetition rate of this fiber laser had a characteristic of monotonically increasing, near-linear with the changing of pump power. The stable Q-switching pulse output can be observed on the oscilloscope with differently specific repetition rate and pump power. Theory analysis of this fiber laser and further improvement methods is also studied combined with the experimental results.

8601-75, Session PTue

System technology for laser-assisted milling with tool integrated optics

Jan-Patrick Hermani, Michael Emonts, Christian Brecher, Fraunhofer-Institut für Produktionstechnologie (Germany)

High strength metal alloys and ceramics offer a huge potential for increased efficiency (e. g. in engine components for aerospace or components for gas turbines). However, mass application is still hampered by cost- and time-consuming end-machining due to long processing times and high tool wear. Laser-induced heating shortly before machining can reduce the material strength and improve machinability significantly.

The Fraunhofer IPT has developed and successfully realized a new approach for laser-assisted milling with spindle and tool integrated, co-rotating optics. The novel optical system inside the tool consists of one deflection prism to position the laser spot in front of the cutting insert and one focusing lens. Using a fiber laser with high beam quality the laser spot diameter can be precisely adjusted to the chip size. A high dynamic adaption of the laser power signal according to the engagement condition of the cutting tool was realized in order not to irradiate already machined work piece material. During the tool engagement the laser power is controlled in proportion to the current material removal rate, which has to be calculated continuously. The needed geometric values are generated by a CAD/CAM program and converted into a laser power signal by a real-time controller.

First experimental results revealed a significant reduction of process forces for linear milling of e.g. Titanium alloy Ti6Al4V. The developed milling tool with integrated optics and the CAD/CAM system enables a multi-axis laser-assisted machining of complex parts.

8601-76, Session PTue

Yb-doped phosphate double-cladding optical fiber for high-power laser applications

Emanuele Mura, Politecnico di Torino (Italy); Joris Lousteau, Politecnico di Torino (Italy) and Istituto Superiore Mario Boella (Italy); Nadia Giovanna Boetti, Gerardo C. Scarpignato, Davide Negro, Guido Perrone, Massimo Olivero, Politecnico di Torino (Italy); Silvio Abrate, Istituto Superiore Mario Boella (Italy); Daniel Milanese, Politecnico di Torino (Italy)

An Yb-doped phosphate glass double cladding optical fiber was prepared using a custom designed glass composition (P_2O_5 - Al_2O_3 - Li_2O - B_2O_3 - BaO - PbO - La_2O_3) for high-power amplifier and laser applications. The preform drawing method was followed, with the preform being fabricated using the rotational casting technique. This technique, previously developed for tellurite, fluoride or chalcogenide glass preforms is reported for the first time using rare earth doped phosphate glasses. The main challenge was to design an adequate numerical aperture (NA>0.4) between first and second cladding while maintaining similar thermo-mechanical properties in view of the fiber drawing process. The preform used for the fibre drawing was produced by rod-in-tube technique at a rotation speed of 3000 rpm. Optical fiber drawing was carried out using an in-house developed drawing tower and with online fiber diameter monitoring. The rotational casting technique allowed the manufacturing of an optical fiber featuring high quality interfaces between core and internal cladding and between the internal and external cladding, respectively. Loss attenuation was measured using the cut-back method and lasing was demonstrated at 1064 nm by pumping with a fiber pigtailed laser diode at the wavelength of 976 nm.

8601-77, Session PTue

Wavelength-tunable optical fiber laser with suppression of multiple longitudinal modes by using a microfiber-based-ring cavity

Sunduck Kim, Min-Seok Yoon, Young-Geun Han, Hanyang Univ. (Korea, Republic of)

Wavelength-tunable optical fiber lasers have attracted considerable attention for their potential applications in optical communications, fiber-optic sensors, and microwave photonic systems. However, optical fiber lasers suffer from a huge number of densely spaced longitudinal modes around the central lasing wavelength due to the long cavity length, which results in large power fluctuation. To realize single-longitudinal-mode (SML) lasing output, various methods using a saturable-absorber filter and sub-ring cavities for Vernier effect have been proposed. For the case of the SML laser based on Vernier effect, optical couplers have been exploited to realize sub-ring cavities with different diameters, which can broaden the longitudinal mode spacing and suppress the longitudinal modes. However, the sub-ring cavities have small free spectral range (FSP) due to long sub-ring cavities with tens of centimeters in length. In this paper, we demonstrate a novel optical fiber laser for the suppression of multiple longitudinal modes by using a microfiber-based-ring cavity. The proposed fiber ring laser consists of a semiconductor optical amplifier (SOA) as a gain medium, fiber Fabry-Perot tunable filter (FFP-TF), a microfiber-based-ring cavity. Microfibers with the 2 ?m diameters were fabricated by a fused biconical tapering method (FBT), and coiled with an 800-?m-diameter support rod. In addition, the suppression efficiencies of the longitudinal modes were observed with respect to different Q factors of 7357, 9656, 12875. When the microfiber-based-ring cavity has a higher Q factor, the suppression of multi-longitudinal modes was enhanced. With the SML lasing, the proposed optical fiber laser showed the wide tunable wavelength range of 49.6 nm.

8601-78, Session PTue

Experimental and theoretical study of Yb-doped gain-switched fiber laser

Rok Petkovsek, Vid Agrez, Univ. of Ljubljana (Slovenia); Ferdinand Bammer, Technische Univ. Wien (Austria)

Relaxation oscillation that appears after start of the pumping of the gain medium inside the resonator, are usually treated as an unwanted effect. However it can also be as a base for very simple pulsed laser construction as there is no need for any additional active element inside the laser cavity. This represents important advantage also in the case of fiber lasers because it makes easy to build a fully integrated design. Pulse parameters of the gain switched laser based on Yb-doped double-clad fiber strongly depend on pumping as well resonator construction (resonator lengths, gain medium, loses,…).

In this paper we present an experimental and theoretical study of different parameters that affect the pulse duration and peak power of the gain switched fiber lasers. The experimental setup consist of a custom made driver and control electronics that is capable of switching pumping light on and off within few tens of ns. The laser was modeled with numerical model based on rate equations. It describes the dynamics and spatial distribution of inversion population and photons within the resonator.

From our theoretical as well numerical results it is clear that that by using adequate active fiber resonator geometry, active ion doping and high enough pumping power a pulses with duration in range of 30-40 ns and peak power of approximately 1 kW can be achieved. Such kind of system can be interesting for some application in micro-processing like thin film removal (scribing) due to its simple design.

8601-79, Session PTue

Heating power feedback control for CO2 laser fusion splicers

Wenxin Zheng, Hiroshi Sugawara, William R. Klimowych, AFL (United States)

Fabrication consistency of fused glass components, such as tapers, couplers, combiners, mode-field adaptors, and fusion splices is critical to fiber laser production. Automated splicers using CO2 laser heating can provide such consistency due to operation that is contamination-free from metal oxide particles, low maintenance due to the absence of electrodes or filaments, accurate and adjustable heating area, and uniform heating for large ratio tapers due to heating by absorption. However, the well known 5% beam power variation of most CO2 lasers is a significant obstacle to acceptance.

As shown in Fig.1, CO2 beam power variation can be measured simultaneously using thermopiles and CMOS cameras. Heated fiber luminescence varies tremendously even for a 2% beam power variation. This allows both thermopile detectors and cameras to be employed as measurement sensors to form a closed loop feedback control resulting in very stable CO2 laser output (Fig.2). Feedback from thermopiles, either near field or far field, can regulate the beam power. Camera feedback can directly regulate the temperature of glass rod during tapering with an automated splicer (Fig.3).

A feedback controlled CO2 laser exhibits remarkable stability and consistency. Measured splice loss and splice strength for stabilized and unstabilized CO2 laser splicing of SMF28 are compared in Fig.4. Splice loss performance is very much improved while splice strength is not affected. Moreover, feedback control reduces peak-to-peak ripple during tapering operations. As an example, 10 µm ripple is achieved for tapering from 2 mm to a 1 mm diameter over an 80 mm length.

8601-80, Session PTue

Investigation of temperature influence on output properties of high-power cladding-pumped Er,Yb co-doped fiber laser

Wenting Chen, Jianjian Sha, Yong Wang, DeYuan Y. Shen, Fudan Univ. (China)

Effect of the fiber's temperature on lasing performance was investigated in high-power, cladding-pumped Er, Yb co-doped fiber laser system. A three-layer symmetric cylindrical model was applied to describe the temperature distribution of the fiber under natural air convection. Radial temperature distribution of the fiber was calculated with consideration of the quantum defect heat, the heat from the absorption of spontaneous emission, and the convection and radiation at the heat transfer boundaries. The steady-state theoretical model based on rate equations took into account of the energy transfers between Er3+-ions and Yb3+-ions and a fraction of nonparticipatory Yb3+-ions. Shooting method and Newton iteration method were used to solve the boundary-value problems under different environment temperatures, pump powers and reflectivities at the fiber ends. Numerical simulations was consistent with experimental results and showed that increasing the fiber's temperature was an effective strategy to suppress the 1 ?m parasitic lasing and improve the lasing performance at 1.5 ?m, a similar phenomenon was found with enhancing doping concentrations of the two ions and decreasing the reflectivities at the fiber ends. Our numerical results presented a theoretical guideline for further improving the laser performance in terms of output power of ~1.5 ?m in high-power Er,Yb-doped fiber laser systems.

8601-81, Session PTue

Mode coupling in large-diameter multi-mode silica optical fibers

Changgeng Ye, Joona J. Koponen, Ville Aallos, Teemu Kokki, nLIGHT Corp., Lohja (Finland)

Large-diameter multi-mode(MM) silica optical fibers are widely used in various applications to deliver high-power, high-brightness laser beams.

Many high-power fiber-coupled laser diodes (LDs) are equipped with the industry-standard power delivery cables, whose core/cladding diameters range from 105/125µm, 200/220µm, 400/480µm to 600/680µm, and numerical apertures (NAs) range from 0.15 to 0.22, depending the output power level and brightness.

Solid-state lasers and fiber lasers usually provide high beam quality, which is close to single-mode(SM). In principle, small core diameter, SM fibers could be used as power delivery cables. However, in some applications, especially when the average/peak power is very high and the desired delivery length is relatively long, one has to consider making compromises between the excellence of beam quality and other factors, including the capability of power handling, the ease of fiber coupling and the onset of nonlinearities. Thus, sometimes the large-diameter MM fibers turn out to become the practical solution.

In those applications, the input beam is considerably underfilled, i.e. the input beam has a smaller NA than the nominal NA of the fiber (typically a factor of ~0.5 for LDs and as low as <0.1 for solid-state and fiber lasers). Only a group of lower-order modes are excited. As the beam propagates along the fiber, mode coupling occurs, which couples the power to higher-order modes, resulting in a large output NA and lower output brightness than the input.

In this study, we report a comprehensive experimental study on mode coupling in commercial large-diameter multi-mode silica optical fibers. The evolution of the far-field angular power distribution is experimentally measured, and the mode coupling coefficients are characterized on a variety of fibers with diverse parameters, including core/cladding diameter (50-600µm/125-680µm), length (few to hundreds of meters), NA (0.15-0.46), etc.

Mode coupling plays an important role, even in very short fiber samples. Fiber NA has little influence on the mode coupling and the output NA. However, both the cladding diameter and the core-to-cladding ratio have strong influence. By increasing the cladding diameter and decreasing the core-to-cladding ratio (e.g. using 105/400 fiber geometry), mode coupling could be significantly reduced. Output NA could also be optimized by using tailored index shape, which will be discussed in this study.

The influences of bending, stress and high transmission power will be discussed.

This study could provide practical guidance in designing power delivery fibers for high-power diode, solid-state and fiber lasers to preserve the input brightness and beam quality.

8601-82, Session PTue

Tunable actively Q-switched fiber laser based on fiber Bragg grating

Andres Gonzalez Garcia, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); Baldemar Ibarra Escamilla, Eugene A. Kuzin, Felipe Maya Ordoñez, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); Manuel Duran Sanchez, Univ. Tecnológica de Puebla (Mexico)

We report a tunable actively Q-switched laser. A Fabry-Perot cavity is formed by a tunable fiber Bragg grating and two short-wave pass dichroic mirrors, (SWP-0-R1550-T1064-0525-C) and (SWP-45-RU1550-TU1064-PW-0525-C) incident angles, with high reflectivity (>99.5%) at 1550 nm and high transmission (>90%) at 1064 nm. The Er3+/Yb3+ double-clad fiber was pumped by a high power diode laser (JOLD-30-FC-12-976). The diode laser has output fiber with a core diameter and numerical aperture of 200 µm and 0.22, respectively. The Er3+/Yb3+ fiber has a core diameter of 7 µm and numerical aperture of 0.17. The pump was coupled into the doped fiber through the collimating aspherical lens with focal distance 18 mm, 45o dichroic mirror, focusing aspheric lens with focal distance of 8 mm, and a 7.5o cleave at one end of the doped fiber. The use of aspherical lenses allows reducing the spherical aberration caused by the large numerical aperture of the fibers and increasing the coupling efficiency for both pump and signal. An acousto-optic IR modulator with a diffraction efficiency of >60% at first order was inserted in the cavity. The pump power used in experiments was limited to a maximum power of 5 W. The laser was tunable over 5 nm in the wavelength region of 1550 nm with a wavelength selectivity of 0.8 nm from 1549 to 1544 nm. The Q-switch operation was achieved at pulse repetition rate of 120 kHz. Average output power was 1 W at 5 W of pump with a pulse duration of 530 ns.

8601-83, Session PTue

Tm3+/Sm3+ co-doped Tellurite glass for amplification at 1.4 µm

Luiz C. Barbosa, Marcos P. Belançon, Enver F. Chillcce, Univ. Estadual de Campinas (Brazil)

Tm3+ ion has an well-known transition at 1.44um [1], which can be useful to produce, when co-doped with Er3+ a amplifier covering continuously the S and C bands of optical communication. In this work, we propose a study of the glass system 71.5% TeO2, 22.5% WO3, 5% Na2O and 1.5% Nb2O5 doped with Tm2O3 and a co-doping scheme involving Tm2O3 and Sm2O3, to investigate if a energy transfer between the lower level of the 1.44um transition in Tm3+ to Sm3+ ions can enhance the intensity of this emission band. The samples were fabricated by the conventional melt quenching process, and different concentrations of each dopant were chosen. The characterization consists in measurements of optical absorption spectra, optical emission spectra and life-time decay pumping the Tm3+ ions at 790 nm.

[1] E. F. Chillcce, E. Rodriguez, A. A. R. Neves, W. C. Moreira, C. L. César, and L. C. Barbosa, Optical Fiber Technology 12, 185-195 (2006).

8601-84, Session PTue

Strategy of efficient milli-joule output in single mode from a highly-controlled all-fiber MOPA system with 60 dB gain

Chun-Lin L. Chang, National Taiwan Univ. (Taiwan); Po-Yen Lai, National Central Univ. (Taiwan); Yen-Yin Li, National Taiwan Univ. (Taiwan); Shih-Hung Chen, National Central Univ. (Taiwan); Sheng-Lung L. Huang, National Taiwan Univ. (Taiwan) and National Taiwan Univ. (Taiwan)

Nanosecond fiber MOPA system has been proved experimentally to produce the milli-joule output in the past years [1,2]. However, the previous strategies are to further increase the LMA core diameter but sacrifice the efficiency by coiling effect for beam quality [1], and to use the rod-type fiber amplifier but forgo the splice feasibility for all-fiber structure [2]. In addition, the highly-controlled MOPA system is usually achieved by a very weak seed and therefore limits efficiency and output energy [3]. It is noted that the mature product of 30/250 LMA fiber with core NA of 0.06 has been demonstrated to approach the ideal maximum extractable energy of > 2 mJ as single-stage amplifier using well-saturated Q-switched input energy of > 200 ?J and pump power of >140 W at 976 nm [4]. For a highly-controlled all-fiber MOPA system using the maximum core diameter of 30 ?m as the final stage to reach the milli-joule output, the primary solution is to increase the input energy as can as possible by designing a preamplifier series with the overall gain of >50 dB at least. The secondary issue is to overcome the SRS-limited energy by active and passive fiber length, and the pumping scheme according to a scaling law. In this paper, we report how a highly-controlled all-fiber MOPA system to efficiently reach the milli-joule output in high repetition rate according to a modified numerical model [5] based on coupled rate equations verified by experiments. Such a milli-joule MOPA system in all-fiber layout with V parameter of <6.5 (~10 modes) does provide the compactness and stability, and better beam quality without too much coiling effect to meet more kinds of applications.

8601-85, Session PTue

Spectroscopic investigation of the glass system TeO2-WO3-Na2O-Nb2O5 for mid-infrared amplifiers

Luiz C. Barbosa, Marcos P. Belançon, Enver F. Chillcce, Univ. Estadual de Campinas (Brazil)

Tellurite glasses following the molar concentration 71.5% TeO2, 22.5% WO3, 5% Na2O and 1.5% Nb2O5 have been investigated. Samples doped with Tm2O3, Pr2O3, Yb2O3 or Bi2O3 were fabricated by the conventional melt quenching process. Rare-earth (RE) 3+ ions have well defined emission bands. Bismuth emission in the infrared region have been found in some glasses and emission laser have been already obtained [1,2]??. The Bismuth emission is sometimes referred as a “superbroadband” [3]? emission around 1.3um, which is very promising for an optical amplifier, but, to the best of our knowledge a bismuth based optical amplifier have not been produced yet. Our purpose is investigate the mechanism behind this misunderstood “superbroadband” luminescence, and compare it with the rare-earths properties in the same range. The characterization consists in measurements of optical absorption spectra, optical emission spectra and life-time decay. Differential thermal analysis (DTA) was also performed, to identify changes in Tg and Tx as function of the doping concentration, which is important to the drawing process of a fiber.

8601-86, Session PTue

Tunable dual-wavelength fiber laser within the gain curve of the erbium doped fiber

Manuel Duran Sanchez, Univ. Tecnológica de Puebla (Mexico); Evgeny A. Kuzin, Baldemar Ibarra-Escamilla, Andres Gonzalez Garcia, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); Miguel V. Andrés, Jose L. Cruz Munoz, Univ. de València (Spain); Olivier J. Pottiez, Centro de Investigaciones en Óptica, A.C. (Mexico)

We study experimentally the behavior of the losses in a double-wavelength laser in the gain spectrum of the Erbium doped fiber in a linear cavity based on a superimposed fiber Bragg gratings (SI-FBGs).The linear cavity is formed by a Hi-Bi Fiber Optical Loop Mirror (HBFOLM) and three pairs of SI-FBGs were also used to tune the dual wavelength laser. The SI-FBGs were placed on a mechanical mount that allow compression, both lines are shifted simultaneously. The separation of SI-FBGs is 5 nm, and covers almost the entire spectrum of erbium from 1529nm to 1556nm approximately.The Hi-Bi fiber FOLM is used as a spectral tunable filter, which adjusts the losses by controlling the temperature in the Hi-Bi fiber.

8601-87, Session PTue

All-fiber highly-chirped dissipative soliton oscillator and its scaling

Denis Kharenko, Institute of Automation and Electrometry (Russian Federation) and Novosibirsk State Univ. (Russian Federation); Evgeniy V. Podovilov, Institute of Automation and Electrometry (Russian Federation); Alexander A. Apolonskiy, Ludwig-Maximilians-Univ. München (Russian Federation) and Institute of Automation and Electrometry (Russian Federation); Sergey A. Babin, Institute of Automation and Electrometry (Russian Federation) and Novosibirsk State Univ. (Russian Federation)

It is known that dissipative solitons (DS) generated in fiber oscillators with mode-locking mechanism based on nonlinear polarization evolution (NPE) in a single-mode fiber (SMF), exhibit stability and energy limits at the cavity lengthening [1]. The reason of the stability break is shown to be an excessive rotation of the polarization ellipse at SMF lengthening [2], therefore we proposed in [2] a combined cavity consisting of short SMF part (for NPE mode locking) and a long PM fiber part (for generating highly-chirped DS pulses).

Here we report on the experimental realization of this approach that enables us to increase the cavity length of the DS oscillator to L=90 m in an all-fiber configuration. We have also identified the next limit of energy scaling related to the onset of Raman conversion of the DS spectrum. At 7 MHz repetition rate (L~30 m) the maximum energy of the stable highly-chirped DS realized with 5.5-?m-core PM fiber amounts to ~20 nJ in ~30 ps pulses compressed to ~200 fs. The Stokes pulse having half of DS energy, and being shifted by 40 nm spectrally and 30 ps temporally from DS, does not break the stability of the latter. At 2.35 MHz rate (L~90 m) the DS and Stokes pulse energies become comparable amounting to ~30 nJ each while the second Stokes pulse starts to grow. Higher DS energy will be possible by means of a core enlargement, corresponding experiments are also performed.

1. A. Chong et al., Opt. Lett. 14, 10095-10100 (2007).

2. D. S. Kharenko et al. Las. Phys. Lett., 9 (2012)[DOI:10.7452/lapl.201210060].

8601-88, Session PTue

Single-frequency ytterbium-doped phosphate fiber laser at 976 nm

Xiushan Zhu, College of Optical Sciences, The Univ. of Arizona (United States) and NP Photonics, Inc. (United States); Wei Shi, Jie Zong, Dan T. Nguyen, NP Photonics, Inc. (United States); Robert A. Norwood, College of Optical Sciences, The Univ. of Arizona (United States); Arturo Chavez-Pirson, NP Photonics, Inc. (United States); Nasser N. Peyghambarian, College of Optical Sciences, The Univ. of Arizona (United States)

Linearly polarized wavelength stable single frequency ytterbium (Yb^{3+}) doped fiber lasers below 1 µm, namely three-level Yb^{3+} fiber lasers, are highly demanded for nonlinear wavelength conversion to generate coherent blue light or even deep ultraviolet coherent sources. We report a 976 nm single-frequency core-pumped distributed Bragg reflector (DBR) fiber laser consisting of a 2-cm long highly ytterbium-doped phosphate fiber and a pair of silica fiber Bragg gratings (FBGs). The high reflection (HR > 99%) and partial reflection (PR = 60%) FBGs were cleaved very close to the index modulation region and directly spliced to a 2-cm-long highly Yb^{3+}-doped phosphate fiber. Over 100 mW of linearly polarized output with a linewidth less than 2 kHz can be obtained when the launched pump power is about 450 mW. The efficiency of the 976 nm single-frequency fiber laser (the output power vs the launched pump power) is about 25%. The relative intensity noise was measured to be -110 dB/Hz at 1 MHz and the variation of the center wavelength is less than 0.0005 nm during a measurement period of 2.5 hours. This single-frequency fiber laser has an SNR of over 50 dB and there is no strong ASE or spurious lasing at long wavelengths even at the maximum pump power. This all-fiber single-frequency DBR laser with attractive features can be used for efficient blue and UV generation through nonlinear frequency conversion. Moreover, this high-performance 976 nm single-frequency fiber laser can be used as a single-frequency, low RIN pump laser for long wavelength Yb^{3+}-, Er^{3+}-, or Yb^{3+}/Er^{3+}-doped fiber lasers and amplifiers.

8601-90, Session PTue

1.3 micron flat-gain optical amplification with Bi doped silica fiber

Soichi Kobayashi, Chitose Institute of Science and Technology (Japan)

1.3 ?m optical amplifiers for the long-distance up-stream networks are attractive for a future increase of fiber access network in telecommunications. Bismuth-doped silica glass was proposed as a laser application at 1.3 ?m by Y. Fujimoto and M. Nakatsuka. The bismuth-doped fiber lasers and amplifiers were discussed by the Dianov group fabricating by the MOCVD method. In this report a new flat-gain amplification at 1.3 ?m is presented with the bismuth-doped silica fiber (BDSF) made by the VAD method. The BDSF preform consists of Si, Ge, Al and Bi oxides. Bismuth and aluminum ions were solution-doped into a porous germanosilicate layer. The concentration of Bi in the core glass was measured as 0.5 mol% by EDX spectroscopy. Refractive index difference between core and cladding in the preform was measured as 0.95 % by the optical fiber preform analyzer. The preform was drawn into the fiber where core and cladding diameters were measured as 8??m and 125 ?m, respectively. Luminescence spectra of BDSF show the flat characteristics over 1200-1385 nm by LD pumping at 805.3 nm. Core pumping into the BDSF was performed by splicing with the pigtail of the pumping LD. The 10 dB amplification was measured by launching 1300 nm LD light with the WDM coupler. An absorption loss at 1380 nm was observed and an amount of the OH ions seems to be contributing to the gain flatness in the 1.3 ?m bandwidth of the BDSF made by VAD method.

8601-91, Session PTue

Impact of P2 scribe geometry on monolithic series interconnected CIGS modules

Mathew N. Rekow, EOLITE Systems (France); Dominik Bartle, Robert Bosch GmbH (Germany); Christian Sandfort, Bosch Solar CISTech GmbH (Germany); Andreas Letsch, Robert Bosch GmbH (Germany)

The motivation for this work arises from the fact that series resistance is a critical parameter in the efficiency of monolithically series interconnected CIGS modules. Indeed, concern over the contact resistance between the transparent conductive layer and the Mo layer has been one concern that has slowed adoption of laser processes in CIGS (3). It is our hypothesis that the geometry of the edge of the may play a significant role in determining the contact resistance of the P2 scribe and it is the aim of this work to determine if a reduction in contact resistance can be obtained by tailoring the geometry of the P2 scribe to maximize the effective contact area.

Figure 1 below illustrates the geometrical arrangement of an idealize P2 scribe as they are commonly applied in industry today. The hallmark of this scribe is that the edge is straight. The transparent conductive top layer (TCO) then makes the connection to the Mo layer below. Although there will be some current spreading, the contact surface area can be seen to be proportional to the total scribe length. By extension the contact resistance should be inversely proportional to the scribe edge length per overall length ratio. In the case of a straight scribe this ratio is 1, or in other words the scribe edge length is equal to the total scribe length.

By way of contrast, Figure 2 depicts real scribes that were applied with the scalloped geometry typical of ns laser processing. By inspection it is clear that the linear edge length per unit scribe ratio in this geometry is significantly higher than for a single continuous linear scribe. In Figure 2-left we can see that once the laser spots have separated the full diameter of the laser spot become active in transporting photo current to the Mo layer where as when the line is continuous only one edge plays a meaningful role in current conduction.

Based on this simplistic geometric interpretation we have developed a simple model that predicts the hypothetical contact area based on a dimensionless parameter we call the spot overlap ratio. Positive spot over lap ratio indicates overlapping spots in the usual sense used within the industry. Negative overlap indicates resolved laser ablation spots with 0 indicating spots that they are tangent, -1 indicating spots separated by one diameter and -2 indicating spots that are separated by 2 diameters and so forth. To add a degree of sophistication to this simple model we also include an adjustable parameter that models the impact of current crowding in the channel between adjacent resolved laser spots. The physical interpretation of this parameter is simply the sheet resistance of the TCO layer. The prediction of this model for the variation of relative contact resistance vs. spot overlap ratio is shown in Figure 3.

In this work we process 8, P2 test structures with a selection of laser spot overlap ratios that span the curve plotted in

Working CIGS modules will also be fabricated using a selection of these scribe geometries and compared directly to mechanically scribed modules and the results will be included in this paper if they are completed in time.

8601-92, Session PTue

Low noise and gain-ripple fiber Raman amplifiers pumped by single wavelength-swept Raman lasers with designed gain spectral profile

Changren Qiu, Tianxin Yang, Dongfang Jia, Zhaoying Wang, Mei Sang, Chai Lu, Tianjin Univ. (China)

A single wavelength-swept broadband Raman laser is designed specifically to implement time-division multiplexing (TDM) pumping of a low gain-ripple broadband Raman amplifier (BRA) which can result in significant noise-reductions. In TDM pumping, dwell time at a certain pump wavelength indicates the amount of Raman gain arising from that wavelength so that the sweep pump weighting function (SPWF), an uneven and complex temporal pump pattern, can be determined to meet the requirement of broadband constant Raman gain using optimization iteration algorithms. If the sweep pump pattern (SPP) repetitive rate is high enough, counter-propagating signals do not experience significant temporal gain variations but faces the composite Raman gain of all pump wavelengths of the sweep pattern. Implementing SPP along with an uneven wavelength-swept rate in a single laser system is difficult. In this paper, the single wavelength-swept broadband Raman laser is designed as a single TMD pumping source to generate the SPP using an uneven-power output at a constant wavelength-swept rate per cycle based on the combination of Fourier-domain mode locking (FDML) and BRA using multiple pumps. Basically, this system is a type of FDML Raman fiber laser (FDML-RFL) with a ring cavity consisting of several kilometer fibers as Raman gain material. The Raman gain spectral profile (RGSP) of this FDML-RFL is not flat in a 80 nm broadband for a center wavelength of 1460 nm although it is pumped simultaneously by 4 different wavelength-fixed lasers. Its RGSP is designed to coincide with the complex SPP which the wavelength-swept rate is constant but the output intensity is various. The designed system can implement the TDM pumping scheme in a conventional Raman amplifier. The procedures, including determining optimum sets of 4 pump wavelengths and the appropriate powers to obtain the desired uneven RGSP, and the results of the design will be presented.

8601-93, Session PTue

Picosecond supercontinuum laser with consistent emission parameters over variable repetition rates from 1 to 40 MHz

Thomas Schönau, Torsten Siebert, Romano Haertel, Thomas Eckhardt, Dietmar Klemme, Kristian Lauritsen, Rainer Erdmann, PicoQuant GmbH (Germany)

An all-fiber picosecond visible supercontinuum laser source is presented that allows for a uniform spectral profile and equivalent pulse characteristics over variable repetition rates from 1 to 40 MHz. The system is based on a polarization maintaining (PM) Yb^{3+}-doped fiber amplification of a picosecond gain-switched seed diode at 1062 nm that guarantees full flexibility in repetition rates and can be triggered freely. The pump power in the multi-stage amplifier is actively adjusted by a microcontroller for a consistent peak power of the 1062 nm signal in the full range of repetition rates. This allows for spectral broadening in a photonic crystal fiber (PCF) at constant signal input parameters. The length of the PCF is scaled to deliver a homogeneous spectrum and minimized distortion of the temporal pulse shape. With this approach, a power density of up to 1 mW/nm and pulse durations of sub 150 ps can be provided over the entire spectral range of the supercontinuum. Additionally, a broadband PM delivery fiber is spliced to the end of the PCF to strip out residual NIR over 750 nm and to clean up the transversal mode from the originally hexagonal geometry.

Applications can be found in time-resolved fluorescence spectroscopy. The wide range of repetition rate and the option for free triggering makes it easy to adapt it to different fluorescence lifetimes and experimental setups.

8601-95, Session PTue

Experimental study on ultra-long cavity passively mode-locked fiber laser based on semiconductor optical amplifier

Tonghui Liu, Dongfang Jia, Zhongyuan Zhang, Jiong Chen, Jingwen Yang, Zhaoying Wang, Tianxin Yang, Tianjin Univ. (China)

Passively mode-locked fiber laser (MLFL) has got more attention of researchers for its small size, simple structure in generating ultra-short pulse. In recent years, nonlinear polarization rotation (NPR) in semiconductor optical amplifier (SOA) has been studied and applied as a mode-locking mechanism. It has many advantages: firstly, SOA acts as not only a laser gain medium, but also a mode-locking element. Compared with traditional methods, it is able to simplify the structure of the mode-locked lasers. Secondly, as an ultra-fast optical device, SOA has a shorter recovery time that enables the laser to have an output with high repetition rate. So, study of mode-locked fiber laser based on NPR in SOA has got great importance for further improvement and applications of mode-locked fiber laser. In this paper, an experimental setup for passively mode-locked fiber laser by NPR mechanism in SOA is built. Through adding 4km single mode fiber into the ring cavity, a stable fundamental-order mode-locked pulse train with the repetition frequency of 50.72 kHz is generated through NPR effect in SOA. The central wavelength, 3dB bandwidth, and single pulse energy of output pulse are 1544.65nm, 1.506nm, and 33.12nJ, respectively. At the same time, harmonic mode-locked pulse train with highest order of 24 is observed by increasing SOA current.

8601-96, Session PTue

Thermal effect-resilient design of large mode area double-cladding Yb-doped photonic crystal fibers

Enrico Coscelli, Federica Poli, Univ. degli Studi di Parma (Italy); Mette M. Jørgensen, Technical Univ. of Denmark (Denmark); Thomas T. Alkeskjold, Lasse Leick, Jes Broeng, NKT Photonics A/S (Denmark); Michele Sozzi, Alessandro Candiani, Annamaria Cucinotta, Stefano Selleri, Univ. degli Studi di Parma (Italy)

Thermo-optic effect, which causes refractive index change in active optical fibers, has recently emerged as one of the most limiting factors to power scaling of fiber lasers and amplifiers. Indeed, the thermally-induced parabolic refractive index increase in the fiber core jeopardizes the extreme guiding properties required to obtain single-mode propagation in ultra Large Mode Area (LMA) fibers, therefore causing the rise of mode instabilities.

Double-Cladding Photonic Crystal Fibers (DC-PCFs), which are currently appointed as one of the most valuable solutions for high-power systems, are not immune to thermal effects. Nevertheless, the large degree of freedom of their design allows for the implementation of proper counter-measures to mitigate the effects of thermally-induced index changes.

In this paper the guiding properties of different novel LMA DC-PCF designs, such as distributed modal filtering and 19 cell-core PCFs, have been numerically analyzed, and their resilience to thermal effects have been compared. A simple but accurate model has been applied to obtain the refractive index change in the fiber cross-section, and a full-vector modal solver based on the finite-element method has been used to calculate the guided modes of the PCFs operating at high power levels. The width and spectral position of the single-mode range have been calculated at different power levels for each fiber design, and the effective area decrease due to mode focusing has been determined.

Results constitute a comprehensive view of the impact of thermally-induced refractive index change on the guiding properties of DC-PCFs, providing guidelines for the design of LMA fibers.

8601-97, Session PTue

Chirped pulse amplification in Tm doped fiber using a chirped Bragg grating

Robert A. Sims, Pankaj Kadwani, Lawrence Shah, Martin C. Richardson, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

Femtosecond pulses were generated then amplified using chirped pulse amplification in Tm:fiber. A mode-locked oscillator centered at 1975 nm generated time bandwidth pulses with 800 fs pulse duration, ~5 nm (FWHM) spectral width, and 40 pJ energy. The soliton pulses generated in the oscillator were then amplified using a soliton self-frequency shift process in a doped Tm fiber. This process amplified pulses to 3 nJ, provided a tunable center wavelength, and reduced the pulse duration to 150 fs corresponding to a 30 nm spectral bandwidth. The pulse was tuned to 2020 nm which matched the center wavelength of a chirped Bragg grating (CBG) which stretched the pulse to >160 ps. The average reflectivity of the element was ~82% with a 52 nm rectangular bandwidth and the group velocity dispersion was calculated to be 12.3 ps^2. In order to compensate the additional dispersion of the Tm:fiber amplifier a ~9 m section of normal dispersion fiber was spliced into the system prior to the single mode amplifier. Stretched pulses were amplified to 85 nJ in single-mode Tm:fiber and recompressed with the CBG to 400 fs. In order to confirm the high peak power of the output pulses, we have conducted several experiments to generate supercontinuum in highly nonlinear fiber. We are currently investigating single-mode and large mode area amplifiers to be implemented to amplify pulses to µJ energy levels.

8601-98, Session PTue

Design and demonstration of tunable q-switched fiber laser

Manas Srivastava, Deepa Venkitesh, Balaji Srinivasan, Indian Institute of Technology Madras (India)

High energy pulses which are useful for LIDAR, material processing and nonlinear optical applications can be obtained from compact fiber-based Q-switched lasers. Narrow linewidth, wavelength-tunable and variable repetition-rate short pulse lasers are desirable for applications such as optical parametric amplification, second harmonic generation and stimulated Raman scattering.

In this paper, we present the simulation results towards the design of such a laser and demonstrate the design experimentally. This model is applicable to Erbium-doped fiber (EDF) lasers (at C-band), Ytterbium-doped fiber laser (at 1064 nm) or Thulium-doped fiber laser (at 2 ?m). We present the results of EDF based actively Q-switched laser, modeled in the ring configuration with an acousto-optic modulator as the intra-cavity Q-switching element. The evolution of the laser pulse in the cavity is numerically simulated in the traveling wave model using Finite different time domain method, and accounts for propagation delays, spatial distribution of powers and population densities.

Wavelength tuning is achieved using an intra-cavity bandpass filter tunable in the C band. The temporal and spectral characteristics of all intra-cavity elements are incorporated in the numerical simulation. A tunable repetition rate and tunable wavelength laser is demonstrated experimentally, yielding pulses of peak power 7.1 W, width 212 ns (at 1533 nm) and a repetition rate of 10 kHz. These results are found to agree reasonably with the simulation results, thus ratifying the simulation model. The paper further discusses the numerical and experimental results of the tunable wavelength and tunable repetition rate pulsed laser, in a black-box implementation.

8601-99, Session PTue

Novel all-silica, large mode area fiber with microstructured cladding elements

Sonali Dasgupta, John R. Hayes, David J. Richardson, Univ. of Southampton (United Kingdom)

All-solid LCFs and rod-type photonic crystal fibers (PCFs) have proved to be most promising as LMA fibers. However, the rod-type PCFs allow extremely large mode areas in a rigid configuration only [ ]. In contrast, all-solid LCFs offer bending flexibility down to few tens of centimetres for effective area as high as 1300μm2 (at 1.05μm) [ ]. However, issues with out-gassing and diffusion of high concentrations of Fluorine limit the maximum index contrast that can be achieved in these fibers and hence, their performance.

Here, we propose a novel, single-material design that exhibits bending characteristics comparable to all-solid LCFs along with an additional degree of freedom in terms of the cladding element lattice to control the effective index difference between the core and cladding, which can be exploited to tune the bend loss and modal index difference. The proposed design consists of 6 microstructured cladding elements arranged in a hexagonal lattice, where each element itself is a hexagonal lattice of 3-4 rings of small air holes. The resulting leaky waveguide allows single-mode output due to the high differential loss suffered by the higher order modes (HOMs), which 'leak out' from the regions in between the cladding elements (similar to LCFs). Here, we present a detailed study on the bend characteristics and differential loss limitations of the proposed design. We report a fiber with an effective area of 1600μm2 at 1.05μm, with a FM and HOM loss of ~0.05dB/m and ~1dB/m, respectively. Experimental characterization of the proposed fiber is also reported.

8601-100, Session PTue

Robust 1550-nm single-frequency all-fiber ns-pulsed fiber amplifier for wind-turbine predictive control by wind Lidar

Oliver de Vries, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Christoph Bollig, Paul Gerke Hofmeister, Rainer Reuter, Carl von Ossietzky Univ. Oldenburg (Germany); Franz Beier, Thomas Schreiber, Ramona Eberhardt, Andreas Tünnermann, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

The disastrous incidents of Chernobyl in 1986 and most recently at Fukushima Daiichi nuclear power plant caused a worldwide rethinking of the necessity of sufficient, nonpolluting and above all safe alternative energy sources. The environment-friendly utilization of wind power is one promising alternative. Clustered in wind farms, todays wind turbines can produce Megawatt-level output powers. To reach the ambitious and politically motivated aims of Multi-GW offshore wind farms - capable of substituting several nuclear power plants - not only the number of turbines in a wind park but the yield of the individual turbine has to be scaled as well. But with growing rotor diameters the influence of a complex inflow within the rotor area makes it more and more difficult to control and operate the wind energy converters. To ensure stable operation as well as a long lifetime at high output levels, it is crucial to monitor the inhomogeneous wind field in front of the system at different distances. In this contribution, we demonstrate an all-fiber ~250ns-pulsed 1550nm fiber amplifier system suitable for coherent Doppler Lidar making a predictive control of the turbine conceivable. Since this laser should be cost-efficient and suitable for industrialization all components have to be commercially available. Furthermore, we will discuss the experimental results of two different pumping schemes (co- vs. counter-propagation) and argue pros and cons in regard to efficiency and nonlinear limitations. Future power scaling toward 100 μJ, ideal packaging and issues of mechanical and thermal robustness will also be considered.

8601-101, Session PTue

Pulsed Yb:fiber system capable of >250 kW peak power with tunable pulses in the 50 ps to 1.5 ns range

Timothy S. McComb, Tyson L. Lowder, Joel Hutchinson, Matthieu J. Saracco, Adam S. Dittli, Jared Green, Matthew Randall, Geoff Fanning, Jake Bell, nLIGHT Corp. (United States)

A pulsed 1064nm PM Yb:fiber laser system incorporating a tunable pulse repetition rate, pulse duration seed source and a multistage fiber amplifier, ending in a large core (>30 um mode field diameter), tapered fiber amplifier is demonstrated. The amplifier chain is an all-fiber system, with exception to the final amplifier's pump combiner, allowing robust, compact packaging. The air-cooled laser system is rated for >60W of average power and beam quality of M2 < 1.3 at repetition rates below 100 kHz to over 2 MHz in pulses discretely tunable over a range from 50 ps to greater than 1.5 ns. Maximum pulse energies, limited by the onset of self phase modulation and SRS, are greater than 12.5uJ at 50 ps and 375 uJ at 1.5 ns , corresponding to >250 kW peak power across the pulse tuning range. Frequency conversion to 532 nm wavelength with efficiencies greater than 60% is achieved for pulses in the 50ps to 1ns range. The spectral purity is expected to be suitable for future conversion to UV via frequency tripling or further doubling of the 532 nm and experiments to demonstrate this are underway. Application results of the laser in scribing, thin film removal and micro-machining in the IR and Green will be discussed, as will the outlook for further scaling of the laser system to higher peak power levels, higher repetition rates, shorter pulses, tailored pulse trains and higher average powers.

8601-102, Session PTue

A compact, >17W average power, high peak power (>100 kW), ns and sub-ns fiber laser system

Matthieu J. Saracco, Joe Kollmann, David Logan, Scott W. Mettlen, Jared Green, Tyson L. Lowder, David R. Balsley, Timothy S. McComb, Gary Burkholder, Matthew Randall, Geoff Fanning, Jake Bell, nLIGHT Corp. (United States)

Timothy S. McComb, Gary Burkholder, Matt Randall, Geoff Fanning, Jake Bell

250 Word Abstract: We demonstrate a robust, compact, and low cost, pulsed 1064nm Yb:fiber laser system capable of >130uJ and >17 W average power in repetition rates of 80-300 kHz. The system consists of a configurable microchip seed laser capable of producing sub nanosecond (~500 ps) and nanosecond (~1-1.7ns) pulse widths. Pulses are amplified in an all-fiber PM LMA fiber amplifier optimized for high peak power operation. The LMA Yb:fiber amplifier enables near single mode operation at peak powers greater than 100 kW while preserving beam quality of M2 < 1.3. The seeder, amplifier and beam delivery are packaged into an air-cooled laser head of 152x330x87 mm with pump power provided from a separate air-cooled laser controller. Due to the high peak power, high beam quality and polarized nature of the output beam, the laser is readily frequency doubled to 532 nm at conversion efficiencies exceeding 60%. Average 532 nm power has been demonstrated to 7 W, corresponding to a peak power exceeding 70 uJ. Potential for scaling to higher peak and average powers in both green and IR will be discussed. This laser system has been field tested and demonstrated as a feasible source for numerous materials processing, scribing and marking applications in both IR and green. Some of these application results will be briefly discussed.

8601-103, Session PTue

On the SBS threshold of optical pulse shapes compensated for gain saturation

Louis Desbiens, Vincent Roy, Marc Deladurantaye, Yves Taillon, INO (Canada)

Nanosecond pulsed fiber laser sources have found multiple usages in material processing applications. Their reliability, flexibility, low cost, high average power and high beam quality are the reasons for their commercial success. With appropriate means, nanosecond fiber lasers based on a MOPA configuration can emit pulses with tailored shapes. This feature greatly increases the flexibility of the laser as it allows the emission of pulses of adjustable duration, complex pulse shapes such as bursts of short pulses, gain saturation-compensated shapes, chair-like shapes, or any other variations. Pulse shaping can have a significant impact on the ablation rate, the surface quality of the processed sample and different materials have been shown to respond differently to those pulse shape variations (the thermal conductivity of the material being a key parameter). Pulse shaping is also very valuable for optimizing the pulse energy from a system as it allows pre-compensation for the pulse distortion caused by gain saturation which tends to narrow the pulse duration, increase the peak power and associated SRS sensitivity. Through pulse shaping, one can achieve pulse energies that are significantly higher than the saturation energy of the amplifier while mitigating the detrimental effects of SRS. It is however important to consider the impact of pulse shape and pulse duration on the SBS threshold of an optical system. We have performed numerous SBS threshold measurements for pulses of varying duration and of varying levels of pre-compensation for gain saturation. We have demonstrated that pulse shapes with effective pulse duration of 40 ns have the lowest SBS threshold.

8601-104, Session PTue

Polarization dependent nonlinear limitations in continuous-wave high power fiber amplifiers

Nicoletta Haarlammert, Miroslaw Rekas, Oliver de Vries, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Andrea Kliner, Friedrich-Schiller-Univ. Jena (Germany); Andreas Liem, Thomas Schreiber, Ramona Eberhardt, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Andreas Tünnermann, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany) and Friedrich-Schiller-Univ. Jena (Germany)

State-of-the-art Yb-doped high power (kW range) fiber amplifiers are often based on non-polarization maintaining fiber designs. Commonly, such fiber amplifiers are characterized regarding the pump power, pump wavelength, as well as the seed power and seed wavelength but not regarding the input polarization. However, due to intrinsic irregularities of the fiber, that might, for example, be caused by material inhomogeneities or by bending, fibers are usually birefringent. Consequently, the input polarization should show influences on nonlinear effects that typically limit a further power scaling of narrow bandwidth amplifiers. In this contribution we experimentally investigate the influence of the seed polarization on the observed nonlinear effects at differently orientated linear polarizations as well as at the transition from linear to circular polarization. It is well known that self-phase modulation can be changed by only changing the seed polarization while keeping all other amplifier parameters constant. We show that it is also possible to considerably reduce the Raman effect. Furthermore we demonstrate that not only the threshold of nonlinear effects can be influenced by changing the seed polarization as only parameter but even the limited effect can be changed: For most polarization states Raman scattering is observed but for some polarization states also four-wave mixing becomes dominant. We investigate the strength of the influence of the seed polarization on nonlinear effects. From our results we estimate the importance of the polarization state as further parameter to increase the nonlinear threshold of high power non-polarization maintaining fiber amplifier systems.

8601-106, Session PTue

Novel Y2O3 codoped Yb-Tm-doped picosecond fiber laser

Vladislav Dvoyrin, Dmitry Klimentov, Norwegian Univ. of Science and Technology (Norway); Arindam Halder, Mukul Chandra Paul, Mrinmay Pal, Shyamal K. Bhadra, Central Glass and Ceramic Research Institute (India); Alexander V. Kir'yanov, Centro de Investigaciones en Óptica, A.C. (Mexico); Irina T. Sorokina, Norwegian Univ. of Science and Technology (Norway)

We report here on the fabrication by MCVD method and spectroscopic characterization of a set of double-clad Yb-Tm-doped silica-based fibers. The fibers' cores also contained Y, Al, Ge and P. The total doping level was varied from 4 to 20 wt% with up to 3, 3.5, 2 and 0.9 wt% of Y2O3, Al2O3, Yb2O3 and Tm2O3, respectively. The efficiency of the energy transfer from Yb3+ to Tm3+ was estimated from the fluorescence spectra and analysing the time decays recorded under the optical excitation at 975 nm wavelength. It was found that the energy transfer was the most prominent in the fibers without Ge and P codoping whilst it was dependent on the total concentration of Al and Y oxides in their cores. Moreover, for the fibers with the same total content of Y and Al oxides in core the energy transfer was better in the ones with higher Y content.

We obtained the mode-locking regime in the vicinity of 1950 nm with pieces of such fibers of 15-30 cm length in a linear cavity of 10-25 meters length with one of the couplers in the form of InGaAs SESAM semiconductor structure. The lasers were pumped at 1590 nm by an Er-doped fiber laser. Trains of optical pulses with estimated pulse duration in the range of 10-100 ps, the repetition rate of 4-10 MHz, average power up to 4 mW and pulse energy up to 1 nJ were observed.

The high concentration of the active ions allows using short fiber piecies and making short cavities thus simplifying the dispersion management. The optimization of the system to produce femtosecond pulses as well as laser experiments with direct diode pumping of the existing fibers using 975-nm diode lasers are in progress now.

8601-107, Session PTue

CW lasing performance of thulium-doped rod type PCF

Pankaj Kadwani, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); Christian Gaida, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States) and Friedrich-Schiller-Univ. Jena (Germany); Lasse Leick, Jes Broeng, NKT Photonics A/S (Denmark); Lawrence Shah, Martin C. Richardson, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

We report for the first time, to the best of our knowledge, lasing of a thulium-doped photonic crystal fiber (PCF) rod with 1.36m length, 80µm core diameter, 220µm pump cladding diameter 1520µm outer cladding diameter, a d/? ratio of 0.191 and pitch ?=13.7µm. A cooling system and rod mount was designed to provide water cooling of the PCF rod while pumping. The rod is pumped with a 793nm laser diode and produces a pump limited output power of 22W with a beam quality M?<1.1 in vertical and M?<1.2 in horizontal direction. The M? measurement indicates few mode operation with a slight reduction is beam quality due to astigmatism in the cavity configuration. The laser has a slope efficiency of 26.6% (27.8%) relative to launched (absorbed) pump power with a lasing threshold at 28.6W. The relatively low slope efficiency can be partially explained by the non-optimized cavity configuration. However, weak confinement of the PCF rod core may be adding significant loss thereby reducing optical efficiency. The output wavelength of this oscillator can

be tuned over 180nm from 1810 – 1990nm. Our work shows that PCF rods can be implemented for lasing configurations at 2µm wavelength. Future utilization of this novel PCF rod for amplification of ns pulses could ultimately lead to the generation of pulses with MW peak powers and multi-mJ pulse energies at 2µm wavelength.

8601-108, Session PTue

Crystal fibers for high power lasers

Woohong Kim, U.S. Naval Research Lab. (United States); Catalin Florea, Sotera Defense Solutions, Inc. (United States); Daniel J. Gibson, Brandon Shaw, Steve R. Bowman, Shyam S. Bayya, U.S. Naval Research Lab. (United States); Ishwal Aggalwar, Sotera Defense Solutions, Inc. (United States); Jasbinder S. Sanghera, U.S. Naval Research Lab. (United States)

Crystal fibers offer several advantages over glass fibers (such as silica fiber) due to their higher thermal conductivity and higher SBS threshold, along with excellent environmental stability and higher doping concentrations. Based on their superior properties, it is expected that we can get more than 50kW of single frequency output power from a single mode fiber laser based upon a Yb-doped YAG single crystal fiber. However, it has been difficult to fabricate high quality core/clad crystalline fibers. In this paper, we present our recent results in developing single crystal fibers for high power single frequency fiber lasers. The optical, spectral and morphological properties as well as the loss and gain measured from these crystal fibers drawn by our state-of-the-art LHPG system are also discussed. Results on application of various cladding materials on the crystal core and the methods of fiber end-face polishing are also presented.

8601-109, Session PTue

FM pulse amplification via cascade scheme of length-inhomogeneous normal dispersion active fibers

Christina V. Borisova, Igor O. Zolotovsky, Dmitrii Korobko, Dmitrii I. Sementsov, Ulyanovsk State Univ. (Russian Federation); Alexey A. Sysoliatin, A. M. Prokhorov General Physics Institute (Russian Federation); Marina S. Yavtushenko, Ulyanovsk State Univ. (Russian Federation)

Self-similar parabolic optical pulses have drawn increasing attention due to a wide range of their feasible applications in laser physics and fiber optics. Parabolic pulse is characterized by time-linear chirp variation and it is a stable asymptotic solution of the nonlinear Schrodinger equation in normal dispersion gain medium. High-power femtosecond lasers, spectral broadening, supercontinuum generation, all-optical processing are among the most important practical applications of parabolic pulses [1-3].

The numerical experiments performed by our group demonstrate that well-known methods of parabolic pulse amplification in optical amplifiers are sensitive to the accidental gain increment variations. To avoid these undesirable effects, one should use short length amplifiers with well-controlled parameters (diameter, dispersion, nonlinearity, gain increment) but with high gain (> 0.1 m-1). Besides, group velocity dispersion (GVD) amplifier profile has to be growing in length. However, the amplifier length is restricted by GVD changes and the maximum total gain value is about ten in one element.

To generate parabolic pulses of higher power, we propose to use the cascade amplification scheme, in which an amplifying element with high gain and sharp GVD increasing profile is followed by a fiber-modulator that is the fiber section without gain (or with low gain) and smoothly decreasing GVD. Importantly, in the proposed configuration the fiber-amplifier with cladding diameter decreasing in length (based on the active W-profile fibers) smoothly transforms into a fiber-modulator with an increasing diameter. In this element, the pulse is not amplified but spread over the time and it could acquire an additional rate of frequency modulation (FM). Such fiber cascades could be employed to generate pulses with high FM enabling effective pulse compression by means of diffraction gratings down to duration of 100 fs, energy over 1nJ, and peak power higher that 0.1 MW. Besides, we consider application of passive length-inhomogeneous waveguides with anomalous GVD decreasing in absolute value as a modulator placed before amplifying element to get the target initial pulse parameters, i.e. the given duration and FM rate.

[1] Fermann, V.I. Kruglov, B.C. Thomsen, J.M. Dudley and J.D. Harvey, “Self-similar propagation and amplification of parabolic pulses in optical fibers”, Phys. Rev. Lett. 84, 6010, (2000).

[2] C. Finot, J.M. Dudley, B. Kibler, D.J. Richardson and G. Millot, “Optical parabolic pulse generation and applications,” IEEE J. Quantum Electron.,45, 1482, (2009).

[3] I.O. Zolotovskii, D I Sementsov, A K Senatorov, A A Sysolyatin, M S Yavtushenko, “Dynamics of similariton pulses in length-inhomogeneous active fibres”, QUANTUM ELECTRON, 40 (3), 229 (2010).

8601-110, Session PTue

Multi-kW cw fiber oscillator pumped by wavelength stabilized fiber coupled diode lasers

Frank Becker, Benjamin Neumann, Lutz Winkelmann, Steffen Belke, Stefan Ruppik, Ulrich Hefter, ROFIN-SINAR Laser GmbH (Germany); Bernd Köhler, Paul Wolf, Jens Biesenbach, DILAS Diodenlaser GmbH (Germany)

High power Yb doped fiber laser sources are beside CO2- and disk lasers one of the working horses of industrial laser applications. Because of their inherently given robustness, scalability and high efficiency, fiber laser sources are best suited to fulfill the requirements of modern industrial laser applications in terms of power and beam quality.

Pumping an Yb doped single mode fiber laser at 976nm is very efficient. High power levels can be realized avoiding limiting nonlinear effects like SRS. However the absorption band of Yb doped glass around 976nm is very narrow. Therefore one has to consider the wavelength shift of the diode lasers used for pumping. The output spectrum of the passively cooled diode lasers is mainly defined by the applied current and by the heat sink temperature. Furthermore the overall emission linewidth of a high power pump source is dominated by the large number of needed diode laser emitters, each producing an individual spectrum. Even though it is possible to operate multi-kW, cw single-mode fiber lasers with free running diode laser pumps, wavelength stabilizing techniques for diode lasers (e.g. VHGs) can be utilized in future fiber laser sources to increase the output power level while keeping the energy consumption constant.

To clarify the benefits of wavelength stabilized laser diodes with an integrated VHG the performance of a dual side pumped fiber oscillator will be discussed. Therefore we present different pumping configurations, consisting of stabilized and free running diode lasers and a combination of both.

8601-111, Session PTue

Compact mid-IR source based on a DFB diode, fiber amplifier, and PPLN

Igor V Melnikov, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

Narrow line semiconductor lasers which integrate gain crystals with a length of fiber that has a Bragg grating written in its core, have been proven to be a compact robust source of short picoseconds – to nanosecond pulses with peak power sufficient for effective parametric wavelength-tuning applications. Although these capabilities for the mid-IR conversion have already been demonstrated, the demand for highly

precise and compact remote spectroscopy tools prompts towards their further miniaturization along with bandwidth narrowing while gaining peak power and repetition rate. In this Report, we describe a small-footprint near- to mid-IR source that is based on optical parametric generation in periodically-poled lithium niobate (PPLN) driven by a DFB semiconductor laser, which in turn, is boosted by a diode-pumped fiber amplifier.

In the optical device considered here, the source output is provided by signal and idler from a temperature-tunable OPO, which is seeded by a fiber-pigtailed single-frequency DFB laser [1] and pumped by a pigtailed semiconductor source that operates at repetition rates up to 500 kHz and delivers up to 400 mW of average power with a 10-ns (FWHM) pulse at 1.064 ?m. These pulses are further boosted up in a fiber amplifier made of a length of GTWave-type two-port specialty fiber that provides a 35-dB gain for the system. The polarization maintaining fiber used as a pigtail allows generation of definite polarization mode, which is crucial for stable and effective non-linear wavelength conversion. The pump beam is then focused inside a 5 mm thick PPLN crystal having the poling period of 29.9 ?m. The length of the crystal is optimized to achieve both high parametric conversion efficiency and quality of the output beams without using external cavities. The crystal is mounted in a compact oven allowing controlled variation of temperature from the room level up to 250 oC with long-term stability of 0.1 oC.. The maximum power of the 1542-nm cw seed (10 mW) appeared to be sufficient to initiate narrow-band generation not only at the spectral maximum of parametric superluminescence but also far at the wings of the spectrum. The spectral tuning of the DFB laser within 10-nm range can be achieved either by a built-in temperature controller or by variation of the injection current and is an extra option for wavelength adjustment at the idler wavelength.

The measured overall energy conversion of the system reached 30%, whereas the maximum efficiency of generation in the near IR range achieved 25 % indicating existence of noticeable loses for the idler. Further increase of the pump energy was found to be not favorable, as it might saturate the parametric conversion process via non-phase matched second- and fourth-harmonic generation for the pump and signal waves. The energy threshold of the seedless optical parametric generation amounted to few micro-Joules but can be lowered down significantly by switching on of the spectrally adjusted DFB laser. It is found that the mid-IR wavelength to be tuned as much as 250 nm in the temperature range given. This range can be further extended by increasing temperature up to 350 oC and by tunable seed within the parametric superluminescence spectrum. The generated bandwidth can be narrowed up to 0.05 nm by narrow-band seeding even at the highest level of pumping.

The laser system delivered nearly diffraction-limited beams both at the near- and mid-IR tunable wavelengths. The pulse-to-pulse energy instability does not exceed 5 %. Optical elements of the scheme can be easily incorporated into a housing with the dimensions of 50x15x15 cm3, which, along with the parameters described above, suggests the presented source to be ideal for many applications as high-precision spectroscopy, photo-medicine, environmental control, scanning of remote objects in the eye safe spectral domain, IR-countermeasures, telecommunications, and education, where the device can be used to demonstrate basics of lasers physics and non-linear optics.

References

1. A. R. Charaplyvy et al., Electronics Letters 22, 88 (1986)

8601-112, Session PTue

Pulsed thulium-doped fiber laser at 1.94 µm based on a seed diode

Massimo Olivero, Enkeleda Balliu, Andrea Braglia, Alessio Califano, Guido Perrone, Politecnico di Torino (Italy)

Thulium fiber lasers at about 2 um have driven great attention because of their “eye-safety” emission and the increasing number of applications that this wavelength is finding in industry, medicine, remote sensing and spectroscopy. The development of fiber-based sources at the thulium-emission wavelength has included continuous-wave and pulsed lasers, both in a single cavity and Master Oscillator Power Amplifier (MOPA) configurations. The latter have often been based on a fiber laser seed, which might set limits on the capability of performing a flexible and dynamic pulse shaping of the output beam. In this paper we present some results on the realization of a Thulium doped fiber laser pumped at 793 nm and emitting at 1.94um, based on a MOPA configuration in which the pulses generated by a computer-controlled laser diode are empowered by a thulium doped fiber amplifier. The design of the fiber amplifier has been conducted by performing dynamic simulations on a rate-equations model and optimizing its parameters by a test&error procedure. The output parameters of the laser (average power, gain, pulse shape) have revealed good agreement between measurements and simulations. A gain over 25dB with a pump power of 5W has been measured for pulses with duration 20-200 ns and repetition rate 10-100 kHz.

8601-113, Session PTue

25 ps tunable MOPA at C+L band

Youngjae Kim, Bryan Burgoyne, Alain Villeneuve Jr., Genia Photonics Inc. (Canada)

Fiber-based tunable Master Oscillator Power Amplifiers (MOPA) are quite useful for various applications such as optical spectroscopy, optical microscopy, biomedical imaging and micro machining. In this paper, we present a 25 ps tunable MOPA spanning the C and L bands. The laser structure can be divided into 5 parts; tunable CW seed laser, electro-optic modulator (EOM), preamplifier (EDFA), tunable optical filter, and booster amplifier (Er/Yb DCF). A pulser generating 25 ps electric pulse is used to convert the CW laser signal into pulses in the EOM. Output powers at four different repetition rates at 1530 nm; 10, 20, 40, 80 MHz are 231, 382, 543, and 1000 mW, respectively. Power is higher in the center of the C-band. Peak power at 80 MHz is 500 W and pulse energy is 12.5 nJ. Full width half maximum (FWHM) of 80 MHz pulse is 0.57 nm (chirp of ~3.5) and spectral broadening is due to self phase modulation (SPM). Optical tuning can either be 25 or 50 GHz between 1528-1590 nm. Pulse width below 10 ps is achievable by using a pulse compression scheme after the booster amplifier. It is also important to note that the MOPA output can be synchronized with another laser with since the pulse are triggered by the built-in function generator.

8601-114, Session PTue

Passively stabilized Brillouin fiber lasers with doubly-resonant cavities

Vasily Spirin, Ctr. de Investigación Científica y de Educación Superior de Ensenada (Mexico) and Univ. de Mons (Belgium); Cesar A. López-Mercado, Ctr. de Investigación Científica y de Educación Superior de Ensenada (Mexico); Patrice Mégret, Univ. de Mons (Belgium); Andrei A. Fotiadi, Univ. de Mons (Belgium) and Ioffe Physico-Technical Institute (Russian Federation) and Ulyanovsk State Univ. (Russian Federation)

Single-frequency Brillouin fiber lasers are very promising for many applications, such as coherent optical communication, interferometric sensing, coherent radar detection, and microwave photonics. Brillouin lasers with doubly-resonant cavities exhibit low power threshold, high spectral purity and low intensity noise. In such lasers Stokes wave is generated by a short fiber ring cavities that are simultaneously resonant for pump and Stokes radiation. However, such cavity design makes laser operation extremely sensitive to any variations of the fiber cavity length. Therefore, Brillouin lasers are commonly equipped by complicated active stabilizing systems.

Here we report two new and completely passive solutions enabling perfect stabilization of the Brillouin lasers with doubly-resonant cavities. In our experiments, the first laser configuration was stabilized through self-injection locking mechanism implemented to the laser cavity with DFB semiconductor pump laser. Second configuration comprises a nonlinear fiber mirror based on the population inversion dynamical

gratings induced in low-absorbed Er-doped fiber. In both cases, once the pump laser gets a resonance with the ring laser cavity, the growing optical feedback pushes the DFB pump laser (in the first case) and the nonlinear fiber mirror (in the second case) to operate the cavity resonance frequency. After such locking any slow detuning of the cavity resonance, for example, caused by temperature variations is compensated by corresponding detuning of the pump laser operation wavelength. As a result the operation wavelength of the pump laser occurs to be locked to the ring resonance frequency leading to effective generation of Brillouin Stokes radiation. In our experiment the pump-to-Stokes conversion efficiency of ~40% and the Stokes linewidth of <500Hz have been successfully demonstrated with both laser configurations.

8601-115, Session PTue

Indirect evaluation of active fiber parameters for high-power laser design

Guido Perrone, Andrea Braglia, Alessio Califano, Massimo Olivero, Alberto Vallan, Politecnico di Torino (Italy)

The optimization of high power lasers and amplifiers for industrial applications requires the accurate design of the laser architecture, and this can be achieved only through meaningful simulations, which, in turn, imply the necessity of knowing with a sufficient accuracy the values of all the parameters that model the behavior of the various components, and in particular of the active fiber. However, active fibers are very difficult to characterize because their model has many parameters, most of which not reported into data-sheets. Hence, the necessity of a simple procedure to extract these parameters from the measurement of the fiber behavior in real operative conditions. The proposed approach is based on an optimization process that compares the dynamic behavior of a fiber laser as predicted from a certain set of simulations with experimental data. The procedure has been applied to design the optimal length of a high power CW laser and of the power amplifier in a master-oscillator power-amplifier structure pulsed laser, obtaining results in excellent agreement with experiments conducted for different fiber lengths. An analysis of the impact of the uncertainty in the extracted parameters is also provided.

8601-116, Session PTue

Synchronized ps fiber lasers with pulse durations (25, 50, 100-2000ps) and repetition rates (100kHz-150MHz) continuously tunable over three orders of magnitude

Alexandre Dupuis, Bryan Burgoyne, Guido Pena, Andre Archambault, Dominic Lemieux, Vasile Solomonean, Maxime Duong, Alain Villeneuve Jr., Genia Photonics Inc. (Canada)

Ultrafast lasers are enabling precision machining of a wide variety of materials. However, the optimal laser parameters for proper material processing can differ greatly from one material to another. In order to cut high aspect-ratio features at high processing speeds the laser parameters such as pulse energy, repetition rate, and cutting speed need to be optimized. In particular, a shorter pulse duration plays an important role in reducing the thermal damage in the Heat-Affected Zones. In this paper we present a novel ps fiber laser whose electronically tunable parameters aim to facilitate the search for optimal processing parameters. The 10W 1064nm Yb fiber laser is based on a Master Oscillator Power Amplifier (MOPA) architecture with a repetition rate that can be tuned continuously from 100kHz to 150MHz. More importantly, the integration of three different pulse generators enables the pulse duration to be switched from 25ps to 50ps, or to any value within the 100ps to 2000ps range. By reducing the pulse duration from the ns-regime down to 25ps, the laser approaches the transition from the thermal processing regime to the ablation regime of most materials. Moreover, in this paper we demonstrate the synchronization of the pulses from two such MOPA lasers. This enables more elaborate multi-pulse processing schemes where the pulses of each laser can be set to different parameter values, such as an initial etching pulse followed by a thermal annealing pulse. It should be noted that all the laser parameters are controlled electronically with no moving parts, including the synchronization.

8601-117, Session PTue

100 micro-J ultrafast thulium-doped fiber laser

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

A high energy, high power ultrafast laser system based on Tm doped fiber at low repetition rates was successfully developed. Pulse energy of up to 100 μJ and average power of up to 30 W were achieved. The laser system consisted of a mode-locked 2 μm seed oscillator and multiple-stage power amplifiers. The seed included 30 m-long dispersion compensating fiber and emitted slightly chirped pulses with duration of ~ 1 ps and spectrum bandwidth of 8 nm. The mode-locking was stable and self-started. Repetition rate of seed oscillator was 2.5 MHz. The seed pulses were stretched with normal dispersion fiber to the duration of 40 ps. A two-stage pre-amplifier was used to boost the pulse energy to 4 μJ. The pulse can be compressed to sub-picosecond. An AOM was used as a pulse picker to lower the repetition rate. The pulse was further stretched and amplified in the final stage of power amplifier. Pulse energy of up to 100 μJ was obtained at a repetition rate of 100 kHz and average power of up to 30 W was achieved at a repetition rate of 2.5 MHz. High OSNR, good beam quality and low background noise were also achieved at this low repetition rate.

8601-118, Session PTue

High-efficiency (6+1)x1 combiner for high power fiber lasers and amplifiers

Victor I. Kopp, Jongchul Park, Mitchell S. Wlodawski, Jonathan Singer, Dan Neugroschl, Chiral Photonics, Inc. (United States)

We have developed a (6+1) x 1 combiner for fiber lasers and amplifiers based on a glass fusion technology. We have combined a conventional fiber fusion technology for pump channels with a new design for a single mode signal channel, which utilizes a vanishing core technology. The approach has been developed for single channel spot size converters and pitch reducing optical fiber arrays (PROFAs). Flexibility of this technology allows a custom design to match both a single or large area mode fiber at the input and a required active fiber at the output. The technology allows two parameters, a mode field diameter (MFD) and a numerical aperture (NA) to be adjusted independently resulting in low loss coupling for signal channel at input and output. Utilizing this approach we have obtained better than 0.3 dB coupling for a signal channel at 1550 nm with a standard SMF28 fiber at the input and an active fiber at the output, while using six conventional 105/125 micron fibers as pump channels operating at 975 nm. Low signal loss results in high efficiency lasing or amplification suitable for high power applications. This unique technology allows excellent coupling for the signal channel as well as for the pump channels and is amenable to even more pump channels if desired.

8601-119, Session PTue

Widely tunable fiber ring laser based on two cascaded long period fiber gratings with a core-mode blocker

Hanzheng Wang, Jie Huang, Xinwei Lan, Lei Yuan, Zhang Gao, Hai Xiao, Missouri Univ. of Science and Technology (United States)

Long period fiber grating (LPFG) has a wide variety of applications, including band-rejection filters, gain flattening filter and sensors. LPFG shows its relatively high sensitivity and the characteristic of cladding mode dependent, which can be used in optical fiber laser design. Also, a much higher sensitivity can be achieved in higher order cladding mode for the potential of a widely tunable laser application.

In this paper, we demonstrate a widely tunable fiber ring laser based on a core-mode blocker fabricated by femtosecond laser between two cascaded LPFGs. The light is coupled from the core to the cladding at the first LPFG and then coupled back to the core at the second LPFG. The core-mode blocker scatters most of the propagation light in the fiber core region, and a band pass filter is thus realized. Using this filter in an Erbium-doped fiber (EDF) laser system and by varying the ambient temperature, a widely tunable fiber ring laser will be achieved in the full C and L band.

8601-120, Session PTue

Radio frequency interrogation of a passively mode-locked fiber ring laser for sensing application

Jie Huang, Xinwei Lan, Hanzheng Wang, Lei Yuan, Zhan Gao, Hai Xiao, Missouri Univ. of Science and Technology (United States)

Demodulation of optical sensors in radio frequency (RF) domain has attracted much attention in recent years due to the high measurement precision of frequency, low cost and matured instrumentation in the RF regime. In many optical lasing devices, the beat-frequency between two optical modes falls in the RF regime. As a result, measurement of optical parameters can be achieved by monitoring the beat-frequency changes.

So far, most existing RF-interrogated optical laser sensors are mode-unlocked. An unlocked laser emits continuous waves with unsynchronized longitudinal modes, resulting in unstable beat-frequencies, large phase noises, frequencies pulling and amplitude variations. These instabilities induce errors in sensing. On the other hand, optical lasers can be mode-locked to establish a fixed phase relationship across a broad spectrum. A mode-locked laser emits pulses with low timing jitters and thus has stable beat-frequencies in the spectrum domain. Recently, an actively mode-locked laser has been explored to generate ultrastable microwave signals. A 10 GHz microwave signal with fraction frequency instability less than 8?10-16 observed in 1s was reported. In this letter, we propose a passively mode-locked fiber ring laser interrogated in RF regime for sensing application. Mode-locking of the laser is achieved by injecting a fiber inline saturable absorber. The beat frequencies between arbitrary longitudinal modes can be obtained by using a RF spectrum analyzer once the mode-locking is achieved. The frequency separation of the comb is found linearly proportional to the beat frequency change. The sensing mechanism of the device is shown. Temperature measurement is demonstrated using the proposed passively mode-locked fiber ring laser.

8601-121, Session PTue

Photobleaching investigation of photo darkened fiber using 633 nm irradiation: evidence of color center time evolution

Stefano Taccheo, Hrvoje Gebavi, Swansea Univ. (United Kingdom); Denis Tregoat, Achille Monteville, Plate-forme d'Étude et de Recherche sur les Fibres Optiques Spéciales (France); Benoit Cadier, Thierry Robin, iXFiber SAS (France)

We investigate the effect of photo-bleaching using 633 nm radiation of photodarkened fibers. We tested several fiber using different levels of bleaching power. The main outcome was an unbleachable residual loss for the bleaching powers at 633 nm up to ~100 W/mm2. In addition we found that bleachable and unbleachable loss center are not simultaneously generated. We demonstrated that during photodarkening process first bleachable loss are generated center and later on the unbleachable ones.

8601-122, Session PTue

Forced air cooling effect on beam quality in volume Bragg gratings for spectral beam combination

Brian Anderson, Sergiy Kaim, George B. Venus, Julien Lumeau, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); Vadim Smirnov, OptiGrate Corp. (United States); Boris Y. Zeldovich, Leonid B. Glebov, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

Volume Bragg gratings have been successfully used in spectral beam combining of high power fiber lasers with narrow channel separation and in four channel passive coherent beam combining of fiber lasers. Future application of beam combining with kilowatt level lasers requires a more detailed understanding of how to cool the gratings without hurting beam quality. Forced air cooling blown across both surfaces of the grating is both easy and cheap, but has been avoided in the past due to concerns of how the air density fluctuations will hurt beam quality. It is now shown that forced air cooling has no adverse effect on the M2 parameter due to density fluctuations in the air.

Volume Bragg gratings are routinely made with low absorption on the level of 10-4 cm-1. To model grating operation for kilowatt level lasers, absorption of the studied grating was artificially increased by 140 times. Thus the use of 100 W fiber laser enabled imitation of 10 kW beams, and the effects of forced air cooling on the beam quality were measured. Without cooling, the M2 parameter quickly degrades, and diffraction efficiency is hurt. Forced air cooling for a simulated 9 kW laser beam in resonance with the RBG improved the M2 value from 2.0 to the nominal value of 1.1, and decreased the laser induced temperature increment from 71 to 14°C.

8601-123, Session PTue

Analysis of fiber laser beam combining using multiplexed volume Bragg gratings in resonator configurations

Erik J. Bochove, Chunte A. Lu, William P. Roach, Air Force Research Lab. (United States); Apurva Jain, Daniel Ott, George B. Venus, Leonid B. Glebov, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

Multiplexed volume Bragg gratings (MVBG) are a compact and potentially robust technology for coherent superposition of a number of

high power fiber laser beams in a single medium. Based on theoretical and experimental findings, the relative advantages of reflecting and transmitting MVBGs for passive coherent beam combining are discussed. By applying a version of Kogelnik's coupled mode theory to thick reflecting and transmitting MVBG structures we obtained numerous analytical results such as the dependence of the efficiency of active and passive combining of N collimated laser beams, the lasing threshold and the Bragg bandwidth on the choice of the magnitude of cavity parameters such as the out-coupling loss, angles of incidence and polarization. For example, the Bragg bandwidth of transmitting MVBG is shown to be much larger than for reflecting structures. We discuss misalignment tolerances and the effects of pathlength errors in interferometric cavities for the case of passive combining. It is also shown that for a given number of input beams, the combining efficiency of a transmitting MVBG is much more sensitive to the individual grating efficiency as compared to a reflecting MVBG, and the combining efficiency of a number N>1 of lasers may approach unity even when individual grating efficiencies are much smaller. This result was experimentally confirmed for a double transmitting MVBG.

8601-125, Session PTue

Detailed numerical study of modal instabilities suppression in high power fiber amplifiers

Shadi A. Naderi, Iyad Dajani, Timothy J. Madden, Air Force Research Lab. (United States); Bemjamin G. Ward, U.S. Air Force Academy (United States); Craig Robin, Jacob Grosek, Air Force Research Lab. (United States)

We present a detailed time-dependent numerical model of the modal instability phenomenon. This model is implemented in polar coordinates in order to accommodate different boundary conditions with minimum computational error and includes vectorized field equations. The thermal effects are captured by solving the heat equation in polar coordinate using a 2D second-order time-dependent alternating direction implicit (ADI) method. The nonlinear differential equations are numerically integrated with adaptive step sizes. The order of convergence of this model is numerically verified. Furthermore, this model is used to investigate various suppression techniques. The effect of different pumping configurations such as co-pumping, counter-pumping and bidirectional pumping is studied and compared to results obtained from large mode area Yb-doped photonic crystal fiber (PCF) amplifier experiments. The influence of polarization on the modal instability threshold is presented here. Using this model, a gain-tailored PCF that was shown experimentally to mitigate the modal instability at the kilowatt level is studied [1]. This gain-tailored fiber is designed such that the Yb-ion concentration has preferential overlap with the fundamental mode and reduced pump absorption as compared to a fiber with similar dimensions.

[1] C. Robin, I. Dajani, C. Zeringue, B. Ward, and A. Lanari, “Gain-tailored SBS suppressing photonic crystal fibers for high power applications,” Proc. SPIE 8237, 82371D (2012).

8601-35, Session 9

Broadband and gap-free tunable femtosecond resonant dispersive wave generations in PCF *(Invited Paper)*

Jiahui Peng, National Research Council Canada (Canada); Feng Zhu, Aleksander K. Wojcik, Texas A&M Univ. (United States); Fetah Benabid, Univ. of Bath (United Kingdom); Alexei Sokolov, Texas A&M Univ. (United States)

We demonstrate a simple, compact, femtosecond-oscillator-based system for generating tunable femtosecond pulses. The demonstrated tuning range is extremely broad and covers the entire visible spectrum. The nonlinear process is highly efficient and is insensitive to the pump energy fluctuation. The femtosecond pulse duration is confirmed by measurement made with a cross-correlator.

8601-36, Session 9

Pulsed blue laser source based on frequency quadrupling of a Tm fiber laser

Eric C. Honea, Matthias P. Savage-Leuchs, Tolga Yilmaz, Roy D. Mead, Mark S. Bowers, Lockheed Martin Aculight (United States)

We describe a pulsed blue (485 nm) laser source based on frequency quadrupling a pulsed Tm fiber laser. The approach provides the benefits of fiber lasers with the ability to produce pulsed blue output with multi kW peak power levels. The Tm-doped fiber laser is based on a Master Oscillator Power Amplifier (MOPA) architecture operating at 1940 nm and a repetition rate of 10 kHz. The power amplifier is an LMA fiber that is free-space counter-pumped by a fiber-coupled 790-nm diode laser, generating 9.9 W at the 10 kHz repetition rate with M2 values along x- and y-axes of 1.8 x 1.8. The frequency conversion stage from 1940 nm to 970 nm uses a 47x1x1 mm Periodically Poled Lithium Niobate (PPLN) crystal at room temperature. An x-cut, z-propagating 50x3x3 mm LBO crystal tuned to 269.1 °C was used for converting the 970 nm output of the PPLN crystal to 485 nm (blue light). Up to 1.2 W at 485 nm was generated at the maximum input power of 2.7 W at 970 nm, with M2 values along the x- and y-axes of 1.36 x 1.23. At the 10 kHz pulse repetition frequency, the output pulse at 485 nm was 65 ns FWHM resulting in an estimated peak power of 1.8 kW. We anticipate further improvements in conversion efficiency to the blue with optimized AR coatings and nonlinear optical crystals, and further power scaling as Tm fiber laser power levels increase.

8601-37, Session 9

Single frequency, ultra-low noise, CW, 4W 488nm fiber laser

Romain Dubrasquet, Johan Boullet, Simon Lugan, Gil Mery, Nicholas Traynor, Azur Light Systems (France); Eric Cormier, Univ. Bordeaux 1 (France)

A wide range of applications have been addressed by high power Argon lasers at 488 nm but this technology suffers from major problems of maintenance and running costs, leading to the development of alternative technologies such as Optically Pumped Semi-conductor Lasers (OPSL) and Diode Pumped Solide State Laser (DPSSL). Fiber laser technology exhibits proven advantages in stability and thermal management but, due to previous difficulties in demonstrating efficient three-level lasing on the 976 nm transition in Yb, high power frequency doubled fibre lasers at 488 nm have been limited to low powers.

We have evolved the high power 976 nm fiber laser technology towards a platform compatible with industrial exploitation and developed a compact, up to 15 W power, truly single mode, single frequency, linear polarization fiber laser emitting in this non-conventional spectral range.

Frequency doubling in a 30 mm long Periodically Poled Stoechiometric Lithium Tantalate (PPsLT) of our fundamental 976 nm source in both narrow bandwidth (<60 pm) and single frequency (< 1 MHz) configurations allowed us to generate stable blue radiation up to 4 W at 488 nm, more than an order of magnitude higher than previous demonstrations from fiber-based systems. Furthermore, we have performed RIN measurement and highlighting that this architecture can exhibit ultra-low noise (0,03% RMS in the 0-10 MHz frequency range), one order of magnitude lower than RIN from conventional OPSL and DPSSL sources. This innovative platform is perfectly suited for a wide range of applications in biology, spectroscopy, holography and Doppler analysis.

8601-38, Session 9

High power industrial picosecond laser from IR to UV

Julien Saby, Damien Sangla, Simonette Pierrot, Pierre Deslandes, François Salin, EOLITE Systems (France)

Many industrial applications such as glass cutting, ceramic micro-machining or photovoltaic processes require Picosecond pulses. The main limitation for the expansion of the picosecond market is the cost of high power picosecond laser sources, which is due to the complexity of the architecture used for picosecond pulse amplification, and the difficulty to keep an excellent beam quality at high average power. We have demonstrated a high power-high efficiency industrial picosecond source using single mode Large Pitch rod-type fibers doped with Ytterbium. Large Pitch Rod type fibers can offer a unique combination of singlemode output with a very large mode area from 40 µm up to 100µm and very high gain. This enables to directly amplify a low power-low energy Mode Locked Fiber laser with a simple amplification architecture, achieving very high power together with single mode output independent of power level or repetition rate.

We used a passively modelocked fiber oscillator that produces 60 mW at 30 MHz and 1030 nm with a spectral linewidth lower than 0.2 nm, and pulse duration flexible from 15ps to 50ps. By using an acousto-optic pulse picker, the seeder repetition rate can be tuned from 100kHz up to 30MHz and is then directly amplified with a double stage amplifier using 60cm Large Pitch Rod-Type fibers of various Mode Field Diameter to achieve 2MW of Peak Power at the output which means a pulse energy of 30µJ for 15ps pulses and 100µJ for 50ps pulses. The use of very large mode area fibers allows us to reach high energy levels while keeping reasonable non linear effect during the amplification, leading to an output spectrum lower than 3nm without using Chirped Pulse amplification. This laser source was then frequency converted with LBO Crystals and, for 30ps, we obtained 30µJ at 515nm and 14µJ at 343nm.

8601-39, Session 9

45W second-harmonic and 24.5W third-harmonic generation from a fiber-amplified passively Q-switched microchip laser

Alexander Steinmetz, Reinhold Lehneis, Jens Limpert, Friedrich-Schiller-Univ. Jena (Germany); Andreas Tünnermann, Friedrich-Schiller-Univ. Jena (Germany) and Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

We report on second and third harmonic generation of a fiber amplified passively Q-switched microchip laser operating at repetition rate of 1.4 megahertz. The microchip laser is based on the Nd:YVO4/SESAM combination and provides 120ps pulses at 1064nm. The amplifier chain comprises two ytterbium-doped fiber amplifiers: a double-pass pre-amplifier based on 170/40 photonic crystal fiber and a single-pass main-amplifier based on large pitch fiber (LPF) with 55µm mode field diameter. The pre-amplifier increases the energy of microchip pulses from 100nJ to 3.3µJ and the main-amplifier boosts it to more than 61µJ (85watts). The pulse duration of the amplified pulses is nearly maintained and equals to 117ps at the output while the line width increases from ~30pm to 0.33nm due to the SPM-induced broadening in active fibers.

The second harmonic generation stage is realized with a critically phase-matched (CPM) lithium triborate crystal (type 1) with a length of 10mm. The SHG stage generates up to 45W of 532nm-power at maximum of input IR-power of 85W, which reveals a conversion efficiency of ~53%. The used subsequent sum frequency generator consists of a 6mm long lithium borate (CPM, type 2) and the system provides 24.5W at 355nm from 85W, which shows conversion efficiency from IR to UV of ~29%.

In conclusion, this 1.4 megahertz pulsed laser system provides high-energy, sub-100ps pulses in visible and ultraviolet regions and is a very interesting device for many industrial applications.

8601-41, Session 10

Experimental demonstration of coherent beam combining with an array of 21 adaptive fiber collimators

Thomas Weyrauch, Micah D. Gatz, Univ. of Dayton (United States); Mikhail A. Vorontsov, Univ. of Dayton (United States) and Optonicus (United States); Gary W. Carhart, U.S. Army Research Lab. (United States); Andrew C. Deck, Andrey P. Rostov, Optonicus (United States)

The results of the experimental evaluation of phase locking of an array of 21 adaptive fiber collimators are presented. The array consists of three modules with each seven fiber collimators in a hexagonal arrangement. This modular approach allows for a scalable system, whose overall power output and the optical aperture size can be increased by adding more modules of the same kind to the system. The fiber collimators were connected to a 24-output channel MOPA system comprising a narrow-line fiber seed laser and single-mode polarization-maintaining fiber system, including three 8-channel integrated lithium niobate-based phase shifters and 24 fiber amplifiers with each 250 mW output power. Control of piston phases at the fiber-array pupil plane was performed using a feedback system based on stochastic parallel gradient descent (SPGD) optimization of a performance metric. For array alignment and initial bench-top tests, the parallel and collimated beams emerging from the collimator array were focused by a spherical mirror onto an unresolved target – a pinhole smaller than the diffraction-limited size of the focal spot. The output signal of a photo-detector placed behind this pinhole provided the performance metric used for piston phase and tip/tilt control.

8601-42, Session 10

4-channel coherently combined femtosecond fiber CPA system

Arno Klenke, Sven Breitkopf, Thomas Gottschall, Tino Eidam, Jens Limpert, Andreas Tünnermann, Friedrich-Schiller-Univ. Jena (Germany)

Coherent combination of pulses emitted from spatially separated amplifiers allows for the scaling of the pulse energy and average power beyond the limits given by a single amplifier.

One of the most important aspects of this concept is the total combining efficiency that can be achieved when increasing the number of channels.

Our experimental setup consists of a main-amplifier stage with four spatially separated large-core ytterbium-doped large-pitch fibers (LPF). The combination and stabilization is realized with polarization dependent beam splitter cubes in a cascaded setup and three independently working Hänsch-Couillaud locking systems. This main-amplifier stage is embedded into a CPA system consisting of a femtosecond oscillator, a grating stretcher and compressor and a pre-amplifier system. Using this setup, we could achieve a total combining efficiency of 85% at a compressed average power of 73W and a repetition rate of 10 MHz. When combining just two channels (channel 1 + channel 2 and channel 3 + channel 4), the efficiencies were 92% and 87%, respectively. This corresponds with the theory, which predicts that a convergence of the total efficiency to a constant value takes place when increasing the number of channels. This can be explained experimentally with the cleaning of the output beams that happen in the different combining steps. After combination, the pulses were recompressed to the femtosecond range. We expect that the system allows for further scaling of average power towards 1kW and pulse energies towards 10mJ in the near future.

8601-43, Session 11

Passive coherent beam combining of temporally cascaded pulses

Marco Kienel, Arno Klenke, Jens Limpert, Andreas Tünnermann, Friedrich-Schiller-Univ. Jena (Germany)

Coherent beam combining has been used for the amplification of ultra-short pulses in spatially separated fiber amplifiers to overcome the limitations of a single emitter. Recently, a Sagnac interferometer was used to amplify two counter-propagating ultra-short pulses with no need of control electronics. In this work we report on a scheme to combine eight cascaded pulses with delays in the nanosecond regime. I.e. we combine the concepts of divided pulse amplification (DPA), however, with nanosecond delay, and passive coherent combination in a Sagnac configuration. Therefore, this approach constitutes an interesting scaling concept for ultra-fast amplifiers as it is applicable to strongly stretched pulses in chirped-pulse amplification systems.

The proof-of-principle experimental setup consists of a femtosecond oscillator delivering an average power of 160mW at a repetition rate of 40MHz as the input for two chained pulse division systems. These are followed by a Sagnac interferometer which includes a passive single-mode fiber. The splitting and the recombination of the pulses are done with three polarization dependent beam-splitter cubes in the Mach-Zehnder-like division systems, which provide a temporal spacing of 2ns per pulse. Overall, this leads to eight pulses which counter-propagate through the single-mode passive fiber inside the Sagnac interferometer and consequently the impact of any nonlinear effect is reduced by a factor of eight. Thus, no measurable self-phase modulation was observed. In comparison, with just one propagating pulse the spectrum was broadened by a factor of three. The presented setup is a promising technique for further performance improvement of chirped-pulse fiber amplifiers.

8601-44, Session 11

Passive coherent beam combination of two nanosecond fiber amplifiers by using an all-optical feedback loop

Houkang Liu, Jun Zhou, Bing He, Qihong Lou, Shanghai Institute of Optics and Fine Mechanics (China)

We present a passive coherent beam combination of two nanosecond amplifiers. For the last few years, active coherent beam combination of fiber sources has been reported in nanosecond and femtosecond regime. However?the active feedback loop used to obtain phase stabilization requires complex electronic servo systems. The passive coherent beam combination by using an all-optical feedback loop is a promising way for power scaling in continuous wave regime, and kilowatt level output power with high combined efficiency was reported. This paper demonstrates that the all-optical feedback loop can handle pulsed coherent beam combination without any phase control element. The key of the method is the self organization properties of the feedback loop. Longitudinal modes, which match the intracavity spatial frequency, have the lowest loss and will be selected to amplify. Then the phase locking of the two fiber amplifiers is achieved. An electro-optic amplitude modulator is used to tune the pulse width and the pulse repetition frequency of the combined pulses. The range of tunable frequency is from 2.023 MHz to 6.069 MHz, and the range of tunable pulse width is from 9.7 ns to 50 ns. The positive correlation between the visibility of far-field coherent patterns and the pulse duty ratio is found. The maximum visibility is up to 85% and the total combined power is 507 mW. In an ongoing work, a passive coherent beam combination with more power and larger number of fiber amplifiers will be demonstrated by using the all-optical feedback loop.

8601-45, Session 11

Active coherent superposition of five fiber amplifiers at 670W using multiplexed volume Bragg grating

Chunte A. Lu, Angel Flores, Erik J. Bochove, William P. Roach, Air Force Research Lab. (United States); Vadim Smirnov, OptiGrate Corp. (United States); Leonid B. Glebov, OptiGrate Corp. (United States) and OptiGrate Corp. (United States)

We present an experimental study on active coherent combining of five Yb-doped fiber laser amplifiers that employs multiplexed volume Bragg gratings (MVBG), reporting a combining efficiency ?=82% and near-diffraction limited beam quality (BQ) at a combined input power Pin =380 W, and ?=70% with equal beam quality at Pin =670 W. Previously, in a proof-of-principle experiment, we reported ? >80% at Pin equal to only 70W, while increase to Pin= 314W significantly degraded both ? and output BQ. The previous measurements revealed that the MVBGs heated to over T ~115C, which resulted in an overall degradation of the experiment. Since then, improvements made at OptiGrate Inc. in recording MVBGs in photo-thermo-refractive (PTR) glass and the anti-reflecting (AR) coating of surfaces, have resulted in reduced heating. At 0.6kW input power and 3mm beam diameter, less heating (T~50C) was observed in MVBG without external cooling. The experiment employed the active phase locking scheme LOCSET (Locking of Optical Coherence by Single-detector Electronic-frequency Tagging) to achieve mutual phasing of the five input fiber amplifiers using a single detector. The combining efficiency as a function of input power shown a 10% reduction in combining efficiency from 400W input power to 670W input power.

8601-46, Session 11

Scalable passive coherent beam combining of fiber lasers using multiplexed volume Bragg gratings

Apurva Jain, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); Chunte A. Lu, Air Force Research Lab. (United States); George B. Venus, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); Vadim Smirnov, OptiGrate Corp. (United States); Erik J. Bochove, Air Force Research Lab. (United States); Leonid B. Glebov, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

Scaling to power levels beyond the limitations of a single source requires beam combining, and passive coherent beam combining (CBC) has been touted as the "ideal technique" since it is capable of generating a high quality combined beam from cheap amplifier arrays using a simple, low-cost, and compact implementation. Multiplexed volume Bragg gratings (M-VBGs) are very promising for passive CBC as they are able to provide efficient and equal radiation exchange between large numbers of amplifiers. A double reflecting M-VBG was previously recorded and shown to be a perfect combiner of coherent beams. Two single-mode fiber laser channels were coherently combined using this M-VBG in an interferometric common-cavity setup with >90% efficiency.

In this report, we demonstrate the scalability of this technique to both larger arrays and higher output powers. Quadruple transmitting and reflecting M-VBGs (M4-VBG) capable of combining 4 fiber laser channels are recorded. Slope efficiency comparable to the slope efficiency of individual laser channels is demonstrated. Combining efficiency close to the theoretical limit for existing losses in the system is achieved with the transmitting M-VBG. The combined output is diffraction-limited and highly stable over long periods of operation.

In parallel efforts, we have been working on demonstrating this technique at higher power levels. Two 100 W level fiber lasers have been

constructed using large-mode-area (LMA) fibers. Results of combining with double reflecting M-VBG will be presented.

8601-47, Session 12

Fiber optical parametric chirped pulse amplification *(Invited Paper)*

Arnaud Mussot, Alexandre Kudlinski, Univ. des Sciences et Technologies de Lille (France); Damien Bigourd, Imperial College London (United Kingdom); Emmanuel Hugonnot, Patrick Beauredaugeres, Commissariat à l'Énergie Atomique (France)

Optical parametric chirped pulse amplification (OPCPA) is one of the most popular techniques to amplify ultra-short clean pulses with huge peak powers. This solution is now commonly used but it is very cumbersome, quite difficult to align and sensitive to external perturbations. Recently, impressive performances have been reported in Ytterbium doped optical fiber. While operating at lower level of energy, this all-fiber format is very attractive for many applications. However, this alternative requires storage of the pump energy inside the medium on a time scale of the same order of magnitude than the fluorescence lifetime of rare earth dopants. As a consequence, an important amount of amplified spontaneous emission (ASE) is emitted between amplified pulses. To circumvent this problem by still keeping the advantages of the all fiber format, fiber parametric amplifiers relying on the third order nonlinearity have recently been proposed and then experimentally demonstrated. These fiber optical parametric chirped pulse amplifiers (FOPCPA) combine most of the advantage of bulky OPCPA Yb fibers setups, at the exception of the energy level that was limited to a few nano-Joule in this first demonstration of principle. In this communication, we will review the basic principle of operation of such amplifiers and we will present realistic solutions to increase the output energy of these amplifiers to rise tens of micro-Joule level. These energy levels correspond typically to the ones available of the output of the first stage of high power amplifying chains and as a consequence, FOPCPA setups should advantageously replace these first bulky stages.

8601-48, Session 12

High average power fiber laser system for attosecond science

Jan Rothhardt, Steffen Hädrich, Helmholtz Institute Jena (Germany) and Friedrich-Schiller-Univ. Jena (Germany); Stefan Demmler, Manuel Krebs, Friedrich-Schiller-Univ. Jena (Germany); Jens Limpert, Friedrich-Schiller-Univ. Jena (Germany) and Helmholtz-Institut Jena (Germany); Andreas Tünnermann, Friedrich-Schiller-Univ. Jena (Germany) and Helmholtz-Institut Jena (Germany) and Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

The process of high harmonic generation allows for up-conversion of infrared laser light towards the EUV or soft X-ray region. If very short (few-cycle) laser pulses are employed and their carrier envelope phase (CEP) is well controlled the generation of so-called isolated attosecond pulses becomes feasible. Today's few-cycle laser technology relies on Ti:Sapphire laser systems and hollow fiber based post-compression. The output power of such lasers is typically below 1 W and the repetition rate is limited to a few kilohertz due to thermo-optical limitations of the Ti:Sapphire amplifiers.

In this contribution we present a different approach combining the advantages of fiber laser technology with nonlinear frequency conversion. A high power femtosecond fiber laser system serves as pump laser for an ultra-broadband optical parametric amplifier. As a result we are able to generate intense CEP-stable pulses with only two optical cycles duration at repetition rates up to 1 MHz. The excellent beam quality ensured by the fiber based pump laser enables focusing of these pulses to high intensities, thus, allowing for the generation of high harmonics and attosecond pulses at exceptionally high repetition rates.

We will present the design of the laser system and discuss specific challenges such as the broadband signal generation, the temporal synchronization of the pump laser and the carrier envelop phase stabilization. In addition, experimental results on high repetition rate XUV continuum generation will be presented, demonstrating the feasibility of our approach.

8601-49, Session 12

Passive spatio-temporal coherent combining of stretcher-free femtosecond fiber systems

Louis Daniault, Marc Hanna, Lab. Charles Fabry (France); Dimitris N. Papadopoulos, Lab. Charles Fabry (France) and Ecole Polytechnique (France); Yoann Zaouter, Eric P. Mottay, Amplitude Systèmes (France); Fréderic Druon, Patrick Georges, Lab. Charles Fabry (France)

During last decade, ytterbium-doped fiber amplifiers have been established as efficient femtosecond pulse sources. The main limitation of these systems comes from the high optical intensity in the fiber core, leading to either excessive nonlinear effects or optical damage. For this reason, in stretcher-free setups, where a controlled amount of nonlinear effects allows the generation of sub-100 fs pulses, the output pulse energy is currently limited to about 1 µJ. Recently, coherent beam combining (CBC) has been used in the femtosecond regime to distribute the optical power over several amplified beams, thereby reducing the impact of nonlinear effects. In particular, we demonstrated a passive CBC scheme that uses a Sagnac interferometer (SI) to combine two counterpropagating beams with high robustness and no control electronics. Another combining architecture, denoted as divided-pulse amplification (DPA), acts in the temporal domain to split and recombine the pulses. It was used to amplify picosecond pulses as a convenient substitute to chirped-pulse amplification.

In this contribution, we demonstrate that both methods can be implemented together in a stretcher-free architecture to notably reduce SPM effects. A combination of spatial and temporal splittings allows to generate and recombine up to 8 replicas in total, thereby decreasing the nonlinearity level by the same factor with the same output energy. The system allows the generation of 50 fs 3.1 µJ compressed pulses, exhibiting a peak power of 52 MW, an unprecedented value from parabolic fiber amplfier experiments. Further scaling of the peak power is also investigated.

8601-50, Session 12

23 fs pulses at 250 W of average power from a FCPA with solid core nonlinear compression

Christoph Jocher, Friedrich-Schiller-Univ. Jena (Germany); Tino Eidam, Steffen Hädrich, Jens Limpert, Friedrich-Schiller-Univ. Jena (Germany) and Helmholtz-Institute Jena (Germany); Andreas Tünnermann, Friedrich-Schiller-Univ. Jena (Germany) and Helmholtz-Institute Jena (Germany) and Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

In recent years fiber chirped-pulse amplification systems have been steadily developed towards higher output powers and shorter pulse durations. Applications such as material processing and high-field physics will benefit from new light sources. Here, we report on a high power femtosecond fiber chirped-pulse amplification system (FCPA) with a nonlinear compression stage emitting an unprecedented combination of repetition rate, pulse duration and average power. The FCPA operates at a repetition rate of 250 MHz and emits 360 W of average power. Thereby, the pulse duration is 265 fs, close to the Fourier-limit pulse duration of the corresponding measured spectrum and the beam quality is excellent with an M2 of 1.2. Pulse shortening is done with a solid-core nonlinear compression stage, consisting of a small piece of photonic-crystal fiber (large-pitch concept) and a chirped mirror compressor for compensating the second order dispersion. In order to prevent self-focusing and realizing higher peak powers in the broadening fiber the polarization is changed from linear to circular. The pulse duration is shortened by more than one order of magnitude to 23 fs (autocorrelation width of 31 fs) at an average power of 250 W and an excellent beam quality, M2 of 1.3. With simulations the compressed pulse energy is estimated to 0.9 µJ and the peak power to 34 MW. This high-power laser system is built for driving cavity-enhanced high-harmonic generation.

8601-51, Session 12

Picosecond passively mode-locked mid-infrared fiber laser

Chen Wei, The Univ. of Arizona (United States) and Nankai Univ. (China); Xiushan Zhu, Robert A. Norwood, Nasser N. Peyghambarian, College of Optical Sciences, The Univ. of Arizona (United States)

Mode-locked mid-infrared (mid-IR) fiber lasers are seeing increased demand due to their many potential applications in spectroscopic sensors, infrared countermeasures, laser surgery, and high-efficiency pump sources for longer-wavelength oscillators. Er3+-doped ZBLAN (ZrF4-BaF2-LaF3-AlF3-NaF) fiber lasers, which can emit mid-IR light at 2.65-2.9 µm through the transition from the upper energy level 4I11/2 to the lower laser level 4I13/2, have attracted much attention because of their broad emission range, high optical efficiency, and the ready availability of diode pump lasers at the two absorption peaks of Er3+ ions (975 nm and 976 nm). In recent years, significant progress on high power Er3+-doped ZBLAN fiber lasers has been achieved and over 20 watt CW output at 2.8 µm has been demonstrated; however, there has been little progress on ultrafast mid-IR ZBLAN fiber lasers to date. We report a passively mode-locked Er3+-doped ZBLAN fiber laser in which a Fe2+:ZnSe crystal was used as the intracavity saturable absorber. Fe2+:ZnSe is an ideal material for mid-IR laser pulse generation because of its large saturable absorption cross-section and small saturation energy along with the excellent opto-mechanical (damage threshold ~2 J/cm2) and physical characteristics of the crystalline ZnSe host. A 1.6 m double-clad 8 mol% Er3+-doped ZBLAN fiber was used in our experiment. The fiber core has a diameter of 15 µm and a numerical aperture (NA) of 0.1. The inner circular cladding has a diameter of 125 µm and an NA of 0.5. Both continuous-wave and Q-switched mode-locking pulses at 2.8 µm were obtained. Continuous-wave mode locking operation with a pulse duration of 19 ps and an average power of 51 mW were achieved when a collimated beam traversed the Fe2+:ZnSe crystal. When the cavity was modified to provide a focused beam at the Fe2+:ZnSe crystal, Q-switched mode-locked operation with a pulse duration of 60 ps and an average power of 4.6 mW was achieved. More powerful and narrower pulses are expected if the dispersion of the cavity can be properly managed.

8601-52, Session 13

Mid-infrared fiber lasers *(Invited Paper)*

Real Vallee, Martin Bernier, Nicolas Caron, Dominic Faucher, Vincent Fortin, Univ. Laval (Canada)

Rare earth doped silica fibers have greatly contributed to the development of compact and reliable laser sources operating at 1µm (Yt3+) at 1.5 µm (Er3+) as well as 2 µm (Tm3+ and Ho3+). Unfortunately, the infrared-limited transparency window of silica glass does not allow for the development of fiber lasers beyond 2.1 µm although a growing number of applications in the biomedical (e.g. dentistry, aesthetics, microsurgery) or environmental (e.g. LIDAR, spectroscopy, pollution detection) sectors would greatly benefit from such sources. Rare-earth doped Fluoride glass optical fibers are especially suited for that purpose since they can now be produced with low background losses. Moreover, the demonstration of the writing of a reliable Fiber Bragg grating (FBG) in a fluoride glass fiber by a femtosecond pulse train at 800 nm has indeed confirmed the huge potential of these fibers for the development of monolithic fiber lasers operating in the Mid-Infrared.

We will present an overview of our recent results pertaining to the development of monolithic fiber lasers operating beyond 2.1 µm. Specifically, we will describe a double-clad highly erbium-doped fluoride glass all-fiber laser operating in the vicinity of 3 µm. The implementation of the various versions of this fiber laser will be discussed along with its cw power scalability up to several tens of watts as well as its pulsed operation mode . Results on the first multi-watt fluoride glass Raman all-fiber laser operating beyond 2.2 µm will also be presented.

8601-53, Session 13

High energy parametric amplification at 1 µm with record large mode area optical fibers

Paul E. Steinvurzel, Boston Univ. (United States); Lars S. Rishøj, Boston Univ. (United States) and Technical Univ. of Denmark (Denmark); Yuhao Chen, Lu Yan, Jeffrey D. Demas, Michael D. W. Grogan, Boston Univ. (United States); Tal Ellenbogen, Kenneth B. Crozier, Harvard Univ. (United States); Karsten Rottwitt, Technical Univ. of Denmark (Denmark); Siddharth Ramachandran, Boston Univ. (United States)

Parametric amplification in single mode optical fibers based on phase-matched four wave mixing (FWM) depends on having anomalous or near-zero dispersion. Below 1.2 ?m, this is possible in the LP0,1 mode only with small core photonic crystal fiber designs, and so is inherently limited in power. However, this constraint is lifted with higher order modes. We demonstrate FWM at 1 ?m with a large area 618 ?m2 higher order mode at pump pulse energies > 100 ?J.

8601-54, Session 13

A combined Yb-Raman fiber amplifier for generating narrow linewidth, high-power pulses in the 1100-1200 nm wavelength range and efficient nonlinear conversion into yellow

Eitan E. Rowen, Guy Vashdi, Jacob Lasri, Eran Inbar, V-Gen Ltd. (Israel)

Yb-doped fiber lasers are widely used due to the excellent beam quality and multi-kilowatt output power level capabilities in the wavelength range of 1030-1100nm. Lately, considerable attention has been paid to extend the useable wavelength range of Yb-based fiber lasers to 1100-1200nm. Specifically, there is a demand for high-brightness frequency doubled 1100-1200nm lasers for producing yellow-orange sources.

We demonstrate a novel scheme for emitting high power, narrow linewidth, laser pulses at 1130nm. A narrowband CW diode laser at 1130nm, and a pulsed broadband laser at 1080nm are combined into a single-mode fiber, and are input to a Large-Mode Area (LMA) Yb amplifier. The 1080nm pulsed laser is amplified to peak powers of tens of kilowatts, leading to efficient Raman conversion of energy into the first Stokes order at 1130nm. Due to the wide Raman scattering spectrum, different wavelengths can be generated by changing the wavelength of the Raman seed.

In our scheme the temporal characteristics of the laser are determined by the pulsed seed at 1080 nm, while the spectral properties are determined by the CW Raman seed. We thus create what is to our knowledge the first demonstration of a sub-100pm linewidth laser with multi-kW peak power and >15W average power, at wavelengths that exceed 1120nm using standard LMA Yb doped fibers.

The excellent beam quality, high peak power and narrow linewidth of the extended wavelength nanosecond pulses are used for single

pass second harmonic generation (SHG) in an LBO crystal with >60% efficiency at a wavelength of 565nm.

8601-55, Session 13

Dynamics of ultra-long Brillouin fiber laser

Andrei A. Fotiadi, Univ. de Mons (Belgium) and Ioffe Physico-Technical Institute (Russian Federation) and Ulyanovsk State Univ. (Russian Federation); Ivan Lobach, Institute of Automation and Electrometry (Russian Federation); Patrice Mégret, Univ. de Mons (Belgium)

In random lasers nonresonant feedback occurs via reflection off a phase scrambling medium instead of a rear laser mirror. In such a laser the amplified photons scatter multiple times and do not return to their initial location periodically, so it is impossible to form a spatial resonance. The absence of the resonant feedback does not mean that the spectrum of the generated laser emission should be continuous, without discrete components at certain resonant frequencies. In contrast, random lasers commonly generate narrow stochastic spikes on the top of the laser emission spectrum. Similar regimes have been achieved in all-fiber laser configurations [1, 2].

Here we report experimental and theoretical studies of random lasing realized in optical fibers with the use of Brillouin amplification and Rayleigh backscattering employed as a distributed feedback instead of cavity mirrors. In contrast to previous experiments with short Brillouin cavities [2] we employed 25-km-long high quality standard telecom single-mode fiber enabling Rayleigh backreflection uniformly distributed over all fiber length. In the experiment we observed clear competition between a classical Brillouin process and Brillouin lasing. A presence of extensive fluctuation-free fragments in the recorded oscilloscope traces highlights Stokes power statistics typical for laser radiation rather than for a classical SBS process. The results of the experiments are in a perfect agreement with the model of Rayleigh-Brillouin cooperative process developed for long optical fibers.

[1] S.K. Turitsyn et al., Nature Photon. 4, 231 (2010).

[2] A.A. Fotiadi, Nature Photon. 4, 204 (2010).

8601-56, Session 13

Effective index numerical modelling of microstructured chalcogenide-glass fiber for frequency conversion to the mid-infrared band

Pierre Bourdon, Anne Durécu, Claire Alhenc-Gelas, Laura Di Bianca, Guillaume Canat, ONERA (France); Frédéric Druon, Lab. Charles Fabry (France)

Chalcogenide glass fibers offer broad transparency range up to the mid-infrared and high nonlinear coefficients and make excellent candidates for four wave mixing frequency conversion. However, the use of microstructured air-chalcogenide fibers is mandatory to achieve phase-matching in such a fiber.

Numerical modelling of the phase matching condition can be done using the simplified effective index model, initially developed and extensively used to design air-silica fibers.

In this paper, we investigate the use of the effective index model in the case of microstructured As2S3 and As2Se3 fibers. One essential step in the method is to evaluate the core radius of a step-index fiber equivalent to the microstructured fiber. Using accurate reference results provided by finite-element computation, we compare the different formulae of the effective core radius proposed in the literature and validated for air-silica fibers.

As expected, some discrepancies are observed, especially for the highest wavelengths. We propose new coefficients for these formulae so that the effective index method can be used for numerical modelling of propagation in air-chalcogenide fibers up to 5 µm wavelength.

We derive a new formula providing both high accuracy of the effective core radius estimate whatever the microstucture geometry and wavelength, as well as uniqueness of its set of coefficients.

This analysis reveals that the value of the effective core radius in the effective index model is only dependent on the microstructure geometry, not on the fiber material. Thus, it can be used for air-silica or air-chalcogenide fibers indifferently.

8601-57, Session 14

3C Yb-doped fiber based high energy and power pulsed fiber lasers *(Invited Paper)*

Thomas S. Sosnowski, Andrey Kuznetsov, Robert Maynard, Arbor Photonics, Inc. (United States); Xiuquan Ma, Cheng Zhu, I-Ning Hu, Almantas Galvanauskas, Univ. of Michigan (United States); Joona J. Koponen, Dahv A. V. Kliner, Timothy S. McComb, nLIGHT Corp. (United States)

Although a principal advantage of fiber laser technology is its compatibility with monolithic integration, enabling practical, compact and robust systems, the technological path towards the highest peak powers and pulse energies have employed fiber formats (i.e. PCF Rods) that are ill-suited for monolithic integration. Achieving MW peak power, multi-mJ energy pulses with practical, integration-compatible fibers remains a critical frontier for enabling wide-ranging practical use of high energy pulsed fiber lasers.

3C fiber technology is closing the performance gap between practical fiber lasers and those producing the highest peak powers. 3C fibers combine robust single-mode performance in large cores (up to 60 ?m demonstrated), environmentally-stable polarized output, and, under specific conditions, stimulated Raman suppression while retaining the handling and packaging benefits associated with single mode fibers. Amplifiers based on first generation ~28-?m-MFD 3C Yb fibers are commercially-available. These fibers demonstrate average-power scaling to greater than 250W, coincident with peak powers greater than 100 kW, pulse energies around 1 mJ and with pulse durations around 10 ns, while maintaining single mode beam quality, a high PER and a net optical efficiency greater than 70%. With sub-ns pulses these amplifiers reached peak power greater than 0.5 MW with negligible spectral distortions. Second-generation 3C Yb-fiber technology based on effectively single-mode core sizes around 55 ?m is currently in development, but has so far produced ~9 mJ, sub-10 ns pulses with peak powers exceeding 1.5 MW.

This talk will provide an overview of the current status of Yb-doped 3C fiber laser technology and its applications.

8601-58, Session 14

A high-energy cladding-pumped nanosecond Q-switched fiber laser using a fiber saturable absorber

Sean W. Moore, Daniel B. Soh, Scott E. Bisson, Brian D. Patterson, Sandia National Labs., California (United States)

We report an experimental demonstration of a passively Q-switched fiber laser using fiber components as the gain and saturable absorbing elements. A collimated free-space optical taper is used to couple the amplified spontaneous emission (ASE) between a large mode area Yb3+-doped fiber pumped at 915 nm and an unpumped single-mode Yb3+-doped fiber saturable absorber. The ASE was coupled between the LMA and saturable absorber fiber using a 1.73 : 1 telescope to nominally match their respective MFD's to the spot sizes of the focused collimated beam. The comparatively high intensity of the ASE in the single mode unpumped fiber saturates the absorption, making the fiber transparent, before the onset of gain depletion in the LMA fiber. Thus, the unpumped single mode Yb3+-doped fiber acts as a saturable absorber in the same manner as traditional bulk saturable absorbers. Using this scheme, we demonstrate a 40 ?J 79 ns Q-switched oscillator at 1026 nm. The associated peak power is more than two orders of magnitude larger than previous studies using unpumped Yb+3 fiber as a saturable absorber. A parametric study in which the length of the saturable absorber, wavelength, and pumping time are varied is conducted to ascertain the effects of these parameters on Q-switched performance. We further demonstrate amplification to 0.40 mJ using an all-fiber master-oscillator power-amplifier (MOPA) system.

8601-59, Session 14

High power amplification of a tailored-pulse fiber laser

Julien Saby, Damien Sangla, François Salin, EOLITE Systems (France)

Pulse Programmable fiber lasers have been used to optimize the quality of several material processing for different markets such as micro-electronics or solar cells manufacturing. Although complicated shapes can be obtained, these lasers generally exhibits too high complexity to meet industrial requirements and lack the average power and energy needed to reach the industrial throughput of real production processes. We demonstrate here that tailored pulses can be efficiently amplified in Large Pitch Rod type fibers enabling the generation of high average powers and high energies. This a perfectly suitable source for high efficiency frequency conversion while keeping the temporal flexibility of the seeder.

We have developed a high power fiber amplifier at 1064nm delivering up to 100W/1mJ at 15ns pulses and 30W/300µJ at 2ns with linearly polarized and diffraction limited output beam (M?<1.2). The specific seeder from ESI – Pyrophotonics Lasers used in the experiment allowed us to obtain tailored-pulse programmable on demand at the output from 2ns to 600ns for various repetition rates from 10 to 500 kHz. We could demonstrate square pulses or any other shapes (also multi-pulses) whatever the repetition rate or the pulse duration. We also performed frequency conversion with LBO crystals leading to 50W at 532nm and 25W at 355nm with a diffraction limited output.

Similar experiments performed at 1032nm will be also presented.

8601-60, Session 14

Study of destructive random backscattering pulses showing Brillouin signature in MOPA fiber laser systems

Miguel Melo, Multiwave Photonics (Portugal) and Univ. do Porto (Portugal); Martin O. Berendt, João M. Sousa, Multiwave Photonics (Portugal)

In this paper, we characterize and study the origin of highly peaked backward pulses arising from(in) pulsed master oscillator power amplifier (MOPA) fiber lasers systems using Fabry-Perot semiconductor laser seeding. The random backscatter is seen as short duration pulses with large amplitude compared to the Rayleigh scattering from the propagating seed pulse. Backscatter in the amplifiers will experience gain and grow in the backward direction compromising the reliable operation of the system, leading in many cases to catastrophic failures. Although the phenomena is typically attributed to stimulated Brillouin scattering (SBS), up to now has been no evidence ruling out spurious lasing or seeded random lasing as the source for peaked backscatter. The characterization of the backscatter is challenging due to its random nature and its extreme peak power levels. This paper presents a systematic study of backscatter in MOPA systems using different master oscillator seed sources in a hardened MOPA setup and a delayed self heterodyne RF domain spectrum analysis technique to characterize the backscatter and determinate its physical origin. This arrangement allowed the first systematic characterization of the backscatter in such MOPA systems. Short high peak power backward pulses with random occurrence in the typical Fabry-Perot seeded non-polarization maintaining system is found to show hallmark Brillouin frequency shift. The frequency of occurrence strongly depends on seed launch state of polarization and on the seed source characteristics. We compare between external and direct modulation of the seeders and evaluate both methods regarding the onset of the undesired phenomena.

8601-61, Session 15

Applications of fiber lasers for remote sensing of atmospheric greenhouse gases *(Invited Paper)*

Jeremy T. Dobler, Michael I. Braun, ITT Exelis Inc. (United States); James A. Nagel, College of Optical Sciences, The Univ. of Arizona (United States) and TIPD, LLC (United States); Valery L. Temyanko, TIPD, LLC (United States); T. Scott Zaccheo, Atmospheric and Environmental Research, Inc. (United States); Edward V. Browell, Fenton W. Harrison, NASA Langley Research Ctr. (United States); Susan A. Kooi, Science Systems and Applications, Inc. (United States)

In 2004 ITT Exelis developed the Multifunctional Fiber Laser Lidar (MFLL) for measuring atmospheric CO2. This lidar relies on high efficiency telecom laser components and Erbium Doped Fiber Amplifiers (EDFA's) to implement a unique Continuous Wave (CW) Intensity modulated (IM) differential absorption lidar measurement. This same approach has also been used to measure atmospheric O2 by replacing the EDFA's with fiber Raman amplifier technology. The use of all fiber coupled components results in a highly reliable, flexible and robust instrument. This presentation will discuss the general architecture of the MFLL, its implementation for greenhouse gas measurements, and as a pseudorandom noise altimeter system. Results from a 2011 flight campaign on the NASA DC-8 aircraft which included CO2, O2, and PN altimetry using a single receiver for all three measurements, will be presented. In addition, a novel variation of this approach that will enable greenhouse gas monitoring from a geostationary orbit will be discussed.

8601-62, Session 15

Fiber laser based high-spectral resolution lidar for earth science measurements

Youming Chen, Fibertek, Inc. (United States); Timothy A. Berkoff, Univ. of Maryland, Baltimore County (United States); Frank Kimpel, Mark E. Storm, Shantanu Gupta, Fibertek, Inc. (United States)

Atmospheric aerosols represent the greatest uncertainty in determining key questions in radiative energy balance for climate change and have important relationships to air quality, atmospheric chemistry, and cloud formation. To reduce uncertainties in accurate aerosol characterization, climate change questions, it is necessary to utilize high-spectral resolution lidar (HSRL) methods. The essential element of the HSRL technique is the ability to distinguish between molecular and aerosol atmospheric laser backscatter returns by spectral delineation between the broad (~4GHz) Rayleigh and the much narrower (<100 MHz) Mie scattering components.

We demonstrate a novel fiber-amplifier based lidar transmitter for HSRL measurements. The multi-stage fiber-amplifier based lidar transmitter produces 5 nsec pulses at 10kHz, with 50?J/pulse at 1064nm, and >25?J/pulse at 532nm. This fiber laser transmitter can be tuned cross the (1111 ? 1104) Iodine absorption lines. The laser transmitter has a ~130MHz linewidth at 1064nm, close to the transform limit line width ~88MHz for a 5nsec pulse width. Even without frequency-drift locking, the laser transmitter has very good frequency stability of ~200MHz over minutes. This fiber laser transmitter was installed in UMBC's lidar

laboratory, that includes a ceiling hatch to enable vertical propagation and viewing of transmitted laser beams into the atmosphere. The receiver fiber guided the atmospheric backscattered light to a separate light-tight box that contained the Iodine-cell detection assembly, consisting of a fiber collimation lens, splitter, Iodine absorption-cell, and a pair of Hamamatsu photo-multiplier-tube (PMT) detectors to monitor the input light before and after the Iodine-cell. Atmospheric measurements over 8 km altitude show good agreement of the signal to the Rayleigh model decay over the profile range. Moreover, HSRL measurements show that the Mie scatter from the cloud is successfully suppressed, while recovering the full molecular back-scatter signal.

8601-63, Session 15

Multi-wavelength S-band Tm:ZBLAN fiber lasers

Blaise Frison, Abdul R. Sarmani, Lawrence R. Chen, McGill Univ. (Canada); Xijia J. Gu, Ryerson Univ. (Canada); Mohammed Saad, IRphotonics Inc. (Canada)

Lasers, and in particular multi-wavelength sources, operating around 1480 nm can be used to extend the transmission capacity of WDM communication systems by exploiting the S-band, as well as for applications in LIDAR systems and fiber optics sensing.

Tm3+ ions offer amplification and lasing in a wide variety of wavelength ranges, including 480 nm, 810 nm, 1480 nm, 1900 nm, and 2300 nm. The 3H4->3F4 transition that provides gain around 1480 nm, however, poses two challenges. First, the ions in the upper level rapidly decay non-radiatively when in high phonon energy hosts. This can be solved by using low phonon energy glasses, such as ZBLAN. Second, this transition is self terminating. As such, the 3F4 level can be depleted either by colasing at 1900 nm or by using a pump at 1064 nm.

Dual- and multi-wavelength lasing has been previously obtained in Tm-doped fibre lasers at 780 nm and 1900 nm . In this paper, we report dual-wavelength operation of an all-fiber Tm-doped ZBLAN laser operating in the S-band. Fiber Bragg gratings at 1476 nm and 1487 nm are used to define the lasing wavelengths and a cascaded cavity configuration with a total of 110 cm of single-mode doped Tm:ZBLAN fiber (8000 ppm, core diameter ~ 8 μm, NA = 0.13) is used to achieve dual-wavelength operation. The laser is pumped at 1064 nm and the threshold pump powers for 1487 nm and 1476 nm are 950 mW and 1100 mW, respectively. A total power of 75 mW is obtained for 1320 mW of pump power.

Conference 8602: High-Power Lasers for Fusion Research II

Thursday 7 –7 February 2013

Part of Proceedings of SPIE Vol. 8602 High Power Lasers for Fusion Research II

8602-1, Session 1

Design of a laser-based fusion power plant *(Invited Paper)*

Mike Dunne, Lawrence Livermore National Lab. (United States)

No Abstract Available

8602-2, Session 1

The National Ignition Facility: beam area increase upgrade *(Invited Paper)*

Scott C. Burkhart, Abdul A. S. Awwal, Michael R. Borden, Tracy S. Budge, John A. Campbell, Mark A. Henesian, Kenneth S. Jancaitis, Donald R. Jedlovec, Richard R. Leach Jr., Roger R. Lowe-Webb, Brian J. MacGowan, Steven M. Pratuch, Jesse C. Palma, Joseph T. Salmon, David A. Smauley, Larry K. Smith, Stanley C. Sommer, Paul J. Wegner, Karl Wilhelmsen, Monika C. Witte, Jen N. Wong, Sham N. Dixit, Lawrence Livermore National Lab. (United States)

The National Ignition Facility (NIF) is the world's most energetic laser, having demonstrated in excess of 1.9MJ @351nm with Inertial Confinement Fusion pulse-shapes in July, 2012. First commissioned with 192 operational beamlines in March, 2009, NIF has since transitioned to routine operation for stockpile stewardship, inertial confinement fusion research, and basic high energy density science.

The NIF design includes component placement and beam alignment tolerances to preclude laser beam clipping on components within the laser chain, indeed lengthy studies and analyses, including various statistical approaches, were done in the design phase as early as 1996. The margin between the available optical aperture and the beam was established to ensure that; given beam centering variations and component placement errors, we would achieve a confidence level such that even low-level clipping, which causes downstream modulation damage, would occur at an acceptably or even vanishingly low rate.

With the completion of NIF and several years of operational experience, it became apparent that we could increase the beam size to more optimally fill the available aperture, and gain an additional 5% to 10% or more energy and power delivered to targets. In addition, beam 'corner blockers' had been installed in May, 2010 to mitigate target counter-propagating light, but operational experience and a recent analysis showed that about 70% of those blockers could be safely removed. Increasing the beam size was a challenging endeavor, however, as it fundamentally meant recommissioning the entire NIF laser chain to tailor all 192 beams to their specific available aperture, individual beam rotation (for the NIF square beam), beam centering offsets, change-out of the 48 front-end aperture (relay-plane "0"), and removal of 48 Laser Mirror #2 line replaceable units for corner-blocker removal. Some of this commissioning, such as tailoring beam sizes to their specific available aperture, had not been performed during the original commissioning. Furthermore, achieving this required precise diagnostics and rapid analysis of massive quantities of images and data in order to direct the changes and feed-back the achieved results. Completed on June 1, 2012, the beam area was increased by 7.5%, and was a significant contributing factor in NIF transitioning from a 1.6MJ laser to it's present 1.9MJ capability

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

8602-3, Session 1

Scaling-up energy: future large scale solutions made of today's micro optics

Manuel Bracker, Thomas Mitra, Oliver Homburg, LIMO Lissotschenko Mikrooptik GmbH (Germany)

Laser induced inertial confinement fusion is regarded as highly attractive solution for the supply with clean and sustainable energy as well as an alternative for currently used means of energy provision based on fossil or nuclear fuels. Apart from the challenge of realizing the fusion process itself, creating a resulting net energy yield from the process is the ultimate goal.

One key element on the way to efficient fusion facilities is the laser source. Producing the required pump fields for the DPSS laser and handling the high energetic laser beams on their way into the target chamber are crucial tasks. While industrial-suited large scale solutions for the required optics and beam shaping systems still need to be fully established, the components for realizing these large scale solutions are already available today.

Waver based, multi-functional micro optic arrays are the basis for high-efficient large scale optic solutions for laser induced fusion facilities. LIMOs unique production technology allows high volume production of almost any glass or crystal material. As the production process in general is not reduced to any maximum waver sizes, there is no fundamental limit in meeting the future large scale requirements. Complex micro optics designed to adopt the function of multiple single optics significantly optimize efficiency and costs of optical systems necessary for laser induced fusion.

Today's micro optic technology is already capable of providing industry-suited solutions for the versatile and demanding requirements of the light infrastructure in a laser induced fusion facility. We will discuss beam shaping solutions for high energy beams (for driving the plasma) as well as approaches for high volume pump sources.

8602-4, Session 2

Opacity of germanium and silicon in ICF plasmas *(Invited Paper)*

Djamel Benredjem, Univ. Paris-Sud 11 (France)

Because germanium and silicon are good candidates as dopants in the ablator of ignition target, the knowledge of their opacity is crucial. We have calculated the opacity by using two approaches. The first one utilizes a detailed line calculation in which the atomic database is provided by the MCDF code [1]. A lineshape code [2] based on a fast algorithm was then adapted to the calculation of opacity profiles. Because the calculation time is prohibitive when the number of lines is huge, a second approach [3], combining detailed line calculations and statistical calculations, is used. This approach necessitates much smaller calculation time than the first one and is then well suited for extensive calculations. The monochromatic opacity and the Rosseland and Planck mean opacities are calculated for various pertinent densities and temperatures.

References

[1] P. Grant et al, Comput. Phys. Comm. 21, 207 (1980).

[2] B. Talin, A. Calisti, L. Godbert, R. Stamm, R. W. Lee and L. Klein, Phys. Rev. A 51 1918 (1995).

[3] Q. Porquerot, F. Gilleron, J.-C. Pain, and T. Blenski, High Energy Density Phys. 7 234 (2011).

8602-5, Session 2

Hybrid filtering for high power laser with the combination of Bragg grating and traditional spatial filter

Xiao Yuan, Xiang Zhang, Kuaisheng Zou, Jiansheng Feng, Soochow Univ. (China)

The coherent properties and nonlinear effects of laser beams will introduce spatial modulations into the beam near field. These modulations will grow quickly during beam propagation chains, seriously degrading the beam quality, even causing damages to key optics, which greatly limits the output ability in advanced laser systems, such as the inertial confinement fusion (ICF) lasers which operates at extremely high intensities.

The volume Bragg grating (VBG) with high diffraction efficiency and angular selectivity is an effective device for angular filtering. Our previous report showed that the 2-D angular filtering on the basis of volume Bragg gratings (VBGs) in photo-thermo-refractive (PTR) glasses could restrain the spatial modulation on laser beams and improve the near field distribution.

A hybrid filter (HF) on the basis of the combination of VBGs and the traditional spatial filter was proposed to obtain lower cutoff frequency, inhibit the fast nonlinear growth and better to improve the near field distribution of lasers. The VBGs with a period of 0.9 ?m and a thickness of 2.5mm recorded in PTR glasses were placed in front of the traditional filter as the optimization elements. The filtering effects were demonstrated by a deeply-modulated beam with the spatial frequencies from 1mm-1 to 20mm?1. Near-field modulation, contrast ratio and power spectral density were used to evaluate the effect of filtering in both spatial and frequency domains. The results showed that most of the spatial frequencies were cleaned up due to angular selectivity of VBGs. Moreover, the near field contrast ratio and modulation was improved 12 times and 1.3 times compared to that of the traditional filter, which is important for high power laser systems.

8602-6, Session 2

Orion facility status update

David N. Winter, Thomas H. Bett, Nicholas Cann, Colin N. Danson, Stuart J. Duffield, Stephen P. Elsmere, David A. Egan, Mark Girling, Ewan J. Harvey, David I. Hillier, Nick W. Hopps, Dianne Hussey, Micheal J. Norman, Stefan Parker, Paul A. Treadwell, AWE plc (United Kingdom)

The Orion laser facility at AWE in the UK began operations at the start of 2012 studying high energy density physics. It consists of ten nanosecond beamlines and two sub-picosecond beamlines. The nanosecond beamlines each delivering 500 J per beam in 1ns at 351nm with a user-definable pulse shape between 0.1ns and 5ns. The short pulse beams each deliver 500J on target in 500fs with an intensity of greater than 1021 Wcm-2 per beam.

All beamlines have been demonstrated, delivering a pulse to target as described. A summary of the design of the facility will be presented, along with its operating performance over the first year of experimental campaigns.

The facility has the capability to frequency-double one of the short pulse beams, at sub aperture, to deliver a high contrast short pulse to target with up to 100J. This occurs post-compression and uses a 3mm thick, 300mm aperture KDP crystal. The design and operational performance of this work will be presented.

During 2012, the laser performance requirements have been demonstrated and key diagnostics commissioned; progress of this will be presented. Target diagnostics are also being commissioned during this period. Also, there is a development programme under way to improve the contrast of the short pulse (at the fundamental) and the operational efficiency of the long pulse.

It is intended that, from March 2013, 15% of facility operating time will be made available to external academic users in addition to collaborative experiments with AWE scientists.

8602-7, Session 2

HiLASE cryogenically-cooled diode-pumped laser prototype for inertial fusion energy

Antonio Lucianetti, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

Diode-pumped solid-state lasers with high pulse energy,high efficiency,and good beam quality are of increasing interest for various kinds of applications, such as inertial fusion, optical parametric chirped-pulse amplification (OPCPA), and laser-accelerated particles. Recent advances in semiconductor technology allowed significant increase of output powers from diode lasers. Diode-pumped lasers are expected to generate laser pulses with high energy at high repetition rates. At present, several high-energy-class diode-pumped solid state lasers are being constructed worldwide with energies of 100 J or higher. The most deleterious problems limiting efficient high power operation are the amplified spontaneous emission (ASE) and the thermal effect which results from various physical phenomena such as quantum defect, non unity quantum efficiency, concentration quenching, upconversion and other sourecs. The internal heating leads to the formation of thermal gradients and to significant degradation of the beam quality.Heating of the gain medium also leads to beam depolarization effects as a consequence of thermal stress-induced birefringence.

We present the design parameters of a 100J-class diode-pumped multi-slab Yb:YAG laser at 10 Hz scalable to the kJ regime. Results of detailed energetics and thermo-optical modelling confirm the viability of cryogenic helium-gas cooling approach to drastically reduce thermally-induced distortions in the laser slabs. In addition, we will show comparative spectral measurements of diode-laser stacks from several vendors, and spectroscopic and LIDT measurements of key optical components (Yb:YAG samples and sapphire windows) at cryogenic temperatures.

8602-8, Session 3

Experimental measurement of frequency transfer function due to smoothing by spectral dispersion

Jacques Luce, Denis Penninckx, Commissariat à l'Énergie Atomique (France)

In order to avoid propagation nonlinearities (Kerr effect, Raman and Brilllouin scattering) and optical damage, nanosecond high power lasers such as the Laser MegaJoule (LMJ) amplify quasi-monochromatic pulses. But they generate a static speckle pattern in the focal spot. This speckle pattern needs to be smoothed in order to avoid high intensity peaks which are detrimental during the propagation and interaction with the plasma in the target. Different techniques are used for smoothing but all high intensity lasers use at least smoothing by spectral dispersion. It consists in broadening the spectrum through a phase modulation and focusing the different wavelengths of the pulse at slightly different positions using a diffractive element such as a grating. In the temporal domain, it has been theoretically shown that the pulse power is thus filtered between near filed and far field [1,2]. The filtering allows techniques such as "picket fence" to increase conversion efficiency [1] and reduces detrimental effects of unwanted intensity distortions called FM-AM conversion [2, 3]. Here, to the best of our knowledge we show the first experimental measurement of the frequency transfer function of this filtering. Measurements are in perfect agreement with the numerical calculations. Usually, they are complicated because the frequency has to be changed and should reach high values which require the use of photodiodes instead of phototubes. But photodiodes do not allow measuring a sufficient portion of the focal spot.

The difficulty has been circumvented by varying the time delay of a

grating with a diaphragm instead of varying the frequency.

[1]: J. E. Rothenberg, "Ultrafast picket fence pulse trains to enhance frequency conversion of shaped inertial confinement fusion laser pulses," Appl. Opt. 39, 6931–6938 (2000).

[2]: S. Hocquet, D. Penninckx, É. Bordenave, C. Gouédard, and Y. Jaouën, "FM-to-AM conversion in high power lasers," Appl. Opt. 47, 3338–3349 (2008).

[3]: J. E. Rothenberg, D. F. Browning, and R. B. Wilcox, "Issue of FM to AM conversion on the National Ignition Facility," Proc. SPIE 3492, 51–61 (1999)

8602-9, Session 3

Image processing and control of a programmable spatial light modulator for spatial beam shaping

Abdul A. S. Awwal, Charles D. Orth, Eddy M. Tse, JoAnn T. Matone, Carla P. Hardy, Mitanu Paul, Gordon K. Brunton, Jean-Michel G. Di Nicola, John E. Heebner, Lawrence Livermore National Lab. (United States)

In order to achieve fusion and operate the lasers reliably, spatially shaped beams must be used to drive inertial confinement fusion reactions. Recently, 48 programmable, liquid crystal based spatial light modulators were added to introduce "blocker" obscurations shadowing isolated flaws on downstream optical elements that could otherwise be affected by high fluence laser illumination. One of the objectives of this spatial shaping, in addition to deploying blockers, is to smooth the intensity variations so that the life of the optics is further extended. Algorithms were developed for implementing the specified shaping of the beam and subsequent verification of the beam profile after the beam shaping mask is applied on the liquid crystal modulator device. The spatially varying nonlinear response of the device, scale and rotation was programmed into the mask deployment process, by a calibrating the local magnification, gray-level to transmittance mapping, performed at regular intervals. We describe the control and associated image processing of this device that helps to enhance the controllability and longevity of the overall system.

*(This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344; LLNL-ABS-567032)

8602-10, Session 3

Radiative power losses in inertial fusion plasmas: detailed and statistical calculations

Guillaume Mondet, Univ. Paris-Sud 11 (France)

In this work we focus on the radiative power losses in inertial confinement fusion (ICF) plasmas. We present recent calculations on carbon and gold. Both ions are involved in the ICF scheme. The first element could also be utilized in the walls of future TOKAMAK reactors such as ITER while the second is present in holraums and its X-ray emission contributes to the heating in ICF.

When the number of emission lines is not prohibitive, typically a few thousands, a detailed line calculation code based on a fast algorithm is used. This code requires a lot of atomic data, which are obtained by using the MCDF code of Grant [1]. All major line broadening mechanisms are taken into account consistently, and the ionic fractions are in NLTE. When millions of atomic transitions are involved and when the line overlapping does not permit to discriminate individual lines, a hybrid approach mixing detailed line calculations and statistical calculations is utilized. This approach is based on the SCO-RCG code [2] which combines statistical calculations ?in terms of supertransition arrays and unresolved transition arrays? and detailed calculations (RCG routine of Cowan code). This approach was proposed to drastically reduce the amount of calculations.

References

[1] I. P. Grant, B. J. McKenzie, P. H. Norrington, D. F. Mayers and N. C. Pyper, Comput. Phys. Comm. 21 207 (1980).

[2] Q. Porquerot, F. Gilleron, J.-C. Pain, and T. Blenski, High Energy Density Phys. 7 234 (2011).

8602-11, Session 3

Multi-objective optimization for the National Ignition Facility's Gamma Reaction History diagnostic

George R. Labaria, Lawrence Livermore National Lab. (United States) and Univ. of California, Berkeley (United States); Judith A. Liebman, Daniel B. Sayre, Lawrence Livermore National Lab. (United States); Hans W. Herrmann, Los Alamos National Lab. (United States); Essex J. Bond, Jennifer A. Church, Lawrence Livermore National Lab. (United States)

The National Ignition Facility (NIF) is producing experimental results for the study of Inertial Confinement Fusion (ICF). The Gamma Reaction History (GRH) diagnostic at NIF can detect gamma rays to measure fusion burn parameters such as fusion burn width, bang time, neutron yield, and areal density of the compressed ablator for cryogenic deuterium-tritium (DT) implosions. Gamma-ray signals detected with this diagnostic are inherently distorted by hardware impulse response functions (IRFs) and gains, and are comprised of several components including gamma rays from laser-plasma interactions (LPI). One method for removing hardware distortions to approximate the gamma-ray reaction history is deconvolution. However, deconvolution of the distorted signal to obtain the gamma-ray reaction history and its associated parameters presents an ill-posed inverse problem and does not separate out the source components of the gamma-ray signal. A multi-dimensional parameter space model for the distorted gamma-ray signal has been developed in the literature. To complement a deconvolution, we develop a multi-objective optimization algorithm to determine the model parameters so that the error between the model and the collected gamma-ray data is minimized in the least-squares sense. The implementation of the optimization algorithm must be sufficiently robust to be used in automated production software. To achieve this level of robustness, impulse response signals must be carefully processed and constraints on the parameter space based on theory and experimentation must be implemented to ensure proper convergence of the algorithm. In this paper, we focus on the optimization algorithm's theory and implementation.

*This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

LLNL-ABS-575320

8602-12, Session 4

Simulations of the propagation of multiple-FM smoothing by spectral dispersion on OMEGA EP

John H. Kelly, Alexander Shvydky, John A. Marozas, Mark J. Guardalben, Brian E. Kruschwitz, Leon J. Waxer, Christophe Dorrer, Elizabeth Hill, Andrey V. Okishev, Univ. of Rochester (United States); Jean-Michel G. Di Nicola, Lawrence Livermore National Lab. (United States)

A one-dimensional (1-D) Smoothing by Spectral Dispersion (SSD) system for smoothing focal spot non-uniformities using multiple modulation frequencies was commissioned on one long-pulse beamline of OMEGA EP, the first use of such a system in a high-energy laser. FM-to-AM

conversion in the IR output, frequency conversion, and final optics affected the accumulation of B-integral in that beam line. Modeling of this FM-to-AM conversion using the code Miró(1) was used as input to set the beam line performance limits for picket (short) -pulses with multiple-FM (m-FM) SSD applied.

This presentation first describes that modeling. The 1-D SSD analytical model of Chuang and Meyerhofer(2) is first extended to the case of multiple modulators and then used to benchmark Miró simulations. Comparison is also made to an alternative analytic model developed by Hocquet et al.(3)

With the confidence engendered by this benchmarking, Miró results for m-FM SSD applied on Omega EP are then presented. The relevant output section(s) of the Omega EP system are described. The additional B-integral in Omega EP IR components upstream of the frequency converters due to AM is modeled. The importance of locating the image of the SSD dispersion grating at the frequency converters is demonstrated. Finally, since frequency conversion is not performed at the target-chamber in Omega EP, the additional AM due to propagation to the target-chamber vacuum window is modeled.

This work was supported by the U.S. Department of Energy Office of Inertial Confinement Fusion under Cooperative Agreement No. DE-FC52-08NA28302, the University of Rochester, and the New York State Energy Research and Development Authority. The support of DOE does not constitute and endorsement by DOE of the views expressed in the article.

(1) O. Morice, "Miró: complete modeling and software for pulse amplification and propagation in high-power laser systems," Opt. Eng. 46, 1530-1541 (2003).

(2) "Amplification of Broad-Bandwidth Phase-Modulated Laser Counter propagating Light Waves in Homogeneous Plasma" Y.-H. Chuang (Ph.D. thesis) (September 1991) Chapter VI.

(3) S. Hocquet, D. Penninckx, E. Bordenave, C. Gouédard and Y. Jaouën, "FM-to-AM conversion in high-power lasers," Appl. Opt. Vol. 47, No. 18, 20 June 2008

8602-13, Session 4

Commissioning of a multiple-FM smoothing by spectral dispersion demonstration system on OMEGA EP

Brian E. Kruschwitz, John H. Kelly, Christophe Dorrer, Andrey V. Okishev, Leon J. Waxer, Gregory Balonek, Ildar A. Begishev, Wade Bittle, Albert Consentino, Robert H. Cuffney, Elizabeth Hill, John A. Marozas, Matthew Moore, Richard G. Roides, Jonathan D. Zuegel, Univ. of Rochester (United States)

A one-dimensional smoothing by spectral dispersion (SSD) demonstration system for smoothing focal-spot nonuniformities using multiple modulation frequencies (multi-FM SSD) was commissioned on one long-pulse beamline of OMEGA EP, the first use of such a system in a high-energy laser. System models of FM-to-AM conversion in the OMEGA EP beamline and final optics were used to develop an amplitude modulation budget. The AM budget in turn provided a UV power limit of 0.85 TW, based on accumulation of B-integral in the final optics. The front end of the demonstration system utilized a NIF preamplifier module (PAM) with a custom SSD grating inserted into the PAM's multipass amplifier section. The dispersion of the SSD grating was selected to cleanly propagate the dispersed SSD bandwidth through various pinholes in the system while maintaining sufficient focal-spot smoothing performance.

A commissioning plan was executed that systematically introduced the new features of the demonstration system into OMEGA EP. Ultimately, the OMEGA EP beamline was ramped to the UV power limit with various pulse shapes. The front-end system was designed to provide flexibility in pulse shaping. Various combinations of pickets and nanosecond-scale drive pulses were demonstrated, with multi-FM SSD modulation selectively applied to portions of the pulse. Analysis of the dispersion measured by the far-field diagnostics at the outputs of the infrared beamline and the frequency-conversion crystals indicated that the SSD modulation spectrum was maintained through both the beamline and the frequency conversion process. At the completion of the plan, a series of equivalent target-plane measurements with distributed phase plates installed was conducted that confirmed the expected time-integrated smoothing of the focal spot.

This work was supported by the U.S. Department of Energy Office of Inertial Confinement Fusion under Cooperative Agreement No. DE-FC52-08NA28302, the University of Rochester, and the New York State Energy Research and Development Authority. The support of DOE does not constitute an endorsement by DOE of the views expressed in this article.

8602-14, Session 4

Deployment of a spatial light modulator-based beam-shaping system on the OMEGA EP laser

Matthew Barczys, Seung-Whan Bahk, Michael Spilatro, Diana Coppenbarger, Elizabeth Hill, Thomas Hinterman, Richard W. Kidder, Jason C. Puth, Todd C. Touris, Jonathan D. Zuegel, Univ. of Rochester (United States)

A beam-shaping system, based on a liquid-crystal-on-silicon spatial light modulator, has been deployed on two of the long-pulse UV beam lines of the OMEGA EP laser. Simultaneous control of both amplitude and phase with a single spatial light modulator is possible by encoding intensity information on a high-frequency carrier phase, which is subsequently removed by a low-pass spatial filter. The beam-shaping system has been integrated into operations of the existing front-end laser source and has demonstrated improved beam uniformity at multiple points in the laser.

The system operates in closed-loop to optimize the input infrared beam's spatial amplitude profile prior to amplification and frequency conversion. Measured amplified beam profiles from near-field cameras along the laser beam path are used to specify the desired input infrared beam shape. The system is used to correct both local hot spots in the input beam profile and to refine the amplifier gain precompensation profile that is applied to the input beam with separate static apodizers. At present, the beam-shaping system is used only to correct amplitude variations in beam profile, but future use may also utilize the system's capability to apply wavefront corrections to the beam.

This work was supported by the U.S. Department of Energy Office of Inertial Confinement Fusion under Cooperative Agreement No. DE-FC52-08NA28302, the University of Rochester, and the New York State Energy Research and Development Authority. The support of DOE does not constitute an endorsement by DOE of the views expressed in this article.

8602-15, Session 4

Update of laser mégajoule large optics wavefront performance requirements

Stéphane Mainguy, Jean-Philippe Airiau, Thierry Bart, Vincent Beau, Edouard Bordenave, Stéphane Bouillet, Christian Chappuis, Sandrine Chico, Philippe Cormont, Nathalie Ferriou-Daurios, Jérôme Daurios D.D.S., Vincent Denis, Laure Eupherte, Nathalie Ferriou-Daurios, Servane Fontaine, Gaël Gaborit, Claire Grosset-Grange, Eric Journot, Laurent Lamaignère, Thomas Lanternier, Eric A. G. Lavastre, Christophe Leymarié, Louis-André Lompré, Mélanie Mangeant, Jérôme Néauport, Etienne Perrot-Minnot, Gérard Razé, Stéphane Reyné, Claude Rouyer, Jean-Michel Sajer, Stéphane E. Seznec, Daniel Taroux, Sébastien Vermersch, Commissariat à l'Énergie Atomique (France)

The Laser Mégajoule (LMJ) [1] has about 40 large optics per beam and, for 22 bundles, about 7.000 optical components. The first LMJ bundles are scheduled to be operational at end 2014. LMJ components are now being delivered and a global strategy for derogation management is developed, even for a very few ratio of non-conform pieces.

First methods of LMJ optics specification were introduced more than a decade ago ([2]). The current methods to evaluate component wavefront performance are mainly based on Miró code numerical simulations ([3]). Recent component wavefront studies were previously presented ([4],[5]).

This paper emphasizes the methodology applied to check or re-evaluate the wavefront requirements of LMJ large optics.

First we recall how LMJ large component optical specifications are expressed and what their corresponding impacts on the laser chain are. Depending on the component location in the laser chain, we explain the criteria on the laser performance considered in our impact analyses.

Then, we give a review of the different propagation issues that we study thanks to the Miró numerical simulations : analytical representations allow to study the propagation downstream local surface or bulk defects and the propagation of a residual periodic aberration along the laser chain. Random phase maps generation is also very used to study the propagation of component wavefront/surface errors, either with uniform distribution and controlled rms value on specific spatial bands, either following a specific wavefront/surface Power Spectral Distribution (PSD).

[1] www-lmj.cea .fr

[2] M. Bray, A. Liard, G. Chabassier, " Laser MégaJoule optics (I) : New methods of optical specification ", EUROPTO conference on Optical Fabrication and Testing, Berlin, SPIE Vol. 3739, May 1999.

[3] O. Morice, Optical Engineering, Vol. 42 No. 6, 1530-1541, June 2003.

[4] S. Mainguy, C. Grosset-Grange, E. Bordenave, "Performance of a high-resolution deformable mirror for wavefront correction on the LIL/ LMJ and PETAL baselines", 6th IFSA conf., J. of Physics : Conference Series 244 (2010) 032021.

[5] S. Mainguy, L. Le Déroff, "Wavefront performance analysis of Laser Mégajoule optical components", 7th IFSA conference, European Physical Journal Web of Conferences, to be published in 2012.

8602-16, Session 4

Image processing methods for characterizing cryogenic target quality during ice layer formation at the National Ignition Facility (NIF)

Richard R. Leach Jr., Randy S. Roberts, Tayyab I. Suratwala, Rebecca Dylla-Spears, Evan Mapoles, Bernie Kozioziemski, Laura Mascio-Kegelmeyer, Lawrence Livermore National Lab. (United States)

A challenging aspect of preparing cryogenic targets for National Ignition Facility (NIF) ignition experiments is growing a single crystal layer (~ 70 um thick) of solid frozen deuterium-tritium (DT) fuel on the inner surface of a spherical hollow plastic capsule 2 mm in diameter. For most experiments, the layer must be smooth, having uniform thickness, and largely free of isolated defects (e.g. grooves). The growth of a single target layer typically takes up to 18 hours to form. Current methods use x-ray images on 3 orthogonal axes to monitor the growth of the crystal and to evaluate the quality of the layer. While these methods provide a good indicator of target layer quality, algorithms using new metrics are currently being developed to take advantage of other properties in the x-ray images. These properties include symmetry of texture, seed formation, and eigenimage analysis. We describe the approach and associated image processing of these metrics, whose goal is to improve and enhance quantifying the quality of the layer during its growth.

8602-17, Session 4

Efficient pumping of inertial fusion energy lasers

Christian Wessling, INGENERIC GmbH (Germany); Saumyabrata Banerjee, Klaus Ertel, Rutherford Appleton Lab. (United Kingdom); Stefan Hambücker, INGENERIC GmbH (Germany); Paul D. Mason, Rutherford Appleton Lab. (United Kingdom); Olaf Rübenach, Volker R. Sinhoff, INGENERIC GmbH (Germany)

Solid-state lasers have been demonstrated as attractive drivers for laser-plasma interaction and are presently been developed for various application like inertial confinement fusion (ICF), particle acceleration and intense X-ray generation. Viable real world application like power production at industrial scale will require high laser system efficiency, repetition rate, and lifetime, which are only possible with semiconductor diode pumping.

The paper describes the work conducted with two 20kW diode laser sources pumping an ytterbium:YAG laser amplifier. The set-up acts as a small scale prototype for the DIPOLE project. This project aims to develop scalable gas cooled cryogenic multi-slab diode pumped solid state lasers capable of producing KJ pulse energy. A scale-down prototype is currently under development at the Central Laser Facility (CLF) designed to generate 10J at 10Hz.

To secure an efficient pumping process the sources have to fulfill aside power requirement in the spectral and time domain, the claim for high homogenization and low divergence of the spatial and angular beam distribution as well as a minimization of losses within the optical path. The existing diode laser sources designed and built by INGENERIC deliver 20 kW pulsed power, concentrated on a plateau of FWHM dimension of 20 x 20 mm? with a homogeneity of more than 90%. The center wavelength of 939.5 nm is controlled in a range of ± 0.1 nm. The time and area integrated spectrum of at least 76 % of the total energy is contained within a 6 nm wide wavelength band around the center wavelength. Repetition rates can be adjusted between 0.1 Hz up to 10 Hz with rise and fall times less than 50 µs and pulse durations from 0.2 ms to 1.2 ms.

The paper details the impact of different designs on the performance of pump sources and puts special emphasis on the influence of the optical components on efficiency and performance. In addition the influence of the measuring principle is discussed.

8603-1, Session 1

Active beam controlling of high power Q-switched Nd:YAG lasers for stable fiber coupling with small numerical aperture for material processing

Mario Goehre, Clean-Lasersysteme GmbH (Germany); Christoph Becker, Betewis GmbH (Germany)

For mobile surface treatment it is convenient to work with flexible fiber coupled lasers. To keep the focusing optic sufficiently small it is necessary to have small fiber core diameters and a small outgoing numerical aperture. The knowledge of the resonator beam parameters is essential for long term stable fiber coupling conditions.

We demonstrate that the outcoupling beam diameter inside the resonator is suitable as a control process variable for this purpose.

For high power side pumped Nd:YAG lasers it is necessary to have an effective rod cooling to compensate thermal lensing. By adapting the rod cooling to the thermal lensing it is possible to keep the beam diameter constant. In this case the water flow of the rod cooling circuit has to be independent from pump diode cooling circuit and has to be controlled by a beam profile measurement inside the resonator.

The half angle of the laser beam outside the resonator is dependent on the resonator length and the pump power and therefore the thermal lensing. If the beam diameter on the mirror is constant, the numerical aperture of the laser is also constant.

If the beam diameter changes due to diode degradation or other effects inside the resonator, the diameter as a process control variable should control the flow of the rod cooling. It can also control the diode current, due to poor absorption inside the laser rod because of degradation.

Thus, the thermal lensing could be adapted, to control the beam diameter and as a result the numerical aperture for the fiber.

8603-2, Session 1

In-situ optical phase distortion measurement of Yb:YAG thin disk in high average power regenerative amplifier

Taisuke Miura, Michal Chyla, Martin Smr?, Patricie Severová, Ond?ej Novák, Akira Endo, Tomá? Mocek, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

Laser-induced plasma generated by high energy and high repetition rate few picosecond pulse is required for precise micromachining and efficient generation of extreme ultraviolet light for medical and industrial applications. We are developing one kilohertz picosecond Yb:YAG regenerative amplifier with 500-W average power based on thin disk technology.

Although the output of thin disk based regenerative amplifier has been achieved up to several hundred millijoules at low repetition rate, poor mode matching due to a thermally induced OPD (optical phase distortion) of thin disk limits the output up to few tens of millijoules at the high repetition rate.

In case of high energy pulse amplification, a large area mode matching in gain media, which is drastically degenerated by the OPD, is required to avoid optical damage. Also, one must evaluate the OPD under the lasing condition to make a precise compensation, since the thermal load of quasi- three-state laser media fluctuates greatly along between lasing and non-lasing condition.

Thus we designed in-situ OPD measurement technique based on a precise wavefront sensor. A probe beam generated from a fiber-pigtailed laser diode is collimated and irradiated to the thin disk. Then the OPD of the thin disk during laser operation is investigated by measuring the distorted wavefront of probe beam. In contrast to a conventional interferometric measurement, this measurement is compact, easy-to-align, and is less affected by mechanical vibrations. One can also evaluate temporally resolved OPDs applying a pulsed laser diode as probe beam. Measured results will be discussed in the presentation.

8603-3, Session 2

Deterioration of beam quality factor of laser pulses due to angular dispersion of optical elements

Sergiy Mokhov, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); Vadim Smirnov, Eugeniu V. Rotari, OptiGrate Corp. (United States); Julien Lumeau, Boris Y. Zeldovich, Leonid B. Glebov, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

Laser pulses are often manipulated by different optical elements in free space for purposes of filtering, stretching/compression, shaping, and splitting. This is due to the impossibility of using fiber optical components to withstand high power pulses. The beam quality factor for free-space propagating optical beams, M2, is typically used to characterize the performance of optical elements. Optical element which preserves M2 in the CW regime may in fact worsen M2 for pulses with the same time-averaged power if this optical element exhibits dispersion in the spectral range of the pulse's bandwidth. Basic dispersive effects can be expressed in terms of aberration-free monochromatic beam optics, and they are longitudinal shift of the waist position, transversal shift of the waist center and angular shift of the propagation direction with wavelength tuning. The first two effects are negligible for optical elements much smaller than the Rayleigh length. We have found an analytical expression for the deterioration of M2 from unity due to angular dispersion for a test pulse which has transverse Gaussian beam profile. This expression depends on both the transverse size of the pulse and the mean square variation of the spectral-angular characteristic of the optical element averaged with the spectral weight distribution of the pulse. In particular, with decreasing of beam size, the M2 deteriorates less because the spectral-angular variation of the propagation direction is mitigated by increasing beam divergence due to diffraction. In our judgment, an optical element should be characterized by its angular dispersion properties rather than measurements of M2.

8603-4, Session 2

Recent results on bulk laser damage threshold of optical glasses

Ralf Jedamzik, Frank Elsmann, SCHOTT AG (Germany)

Modern pulsed laser applications cover a broad range of wavelength, power and pulse widths. Beam guiding optics in laser systems do not only have specific requirements on the imaging quality but also have to withstand high laser powers. The laser damage threshold of an optical component depends on the surface (polishing, coating ..) and also on the bulk material properties. Actual values of bulk laser damage thresholds, particularly at pulse lengths less than 1nsec, of optical glasses are rarely found in literature, except for fused silica which is known as a key optical material for components in high power laser. However, fused silica is rather expensive and limited in optical properties.

That is the reason why customers often ask for laser damage threshold data of optical glasses. Therefore SCHOTT has started a project for the characterization of the bulk laser damage threshold of optical glasses at the wavelengths 532 nm and 1064 nm with pulse lengths in the nano- and pico-second range.

Bulk and surface laser damage testing has been performed by the Laser Zentrum Hannover in Germany according to the S-on-1 test of DIN EN ISO 11254-2 / DIN EN ISO 21254.

In this presentation the measurement approach will be described and results will be presented.

8603-5, Session 2

Limitations of optical antireflective coatings on fused silica optics in high-brightness 2D laser cutting heads

Bjoern Wedel, Hagen Zimer, Roman Niedrig, HIGHYAG Lasertechnologie GmbH (Germany); Marcel Schulze, Bernhard Kley, Institut für Angewandte Physik (Germany)

A major challenge for near infrared high-brightness laser cutting applications at multiple Kilowatts of output power is the full spatial and temporal control of the laser beam parameters on the work piece. Detrimental thermo-optic effects, which are induced by laser light absorption within the key optical elements of the processing head, lead to undesired thermal focus shifts and potentially to a decreased beam quality. Eventually, such effects slow down the process and reduce the cutting quality. Although the purity of nowadays synthetic glasses is excellent, optical elements made from such materials typically suffer strong thermo-optical focus shifts in high-brightness laser applications due to non-vanishing absorption of the laser light within the optical anti-reflective coatings. Thereby, the deposition technique largely determines the stoichiometry and materials purity of the individual dielectric coating layers an by means of this resultant the absorption properties.

We have studied and compared IAD and IBS anti-reflective coatings on fused silica optical elements with respect to laser power induced damaged thresholds and laser power induced focus shifting. With respect to the later, we have investigated the influence of the beam quality on the focus shift parameter in the multi-kW regime. In this context, we propose a set-up for precise focus shift measurements. Finally, we present a novel type of anti-reflective coating which potentially allows for ultra-low laser power induced focus shifts and very high laser power induced damage thresholds. We have implemented such optics into a 2D laser cutting head and carried out cutting experiments with a multi-kW fiber laser. A direct comparison to cutting results with conventional coated optics will be given.

8603-6, Session 2

CVD diamond for high power laser applications

Andrew M. Bennett, Element Six Ltd. (United Kingdom); Eugene V. Anoikin, Element Six (United States); Jan Barten, Gert Pels, Element Six N.V. (Netherlands); John R. Brandon, Element Six Ltd. (United Kingdom)

Chemical vapour deposited bulk diamond products have already found significant applications in high power laser systems including heatspreaders, output couplers and active components such as raman shifting or beam combining crystals.

However as new applications require ever increasing power densities, the processing and integration of diamond parts to fully utilise its exceptional properties becomes more challenging. The very fundamental properties of diamond that lead to its chemical and mechanical robustness, low absorption across a large portion of the spectrum, and very high thermal conductivity, can create challenges for integrating parts into systems previously optimised for alternative materials.

We report on innovation in synthesis and processing of diamond that enables its properties to be fully exploited. Diamond parts with larger dimensions than previously achieved at extremely low defect density have been synthesised, and processed to flatness and roughness significantly beyond those previously reported. Modelling data will demonstrate the efficacy of recent mounting designs, and data on failure mechanisms and power density limits presented.

The achievements reported have allowed a number of exciting new developments in the use of diamond in high power laser systems, which will be discussed.

8603-7, Session 2

Analysis of temperature and thermal stress fields of K9 glass damaged by 1064nm nanosecond pulse laser

Yunxiang Pan, Zhonghua Shen, Jian Lu, Xiao-Wu Ni, Nanjing Univ. of Science and Technology (China)

There are residual scratches, inclusions and other forms of defects at surfaces of optical materials after the processes of grinding and polishing, which could either enhance the local electric field or increase the absorption rate of the material. As a result, the laser-induced damage threshold at the surface of the material is reduced greatly. In order to study underlying mechanisms and process of short pulsed laser-induced damage to K9 glass, a spatial axisymmetric model where the K9 glass was irradiated by a laser whose wavelength and pulse width are respectively 1064nm and 10ns was established. Taking into account the fact that the surface of the K9 glass is more likely to be damaged, 2?m-thick layers whose absorption coefficients are larger than bulk were set at both the input and output surfaces in the model. In addition, the model assumed that once the calculated tensile/compressive stress was greater than the tensile/compressive strength of K9 glass, the local absorption coefficient increased. The finite element method was applied to calculate the temperature and thermal stress fields in the K9 glass. Results show that only the temperature of a small part of interacted region exceeds the melting point, while most of the damage pit is generated by thermal stress. The simulated damage morphology and the size of the damage region are consistent with those reported in literatures, which indicates that the model built in our work is reasonable.

8603-31, Session PTue

Propulsion of targets with different confinement geometries in water by Nd: YAG laser at 1064nm

Jun Chen, Bei-Bei Li, Hong-Chao Zhang, Bing Han, Zhong-Hua Shen, Xiao-Wu Ni, Nanjing Univ. of Science and Technology (China)

Laser propulsion in air or vacuum has been developed as a thruster technology for the attitude control of micro class satellites. Laser propulsion in water can be used as a technology for propelling underwater platform or controlling microfluid device. Laser propulsion effects in water are much better in air due to the force from laser-induced bubble in water. The target geometries will influence the propulsion effects in air. In order to investigate the influence of target geometries on laser propulsion in water, targets with/without conical cavity and hemispherical cavity are designed in this paper. The features of bubble, the momentum IT gained by object and the momentum coupling coefficient Cm are investigated experimentally by highspeed photography method. It shows that the shapes of the bubble generated by laser near the target rear with cavity are very different from that near the target without cavity, in other words the former is not singly-connected, while the latter is. Furthermore, the propulsion effects are better if there is a cavity on the laser irradiated surface of the object, and a hemispherical cavity works better than a conical cavity. In addition, IT increases with the laser energy, but the increasing trend slows gradually, and Cm increases with the laser energy first, and then decreases after the maximum. They are both due to the laser plasma shielding. In conclusion, we need design suitable target geometry and use optimal laser energy to get the best propulsion effect for controlling microfluid device or micro class satellites.

8603-32, Session PTue

Laser processing technologies in limited tubular space by a composite-type optical fiber system

Takaya Terada, Fuyumi Ito, Akihiko Nishimura, Japan Atomic Energy Agency (Japan)

JAEA has been developing high power laser material processing to apply it for maintenance and decommission of nuclear power plants. Q-switched pulse lasers are employed for shock-wave or thermal effects such as peening, cleaning and ablation. High power CW lasers are used for a heat source of annealing welding and cutting. Here, we report two brand new devices. One is an inspection machine with surface cleaning and LIBS by a nanosecond pulsed Nd:YAG laser. Another is a cladding machine for heat exchanger tubes by a CW Yb fiber laser. In both cases, a composite-type optical fiber system successfully delivered the laser beams to limited tubular space. This fiber system was composed of a center fiber for beam delivery surrounded by visible image delivery. Thus this fiber system always keeps target on center of gun-sight. The laser beam and the visible image were split up by a dichroic mirror in a coupling device. The pulsed laser beam repetitively ablated the oxide layer on the inner wall. A spectrometer in the coupling device analyzed the laser induced atomic emission lines. The CW fiber laser cladding with wire feeding was performed to fill up the inner wall wastage. A wire-feeding device continuously supplied 0.4-mm wire to the laser irradiated molten pool. In Japan, some aging nuclear power plants are in operation over 40 years. Public acceptance has become serious after the Great East Japan Earthquake. We are now proposing to apply our technologies to the maintenance of these aging plants.

8603-33, Session PTue

Research of pulse CO2 laser produced tin plasma

Xingbing Wang, Duluo Zuo, Peixiang Lu, Huazhong Univ. of Science and Technology (China); Tao Wu, Wuhan Institute of Technology (China)

Experiments of pulse CO_2 laser produced tin plasma had been carried out. Time-integrated extreme ultraviolet spectral measurement showed that the peak of the spectrum was located at 13.5 nm. Plasma parameters of electron temperature and density measurements both in axial and radial direction had been performed from a two-dimensional time and space resolved image spectra analysis. We found that the electron temperature near the plasma plume center slightly varied with the increase of the axial or radial distance, which was related to a collisional decoupling and reheating of the ionized species in the plasma. Space averaged electron temperature and electron density were obtained. Debris speed of laser produced plasma in various buffer gas was quantitatively estimated by means of a fast gated intensified charge coupled device imaging system as well as by visible emission spectroscopy. The stopping power of the hydrogen buffer gas was assessed under ambient pressure ranging from 30 to 104 Pa. Time-resolved visible emission spectroscopy showed that thermalizing collisions were responsible for slowing down the fast energetic ions and atoms toward a thermal equilibrium.

8603-34, Session PTue

Fiber profilometer for measurement of hard-to-access areas

Zhuang Liu, Nanyang Technological Univ. (Singapore); Xia Yu, A*STAR Singapore Institute of Manufacturing Technology (Singapore); Qijie Wang, Nanyang Technological Univ. (Singapore); Shawwei Kok, Ying Zhang, A*STAR Singapore Institute of Manufacturing Technology (Singapore)

In many laser processing and cleaning applications, it is required to measure internal surfaces of work pieces or components, such as diesel injectors, gear boxes and bladed disks, which have small opening holes or channels. Traditionally, people utilized replication method to reconstruct features of these internal surfaces. The replication is a kind of indirect measurement, and is destructive to the components. A non-destructive direct technique is then demanded for measurement of hard-to-access areas.

In this paper, we present a fiber-based profilometer by using low coherence interferometry technique. A miniaturized probe is fabricated though integration of a single-mode fiber, a GRIN lens and a prism mirror. The probe can be brought into internal spaces of components to inspect the surfaces. Through modulating length of the reference arm, the interference between beams reflected from sample surface and reference mirror is detected by a photo-detector. The relative height of the surface could be recovered from the interference signal. In addition, the fiber profilometer can detect cracks on sample surfaces. Unlike surfaces that reflect light, the cracks scatter light in various directions. The probe is designed to have a high numerical aperture to enhance collection efficiency of light from sample's surfaces.

The developed fiber profilometer has advantages of non-destructiveness, high resolution, flexibility, low cost, and capability of crack detection. It has been applied to measure calibration samples and a metallic cylinder. The results recover profiles of respective samples, and the roughness of the surfaces can be quantified. A micro-meter level resolution is achieved. Thus, the fiber profilometer is a promising technique for various applications, such as in aerospace and semiconductor industries.

8603-35, Session PTue

Effect of laser welding parameters on impact and tensile strength for dissimilar metals joint

Dhia A. Azawi, Dublin City Univ. (Ireland)

ABSTRACT

Joining of dissimilar materials by laser technique became challenging task in engineering industries for both technical and economic reasons. The adoption of dissimilar-metal combinations provides possibilities for benefiting from the mechanical properties of each material in a functional way. In this study, high power CO_2 laser was employed to investigate the weld properties of dissimilar metals (316L stainless steel and AISI1010 carbon steel) in its proper prospective. The joint between austenitic stainless steel and ferritic steel of low carbon content was selected due to the extensively utilization in automotive applications. This paper presents the effect of different levels of laser powers namely (1, 1.25 and 1.5 kW), specimen scanning speeds (500,750 and 1000mm/min) and focal point positions of (-1, -0.5 and 0) on the toughness and tensile strength. L9 Taguchi method was used to develop models to predict the relationship between the processing parameters and the responses. Evidently, the results identify the optimal combinations of the laser welding input variables to obtain superior laser weld joint with excellent mechanical properties. Development of linear and quadratic polynomial equations was built up to predict the impact and tensile strength for the joint zone. However, the results showed that the proposed models predict the responses adequately within the limits of welding parameters being used

8603-36, Session PTue

High-speed laser ablation cutting of metals

Frank Ullmann, Lars Hartwig, Hochschule Mittweida (Germany); Daniel Szczepanski, Otto-von-Guericke-Univ. Magdeburg (Germany); Joerg Schille, Stefan Gronau, Tommy Knebel, Jan Drechsel, Udo Loeschner, Robby Ebert, Horst Exner, Hochschule Mittweida (Germany)

In laser ablation cutting, irradiation of high-intense laser beams lead to ejection of molten and evaporated material out of the cutting zone as a result of high pressure gradients, induced by expanding plasma plumes. This paper investigates highspeed laser ablation cutting of industrial grade metal sheets using high brilliance continuous wave fiber lasers with output powers up to 5 kW. Scan speeds up to 50 m/s were applied utilizing both a fast galvanometer scan system and a polygon scan system. High peak intensities were obtained by sharp beam focusing using different objectives with focal lengths between 160 mm and 500 mm. As a result focal spot diameters ranging between 16 µm and 60 µm were obtained, providing peak intensities between 8*108 W/cm? and 2.5*109 W/cm?, respectively.

In the study the impact of the processing parameters laser power, focal spot diameter, cutting speed, number of scans, and focal plane position relative to the metal surface on both the achievable cutting depth and the cutting edge quality was investigated. The cutting depths, the heights of the cutting burr, as well as the removed material volumes were evaluated by means of digital optical microscope images and cross section photographs. As a result, up to 1.5 mm deep cutting gaps were produced. Finally highspeed laser ablation cutting was studied using an intensified ultra highspeed camera in order to discuss mechanism and phenomena occurring in laser matter interaction.

8603-37, Session PTue

Energy characteristics of cutting of thick steel sheets by a CO2 and fiber laser

Anatoly M. Orishich, Alexander G. Malikov, Victor B. Shulyatyev, Aleksandr Golishev, Khristianovich Institute of Theoretical and Applied Mechanics (Russian Federation)

At the present moment, fiber lasers have demonstrated their high effectiveness in the cutting of thin metal sheets. However, ??2 laser is the best when the high-quality cutting of thick sheets is needed. This report presents the results of the experimental investigation of the interaction between energy and mechanical characteristics of the laser cut for thick sheets in the same condition for CO 2 and fiber laser. The target is to optimize the energy consumptions in of the process of high-quality oxygen and nitrogen assisted gas laser cutting of low-carbon and stainless steel . This task is especially urgent because the efficiency of the ??2-laser is considerably lower than in the case of fiber or disc laser.

The energy balance is measured for the optimal cutting parameters. The cutting mode which results in the minimal surface roughness is optimal. Processing of substantial experimental material enabled to obtain dimensionless criteria governing the high quality of the cut. It is established that as the sheet thickness is 5…25 mm, the roughness is minimum under the condition of Pe = const, Pe is the Peclet number. At the optimum Peclet number we defined experimentally: the laser absorption energy, energy of oxidation reaction and thermal conductivity losses per a unit of sheet thickness. The absorption coefficient was measured during the cutting for CO 2 and fiber laser (oxygen and nitrogen assisted gas).

The obtained results permit to estimate the maximum thickness of the sheet on which the qualitative cutting can be done, as well as the laser power needed to do this cutting.

8603-38, Session PTue

The effect of hardening on ablation rate in aluminum alloys (zeolites) and crater profile development analogized with meteorite craters

Osama M. Khalil, NILES (Egypt)

In laser ablation the laser parameters, material properties, and ambient conditions affect the ablation rate. At high laser intensity the ablated material efficiently attenuates the incoming laser radiation, called plasma shielding, so reduces the ablation rate. In other words the plasma formation limits the ablation rate at high flounces due to absorption of the incident beam by the plume. The ablation depth decrease with the increase of hardness but the fantastic case is that we have strong material with low density and naturally low weight. The decreasing in ablation rate, in other words the saturation of the ablation with respect to power increment is observed in many literatures because of plasma shielding effect, but the new observation is the small increase in ablation rate after the simple crater rim decrease with power increment. This observation hadn't been noticed in the theoretical computer model which simulates the ablation process. It has been proved that there is a direct analogy between the cases when a material macroparticle impacts with a high velocity onto a solid target, and the case when a powerful laser pulse irradiates a similar target [9]. The experimental results indicate that the development of craters in aluminum alloy (Zeolites) with time give a very good analogy with natural meteorite craters, so craters produced from laser-aluminum interaction can simulate the natural meteorite craters creation process.

8603-8, Session 3

Essential building blocks for a flexible approach to laser source design *(Invited Paper)*

Jochen Deile, TRUMPF Inc. (United States); Jochen Doberitzsch, TRUMPF Laser- und Systemtechnik GmbH (Germany)

During the first 20 years of TRUMPF's existence as a laser company, it developed a reputation for standard products for applications, now referred to as the traditional industrial applications: laser cutting and welding of steel and aluminum. During the same time, TRUMPF acquired five basic technology platforms – fast flow and diffusion cooled CO2 lasers, thin disk, diode and fiber lasers.

The standard products cover only a small section of the multi-dimensional parameter space that can be covered with these five basic technologies. These platforms, however, provide enormous flexibility and highly reliable building blocks that are now used to fill white areas in the parameter space, enabling novel applications unrelated to the original applications for these technologies.

Presented are some examples of how the scaling of these technologies has led to unique and novel laser devices and applications. They include the generation of EUV with CO2 lasers, short-pulse applications with diffusion cooled and fast flow CO2 lasers for processing of composite materials and plastics. Laser output power, the traditional main characteristic for CO2 lasers, made way for pulse energies, pulse lengths and wavelength. The traditional cw thin disk laser platform was transformed into short and ultra-short pulse lasers with wavelengths down to 343 nm. Diode lasers evolved from low brightness pump sources for thin disk lasers to diode direct lasers.

This flexibility will ensure that remaining white spaces in the parameter space can be filled in the future as required.

8603-9, Session 3

Fiber lasers based on beam quality converters for diode lasers

Charley Bachert, Georg Rehmann, Axel Luft, Merlin Gerber, Anne Krause, Jihui Song, Volker Krause, Laserline GmbH (Germany)

Fiber laser based brightness converters enable diode laser beam sources to access a superior beam quality of better than 10 mm x mrad in combination with multi kW output power. A design of a fiber laser that is based on a single active optical converter fiber that is pumped by a direct diode is presented. Due to the high transfer efficiency of such brightness converters an electrical/optical efficiency > 25% can be achieved. The current status with an output power > 4 kW in combination with a beam quality of < 5 mm x mrad will be described. The principal design of such

diode laser based fiber brightness converters will be presented and building blocks of such lasers will be outlined.

Lifetime expectation for the fiber laser brightness converters will be presented and compared to direct diode lasers. Long term stability of both laser types will be shown.

As an application example laser welding will be presented of both the fiber converter laser and direct diode laser using optical light guides with identical core diameters on both lasers for comparison. Additionally fibers with a core diameter of 100/200µm will be used on the fiber converter laser to perform remote welding. The weld results will be compared regarding welding depth, gas pores, spillings and stability of the weld to determine the optimum power/brightness levels for different aluminum and steel materials.

8603-10, Session 3

Disk technology enables next generation micromachining laser sources

Oliver H. Heckl, Severin Luzius, TRUMPF Laser- und Systemtechnik GmbH (Germany); Dirk H. Sutter, TRUMPF Laser GmbH & Co. KG (Germany); Sascha Weiler, TRUMPF Inc. (United States)

Ultrashort pulsed lasers based on thin disk technology have entered the 100 W regime and deliver several tens of MW peak power without chirped pulse amplification. Highest uptime and insensitivity to back reflections make them ideal tools for efficient and cost effective industrial micromachining.

On one hand, thin disk oscillators deliver more than 30 MW peak power directly out of the resonator in laboratory setups. These peak power levels are made possible by recent progress in the scaling of the pulse energy in excess of 40 µJ. In these high pulse energy regimes, thin disk technology profits from the limited amount of material and hence the manageable nonlinearity within the resonator. Using new broadband host materials like for example the sesquioxides will eventually reduce the pulse duration during high power operation and further increase the peak power.

On the other hand industry grade amplifier systems deliver even higher peak power levels and enable efficient micromachining of glasses, ceramics or sapphire.

Conventional laser cutting of these materials often requires UV laser sources with pulse durations of several nanoseconds and an average power in the 10 W range. Material processing based on high peak power laser sources makes use of multi-photon absorption processes. This highly nonlinear absorption enables micromachining driven by the fundamental (1030 nm) or frequency doubled (515 nm) wavelength of Yb:YAG. Operation in the IR or green spectral range reduces the complexity and running costs of industrial systems initially based on UV light sources.

8603-11, Session 3

Fiber laser performance in industrial applications

Stuart McCulloch, Andrew Hassey, Paul Harrison, SPI Lasers (United Kingdom)

Medium powered CW fiber lasers in application areas such as high speed cutting of thin section metal sheet, precision welding and generative manufacturing technologies are pushing boundaries . This is due to key features of high reliability and stability, outstanding beam quality and advanced power modulation which leads to greater process control and high repeatability. These laser systems have the flexibility to address ever-changing application needs, delivering machine “up-time” cost savings of up to 50 percent, allowing faster development turn-times and increased capacity. This paper focuses on application areas where the 500W fiber laser has excelled, particularly cutting and welding, demonstrating significant benefits over other laser and non-laser processes. Data has been gathered from extensive testing in the SPI application labs along with results from real world applications that have successfully produced millions of components across the globe.

8603-12, Session 4

Induction of engineered residual stresses fields and enhancement of fatigue life of high reliability metallic components by laser shock processing *(Invited Paper)*

José Luis Ocaña, Juan Antonio Porro, Marcos Díaz, Leonardo Ruiz de Lara, Carlos Correa, Andrea Gil-Santos, Univ. Politécnica de Madrid (Spain)

Laser Shock Processing (LSP) is consolidating as a competitive alternative technology to classical treatments for the improvement of surface properties of metallic alloys involving the fatigue life of critical components. On the basis of laser sources able to provide intensities exceeding the GW/cm2 level, the LSP technology is aimed to be developed from an industrial point of view for the improvement of the fatigue cracking resistance and other surface properties of materials used in the aerospace, nuclear, biomedical and automotive applications, such as Aluminum and Titanium alloys and different types of stainless steel. This confers the LSP technique a clear character of sustainability-supporting technique as far as the whole life cycle of critical components in the referred sectors is considered.

However, as a consequence of the inherent physical complexity of LSP processes, specially stemming on the coexistence of different material phases (including plasma) developing and interacting under the action of the high intensity laser beam, very limited attempts have been developed in the way of full comprehension and predictive assessment of the characteristic physical processes and material transformations with a specific consideration of real material properties. This particular situation, not very common in classical high power laser applications, poses the need for the development of comprehensive analysis and prediction tools enabling an integrated comprehension of the physical phenomena developing in the process and their mutual interrelations.

In this paper, predictive assessment and experimental results on the residual stress profiles created under different irradiation conditions are presented along with the associate effects on characteristic material surface properties. Based on the analysis of these results, experimental guidelines are obtained about the presumable degree of protection provided by the LSP treatment against mechanical failure and the corresponding life extension expectations.

8603-13, Session 4

Lasers and applications in parts cleaning and surface pretreatment

Till Schneider, TRUMPF Laser- und Systemtechnik GmbH (Germany); Thomas Burdel, Sascha Weiler, TRUMPF Inc. (United States); Birgit Faisst, Oliver H. Heckl, TRUMPF Laser- und Systemtechnik GmbH (Germany); Jörn Birkel, TRUMPF Maschinen Grüsch AG (Switzerland); Severin Luzius, TRUMPF Laser- und Systemtechnik GmbH (Germany)

A number of upcoming industrial applications prove that the laser offers great possibilities for parts cleaning and surface pretreatment. Thereby laser technology enables new solutions to reduce production costs and to increase productivity and quality in the manufacturing process. Examples are the removal of oil, grease, phosphate layers or corrosion with the laser.

This paper will focus on parts cleaning and surface pretreatment applications within the automotive industry. From a range of examples it will be shown that the laser not only offers advantages to carry out the

described production step (such as cleaning or the creation of functional textures) but also offers great advantages for a following production step within the chain, such as a welding or gluing process.

It will be demonstrated that several ns and ps laser sources and systems can be selected, depending on the application.

8603-14, Session 4

An exhaustive model for the laser hardening of hypo eutectoid steel

Alessandro Fortunato, Univ. degli Studi di Bologna (Italy); Leonardo Orazi, Gabriele Cuccolini, Univ. degli Studi di Modena e Reggio Emilia (Italy); Alessandro Ascari, Univ. degli Studi di Bologna (Italy)

The paper presents a new and efficient model for surface hardening of hypo eutectoid steels. The aim of the work is to develop a fast and accurate process simulator able to predict the micro structures and the hardness resulting from a laser surface hardening. Laser surface hardening of hypo eutectoid steels is a quite different and more complex process if compared to conventional heat treatment in furnace because heating is very fast and the high cooling rate is obtained by means heat conduction into the bulk. According to these peculiarities, micro structures transformations are subjected to high delay time. Moreover multitrack laser trajectories required to treat surfaces larger than the laser spot leads to tempering effects that depends on the overlapping of two close trajectories. These softening effects are defects that have to be contained. A process simulator capable to optimize the process parameters, such as laser power and speed and the number and the types of trajectories, could sensibly increase the applicability of the process if the model is, in the same time, fast and accurate. In this paper the authors present their model for the complete processes simulation.

8603-15, Session 4

Laser shock peening and warm laser shock peening: process modeling and pulse shape influence

Alessandro Fortunato, Univ. degli Studi di Bologna (Italy); Leonardo Orazi, Gabriele Cuccolini, Univ. degli Studi di Modena e Reggio Emilia (Italy); Alessandro Ascari, Univ. degli Studi di Bologna (Italy)

Laser shock peening (LSP) is a well-known technology able to enhance the fatigue life of mechanical components. Surface residual stress is induced by means of the recoil pressure of an ablated coating in a confining medium interacting with a high power density laser. Warm Laser Shock Peening (WLSP) is obtained by laser peening a pre-warmed workpiece surface: combining the thermal effect of the pre-heated surface and the mechanical phenomenon of the recoil shock pressure, the dynamic aging of the surface microstructure is obtained. In order to develop an efficient and accurate process simulator, the recoil pressure prediction is the key factor. Recoil pressure, in turns, manly depends on the power per pulse value and distribution. In this paper the influence of the pulse shape on the process modeling is presented in LSP and WLSP.

8603-16, Session 4

CO2-laser-assisted processing of glass fiber-reinforced thermoplastic composites

Joffrey Stimpfl, Fraunhofer-Institut für Produktionstechnologie (Germany); Christian Brecher, Michael Emonts, Fraunhofer-Institut für Produktionstechnologie (Germany); Richard Ludwig Schares, Fraunhofer Institute for Production Technology IPT (Germany)

To fully exploit the potential of fiber-reinforced thermoplastic composites (FRTC) and to achieve a broad industrial application, high precision manufacturing systems are crucial. Furthermore investigations at Fraunhofer IPT have proven that the use of laser system technology in processing FRTC enables to achieve high throughput, quality, flexibility, reproducibility and out-of-autoclave processing simultaneously. Due to this and the fact that currently more than 90% of the fiber-reinforced plastics (FRP) in Europe are glass fiber-reinforced the next logical step to maximize the potential of laser-assisted processing is its extension towards glass fiber-reinforced thermoplastics (GFRTC).

For years Fraunhofer IPT has developed the diode laser-assisted tape placement (laying and winding) to process carbon fiber-reinforced thermoplastic composites (CFRTC). Unfortunately this technology cannot be transferred one to one to process milky transparent GFRTC prepregs (preimpregnated fibers). Due to the short wavelength (approx. 980 nm) and therefore high transmission less than 20% of the diode laser energy is induced as heat into non coloured GFRTC prepregs unlike using a CO2-laser (10,6 µm) with more than 90% laser absorption. Also the absorption of CO2-laser radiation at the surface compared to volume absorption of diode laser radiation is beneficial for the interlaminar joining of GFRTC. Fraunhofer IPT is currently developing and investigating the CO2-laser-assisted tape placement including new system, beam guiding, process and monitoring technology to enable a resource and energy efficient mass production of GFRP composites, e.g. pipes, tanks, masts. The successful processing of non coloured glass fiber-reinforced Polypropylene (PP) and Polyphenylene Sulfide (PPS) has already been proven.

8603-17, Session 5

Characterization of disk-laser dissimilar welding of titanium alloy Ti-6Al-4V to aluminum alloy 2024 *(Invited Paper)*

Vincenzo Sergi, Fabrizia Caiazzo, Vittorio Alfieri, Univ. degli studi di Salerno (Italy)

Both technical and economic reasons suggest to join dissimilar metals, benefiting from the specific properties of each material in order to perform flexible design. Adhesive bonding and mechanical joining have been traditionally used although adhesives fail to be effective in high-temperature environments and mechanical joining are not adequate for leak-tight joints. Friction stir welding is a valid alternative, even being difficult to perform for specific joint geometries and thin plates. The attention has therefore been shifted to laser welding.

Interest has been shown in welding titanium to aluminum, especially in the aviation industry, in order to benefit from both corrosive resistance and strength properties of the former, and low weight and cost of the latter.

Titanium alloy Ti-6Al-4V and aluminum alloy 2024 are considered in this work, being them among the most common ones in aerospace and automotive industries. Laser welding is thought to be particularly useful in reducing the heat affected zones and providing deep penetrative beads. Nevertheless, many challenges arise in welding dissimilar metals and the aim is further complicated considering the specific features of the alloys in exam, being them susceptible to oxidation on the upper surface and porosity formation in the fused zone.

As many variables are involved, a systematic approach is used to perform the process and to characterize the beads referring to their shape and mechanical features, since a mixture of phases and structures is formed in the fused zone after recrystallization.

8603-18, Session 5

Laser welding of dissimilar materials for lightweight construction and special applications

Stefan Kaierle, Mitja Schimek, André Springer, Ronny Pfeifer, Volker Wesling, Laser Zentrum Hannover e.V. (Germany)

Against the background of politically-motivated climate objectives and the reduction of CO2 emissions, it is necessary to optimize existing industrial processing.

In order to counter the rising costs of raw materials, substitute materials must be found. This in turn means that new joining technologies for dissimilar materials must be investigated. The principal difficulty is to join these materials cohesively without changing the properties of the base materials. Current research work at the Laser Zentrum Hannover e.V. (LZH) concentrates on joining dissimilar materials for the automotive sector, for solar absorber production and for vacuum-sealed enclosures, in which highly sensitive electronics and sensor technologies must be protected.

For the automotive industry, a laser welding process to join steel and aluminum without the use of additives, but with a spectroscopic welding depth control to increase tensile strength, is currently being investigated. By using spectroscopic welding depth control, tensile strength can be increased. With a specially constructed laser processing head, it is possible to control penetration depth in aluminum, reducing the formation of intermetallic phases.

Flat-plate solar collectors are used for solar heat collection. The central part of the collector is the solar absorber, which consists of copper tubing fixed onto an aluminum sheet. Research on new laser welding processes aims at reducing the energy required for the production of these solar absorbers.

Furthermore, high-vacuum-sealed enclosures are needed for special applications. The main focus of the research at the LZH lies on the optimization of a joining process for aluminum, nickel-based alloys and copper. Investigations, to ensure a high vacuum seal, are being carried out using different laser joining techniques (welding, brazing and braze-welding).

In the field of joining dissimilar materials, laser joining processes, in particular for special applications, can be used to complement established joining techniques.

8603-19, Session 5

Challenges and solution for copper welding with laser

Uwe Kriegshaeuser, TRUMPF Laser- und Systemtechnik GmbH (Germany)

The global demand for copper still remains high. The applications of new technologies in the sectors renewable energy, traffic and transport, mechanical engineering or electronics leads to an increasing usage of copper.

Copper has a superior ability for efficient transmission of electrical energy and signals – therefore copper is one of the most suitable materials.

Due to the specific physical abilities like the high heat conductivity, the low absorption and hence the high reflection copper is posing high challenges to the welding process. Additionally different materials and different cross sections raise the number of technical challenges in the welding process.

Laser welding has got a strong position in the market for welding of copper, because of the high beam intensity and the high beam quality.

The presentation will discuss challenges and suitable solutions of laser welding for copper.

8603-20, Session 5

High speed laser welding of steel using a high power single mode continuous wave fiber laser

Udo Loeschner, Jan Drechsel, Sascha Schwind, Lars Hartwig, Joerg Schille, Horst Exner, Peter Hübner, Andreas Eysert, Hochschule Mittweida (Germany)

Since a few years, high brilliance laser sources find their way into laser material processing. Laser micro processing by applying high brilliance laser radiation up to 3 kW of continuous wave laser power in combination with ultrafast beam deflection systems has been successfully demonstrated at our institute in 2008 for the first time. In the fields of laser welding, high brilliant laser radiation was mainly used for micro welding applications, but up to now in the macro range it is still insufficiently investigated.

Hence, this study reports on detailed investigations of high speed laser welding of different steel grades, performed with a high power single mode fiber laser source. The laser beam was deflected relative to the sample by using both a fast galvanometer scanner system with f-theta focusing objective and a linear axis in combination with a welding head, respectively. In the study, the mainly process influencing parameters such as laser power, welding speed, thickness of the metal sheets, and laser beam spot size were varied in a wide range. The weld seam quality was evaluated by structural analyses, static tensile tests, and EDX measurements. Finally, the laser welding process has been optimized for different weld seam geometries, for example butt welds and lap welds.

8603-21, Session 5

Process characteristics of laser beam welding at reduced ambient pressure

Christian Boerner, Klaus Dilger, Technische Univ. Braunschweig (Germany)

Depending on the process parameters and the thickness of the metal sheet, spatters can occur when welding with solid-state lasers, thus reducing the quality of the weld seam. Mainly at high feed rates, the formation of spatters increases strongly when using solid-state lasers.

The reduced ambient pressure primarily leads to a modification of the vapor plume typical for laser beam welding with the solid-state laser. A slight pressure reduction already effects a visibly smaller form of plume and results in a significant reduction of the number of spatters. The plume and the splattering disappear completely at a pressure of 10 hPa. On the surfaces of the welded components, no adherent splatters can be found, especially with high feed rates. On sheets with thicknesses of 3 mm, the notches occurring in a penetration welding could also be avoided by applying a reduced pressure.

In addition, further characteristics arise in the quality of the weld seam. With the same process parameters, the reduction of the pressure effects an increase of the penetration depth and a distinctive modification of the seam geometry. With a laser power of 6 kW, partial penetration welding with a depth of 25 mm was achieved in a large vacuum at 10 hPa.

Due to the reduced pressure, weld seams are formed which, as regards quality, are comparable to electron beam weldings. Mild steel with a thickness of 10 mm was successfully welded with a laser power of 6 kW and a feed rate of 2 m/min, with a remarkable seam quality without any irregularities. Another advantage of weldings produced with the laser at reduced pressure is the possibility of avoiding a sagging of the seam in thick sheets. Despite excessive energy and power, no geometric irrgeluarities are identified in the cross section. Under atmospheric pressure, the high excess of power would lead to an intense seam collapse.

8603-22, Session 5

Advanced welding techniques with optimized accessories for high brightness 1 µm lasers

David L. Havrilla, TRUMPF Inc. (United States); Volker Rominger, Thomas Harrer, Andrey Andreev, Marco Holzer, TRUMPF Laser- und Systemtechnik GmbH (Germany)

Within the past couple of years one can see several trends in laser material processing. On the one hand optimized application results necessitate advancements of the equipment as e.g. laser sources, laser light cables and focusing optics. On the other hand the optimization of the application results due to a very good process understanding and optimized accessories is indispensible.

This paper will link the gained process understandings e.g. in high power welding based on modern process diagnostic methods to an optimization of accessories. We will show an example on the influence of the metal vapor plume to the achieved welding results and present a component allowing more constant welding results regarding surface quality and penetration depth. The second part of the paper will focus on the latest advances in remote scanner processing.

8603-23, Session 5

Numerical and experimental evaluation of Nd:YAG laser welding efficiency in AZ31 magnesium alloy butt joints

Leonardo Daniele Scintilla, Luigi Tricarico, Politecnico di Bari (Italy)

In this paper, aspects related to the efficiency of laser welding process using a Nd:YAG laser of maximum power of 2 kW were investigated and reported. AZ31B magnesium alloy 3.3 mm thick sheets were butt-welded without filler using Helium and Argon as shielding gases. The effect of processing parameters including laser power and welding speed was studied using numerical simulations, optical microscopy and morphological analysis. Starting from the power balance equation, welding efficiency was defined basing on melting efficiency and absorption coefficient. In this way the energy losses in the material by conduction, convection and radiation, and losses by reflection at the surface that depends on the absorption coefficient were taken into consideration. Experiments were carried out to measure the morphological parameters of laser weld beads and to calibrate numerical model. A three-dimensional and semi-stationary finite element model was developed to simulate the thermal history of magnesium alloy during laser beam welding and to calculate the absorbed power by integrating the total heat input in the workpiece. The applied thermal load depends on process parameters such as laser power, laser beam dimensions, intensity distribution and welding speed. Within the range of process parameters investigated, it is possible to estimate the absorption coefficient and thus to calculate the welding efficiency.

8603-24, Session 5

Corrosion performance of laser-welded austenitic-ferritic connections

Markus Weigl, Michael H. Schmidt, BLZ Bayerisches Laserzentrum GmbH (Germany)

In order to reduce the material costs of white-goods made of stainless steels, such as washing machines and dishwashers, tailored constructions with unequal alloyed materials shall be used. In particular nickel-alloyed austenitic stainless steels are supposed to be limited to zones with demanding needs for corrosions resistance, whereas nickel-free ferritic stainless steels provide an attractive cost-performance ratio for the remaining components of a system. For an adequate long-term stability of the required austenitic-ferritic connections at stainless steels, the welding areas have to feature at least the chemical resistance of the less durable base material.

In this context the present article discusses the corrosion performance of austenitic-ferritic connections, welded with high-power disc lasers at accelerated feed rates, as a function of the base material alloying, the energy input per unit length and the surface condition. Regarding the chemical composition of the base materials primarily the influence of a molybdenum-alloying on the element intermixture and the corrosion behavior will be analyzed. Further more it will be shown, that a significant gain in chemical resistance can be reached by decreasing the energy input also at dynamic laser welding processes. This effect is mainly caused by preventing immoderate segregations at the grain boundaries, which would come along with a sensitization for especially inter-crystalline corrosion. Finally a correlation between the surface topology, i. e. annealing colors and geometrical imperfections, of laser-welded mixed joints and the corresponding time duration till first corrosion works out the importance of an adequate surface condition for long-term stable connections.

8603-25, Session 6

Hyperspectral and gated ICCD imagery for laser irradiated carbon materials

Glen P. Perram, Charles D. Roberts, Michael A. Marciniak, Air Force Institute of Technology (United States)

New optical diagnostics for studying laser ablation and induced combustion for carbon materials are key to monitoring the evolving, spatial distribution of the gas plume. We are developing high speed imaging FTIR and gated ICCD imagery for materials processing, manufacture process control, and high energy laser applications. The results from two projects will be discussed. First, excimer laser pulsed ablation of bulk graphite into low-pressure (0.05 -1 Torr) argon generates highly ionized, high speed (M>40) plumes. A gated, intensified CCD camera with band pass filtering has been used to generate plume imagery with temporal resolution of 10 ns. The Sedov-Taylor shock model characterizes the propagation of the shock front if the dimensionality of the plume is allowed to deviate from ideal spherical expansion. A drag model is more appropriate when the plume approaches extinction (~10 μs) and extends the characterization into the far field. Conversion of laser pulse energy to the shock is efficient. Second, an imaging Fourier Transform Spectrometer with a 320 x 256 InSb focal plane array frames at 1.9 kHz with a spatial resolution of 1 mm and spectral resolution of up to 0.25 cm-1. Gas phase plumes above the surface of laser-irradiated black plexiglass, fiberglass and painted thin metals have been spectrally resolved. Molecular emission from CO, CO2, H2O, and hydrocarbons is readily identified. A line-by-line radiative transfer model is used to derive movies for specie concentrations and temperatures.

8603-26, Session 6

Online characterization of laser beam welds by NIR-camera observation

Friedhelm Dorsch, Holger Braun, Steffen Kessler, Dieter Pfitzner, TRUMPF Werkzeugmaschinen GmbH + Co. KG (Germany); Volker Rominger, TRUMPF Laser- und Systemtechnik GmbH (Germany)

We have investigated process monitoring of laser beam welding with a TruDisk thin disk laser to detect process faults. Additionally to monitoring laser beam welding processes by a conventional VIS camera an NIR (near-infrared) camera reveals new information. Our sensor detects thermal radiation between 1200 and 1700 nm from the weld zone, which represents surface temperatures above 1000 K. Using the thermal radiation from the process we can observe the weld pool and the hot seam without auxiliary illumination.

The camera is integrated in a standard TRUMPF welding optics for

on-axis observation. A real-time image processing system analyzes the camera images regarding welding irregularities and delivers information to characterize the weld process and its result. Actually, we perform an online passive heat-flow thermography that uses the process itself as the heat source and that probes the thermal attributes of the seam. By this means we can detect regions of bad fusion ("false friends") virtually during the welding process.

8603-27, Session 6

Inline coherent imaging applied to high power laser processing

Paul J. Webster, Queen's Univ. (Canada) and Laser Depth Dynamics, Inc. (Canada); Alison W. Kinross, Cole P. Van Vlack, Logan G. Wright, Christopher M. Galbraith, Yang Ji, James M. Fraser, Queen's Univ. (Canada)

Inline Coherent Imaging (ICI) is an emerging technique for direct, real-time observation of depth in laser processes such as welding, cutting, drilling, cladding and coating ablation. ICI opens a unique window into process dynamics with micron-scale depth resolution and > 300 kHz measurement rates. Imaging light is combined coaxially with the process beam resulting in a greater aspect ratio tolerance than triangulation approaches can achieve. Coherent detection provides >90 dB sensitivity, >60 dB dynamic range and renders ICI impervious to blinding from blackbody radiation and the process beam. The technique involves no ionizing radiation, is applicable to virtually any material/laser source and is not restricted to any particular material geometry. Together with these qualities, the hardware simplicity of ICI is consistent with practical applications in production environments.

In this work, we present the first integration of ICI into a kW-class welding and cutting station via a single fiber connection to the camera port of an off-the-shelf welding head. ICI's results are validated against gold-standard methods, confirming ICI's capability for directly and accurately measuring weld depth without laborious destructive testing. Real time monitoring of depth allows for optimized pierce times, immediate remediation of failed welds and/or part rejection. In addition to bead-on-plate studies, we can directly measure top sheet perforation and the gap between parts in lap welding. Finally, using the next generation of real-time automatic feedback control from ICI, we ablate arbitrary topologies into complex and heterogenous materials without the need for extensive process development.

8603-28, Session 7

Advancement of diode lasers and their applications *(Invited Paper)*

Stefan W. Heinemann, Torsten Schmidt, DirectPhotonics Industries GmbH (Germany); Silke Pflueger, DirectPhotonics Industries GmbH (United States)

The brightness of diode lasers is improving continuously and has recently reached the level of some solid state lasers. Power densities at the work piece exceed 1MW/cm2 with industrial practical focus optics. These power densities are sufficient for materials ablation. Single emitter based diode laser system further offer the advantage of fast current modulation due their lower drive current compared to diode bars.

We report on a single emitter based diode laser system with an average power in excess of 200W and a minimum pulse duration of 1?s. The pulse duration and repetition rate are adjustable up to continuous operation. Spot sizes of less than 100?m are obtained at the work piece. Such a diode system allows materials processing with a pulse parameter range that is hardly addressed by any other laser system.

We will present various materials processing applications to include, removal of thin films at high speed, paint removal and drilling. High productivity drilling requires pulse lengths of several microseconds that cannot be obtained with other laser systems. The unique pulsing capabilities and high brightness of our diode laser system together with its shorter wavelength enable efficient ablation processes. Details of the system and hole drilling in silicon will be discussed, which represents the first application ever of diode lasers for drilling to our knowledge.

8603-29, Session 7

Laser cutting of lightweight alloys sheets with 1-µm laser wavelength

Leonardo Daniele Scintilla, Luigi Tricarico, Politecnico di Bari (Italy)

New high power disk and fiber laser sources, with a radiation wavelength equal to 1 µm, offer a great potential in improving the productivity and quality of thin lightweight alloys sheets cutting phase. This is due to their benefits that are of special interest for this application: power efficiency, beam guidance and beam quality. High-power fiber and disk lasers demonstrate to be a valid and reliable alternative heat source with respect to the most established laser beam sources for laser cutting represented by the CO2 laser systems.

In this work, several problems that emerge during laser cutting aluminium, magnesium and titanium alloys are presented and the advantages of using 1 µm laser wavelength are demonstrated. The phenomena that for different reasons affect the laser manufacturing of these materials like the formation of a heat affected zone, the chemical contamination, the change of corrosion resistance, the high thermal reactivity, the negative effect of high conductivity, reflectivity and high viscosity of molten material, were taken into consideration and investigated. The influence of processing parameters and laser wavelength on lightweight alloys sheets up to 3mm was experimentally investigated and cutting performances in terms of cutting quality, processing speeds and severance energies were evaluated.

Results showed that productivity, process efficiency and cutting edges quality obtained with 1µm wavelength open up new solutions for cutting lightweight alloys for applications like coil sheet cutting, laser blanking, trimming thanks to high productivity and easily installation of the cutting head on different movement systems.

8603-30, Session 7

On laser beam cutting of metallic hollow sphere structures

Harald Riegel, Markus Merkel, Joerg Fruhstuck, Rolf Winkler, Hochschule Aalen (Germany); Andreas Oechsner, Univ. Teknologi Malaysia (Malaysia)

Metallic hollow sphere structures (MHSS) represent a group of advanced composite materials. They are characterised by high geometry reproduction leading to relatively constant mechanical and physical properties. Therefore MHSS combine the advantages of cellular metals without major scattering of their material parameters. Various joining technologies such as sintering, soldering and adhering can be used to assemble single metallic hollow spheres to interdependent structures and allow adjusting of different macroscopic properties.

A cutting process for MHSS has to reflect the special characteristic of the composite material. In this paper laser beam cutting is presented as a highly efficient technique. The relatively small amount of heat being involved during the process results in a small heat affected zone. All investigations were done with MHSS having different macroscopic dimensions (length, width, thickness). The experimental work was done by a CO2-laser. Numerical simulation (Finite Element Method) was used to predict heat flux and temperature level for different geometric parameters of the spheres (diameter, wall thickness). The numerical simulation allows a detailed analysis of the physical process in the zone that is influenced by the laser beam and which can hardly be analyzed by measuring technique. The models for the static and transient FE-analysis consider heat conduction, radiation and convection.

8604-1, Session 1

A narrow-band continuous-wave laser source at 191 nm *(Invited Paper)*

Matthias Scholz, Dmitrijs Opalevs, Patrick Leisching, Wilhelm G. Kaenders, TOPTICA Photonics AG (Germany); Guiling Wang, Xiaoyang Wang, Rukang Li, Chuangtian Chen, Beijing Ctr. for Crystal Research and Development (China)

In the ultraviolet, continuous-wave (cw) radiation is commonly produced by second-harmonic (SHG) or sum-frequency generation of visible or near-infrared light sources. Approaching 200 nm, the number of suitable crystals that can mediate the nonlinear interaction is limited, and demonstrations have been mostly done in the pulsed regime. Of all commercially available crystals, beta-Barium-Borate (BBO) can produce the lowest wavelength by a direct SHG process, reaching down to 205 nm. However, operation of BBO below 215 nm becomes challenging since the proximity to its absorption edge around 190 nm leads to enhanced absorption and degradation of the crystal due to the creation of color centers.

The engineering of Potassium Fluoroboratoberyllate (KBBF) and other crystals from the Berylloborate family marked a major breakthrough in the deep-UV generation by direct SHG. With KBBF's absorption edge at around 153 nm, the lowest obtained wavelength to date is 156 nm. An output of nearly 13 mW average power was achieved at 177 nm, the sixth harmonic of the 1064 nm Nd:YAG transition.

While all these experiments were done in the pulsed regime, we aimed at the generation of cw light from KBBF for the first time. To date, the largest achieved crystal extension of KBBF is around 2?3 mm due to the layer structure of KBBF. For fundamental wavelengths shorter than 470 nm, the crystal slab must be embedded between an index matching material to avoid total internal reflection of fundamental and ultraviolet waves at the crystal facets due to its large refractive index. This sandwich structure is usually referred to as a prism-coupled device (PCD).

We generate cw radiation at 191 nm in a two-stage SHG setup. The first conversion process from the initial wavelength of 764 nm to the intermediate wavelength of 382 nm is performed in a commercially available TA-SHG pro by TOPTICA Photonics, generating up to 700 mW. The 382-nm beam acts as the fundamental wave for the nonlinear frequency conversion into the deep-UV. This second frequency doubling stage is realized as a cavity in bow-tie configuration, with the SiO_2 prisms around the KBBF crystal Brewster-cut in the tangential plane while phase-matching was adjusted in the sagittal plane.

More than 1.3 mW of deep-UV power could be generated, and the system passed a first test of its robustness in an 8-hours measurement. By using an extended-cavity diode laser as the fundamental source, a narrow linewidth and tunability of the deep-UV emission could be ensured. We demonstrated a mode hop-free tuning range of 40 GHz around 191 nm which proves the applicability of this cw light source to multiple tasks in spectroscopy. Due to its coherence properties, this light source is thus very promising for multiple applications in both basic research and industry like ARPES, deep-UV metrology, or seeding of excimer lasers.

8604-2, Session 1

Two photon absorption and stimulated Raman scattering in alkali vapor lasers

Glen P. Perram, Jeffrey E. Gallagher, Air Force Institute of Technology (United States)

Diode Pumped Alkali Lasers (DPAL) are being scaled to powers of greater than 1 kW and intensities exceeding 30 kW/cm2. We have demonstrated a pulsed potassium laser with pump intensities of 1 MW/cm2 and efficiency exceeding 10%. At these higher pump intensities, nonlinear processes including two photon absorption and Stimulated Raman Scattering offer alternative wavelengths for these gas lasers. We have observed 1st and 2nd order Stokes and anti-Stokes lasing due to Stimulated Electronic Raman Scattering (SERS) in a potassium cell. When the pump is tuned about halfway between the fine structure levels of the 4 2P state, an efficient hyper-Raman process dominates. Up to 12 mW of red light is produced at a pump input of 232 mW. The threshold for the hyper-Raman process is about 60 mW. This type of laser may be useful for beam propagation experiments where a tunable probe beam spectrally close to the main beam is desired. Two-photon absorption at wavelengths near then DPAL pump transition has also been observed and used to demonstrate lasing in the blue and mid infrared. The transmission of a scanning cw ring laser through a static Rb cell reveals two-photon absorbance of greater than 10%. An absolute determination of the two-photon absorption cross-sections for the Rb 5 2S - 4 2D transitions are reported. The efficiency and operationally feasible of these alternative DPAL wavelengths is assessed.

8604-3, Session 1

Efficient concept generating 3.9 W of diffraction-limited green light with spectrally combined tapered diode lasers

André Müller, Ole B. Jensen, Technical Univ. of Denmark (Denmark); Karl-Heinz Hasler, Bernd Sumpf, Götz Erbert, Ferdinand-Braun-Institut (Germany); Peter E. Andersen, Paul M. Petersen, Technical Univ. of Denmark (Denmark)

Efficient and compact green lasers are of high importance for many applications. Unfortunately, the green power achieved with diode lasers is limited by thermal degradation and beam filamentation at high currents. Therefore the question remains how diode lasers could provide mid-power range, diffraction-limited green light, as required for many biomedical applications?

We propose an efficient concept increasing the power of diode laser systems in the visible spectral range. In comparison with second harmonic generation of single emitters, we show that spectral beam combining with subsequent sum-frequency generation enhances the available power significantly. Combining two 1060 nm distributed Bragg reflector tapered diode lasers (M2 < 5.2), we achieve a 2.5-3.2 fold increase of green light with a maximum power of 3.9 Watts in a diffraction-limited beam (M2 < 1.3). Without any further stabilization the obtained power stability is within ± 2.6 %. The electro-optical and nonlinear conversion efficiencies are 5.7 % and 2.6 %/W, respectively. Due to the intrinsic wavelength stabilization of the diodes we achieve single-mode emission with a side-mode suppression > 15 dB and a spectral width as narrow as 5 pm.

These results increase the application potential of green diode laser systems, for example, within the biomedical field. In order to enhance the power even further, our proposed concept can be expanded combining multiple diode lasers.

8604-4, Session 1

Megawatt peak power UV microlaser

Rakesh Bhandari, Takunori Taira, Institute for Molecular Science (Japan)

Compact, high peak power ultraviolet (UV) lasers are extremely useful for many applications, such as, UV spectroscopy, photolithography, and microprocessing.

However, so far, such applications have been limited by the size, cost and operability of UV lasers. Here, we report the development of a highly efficient UV microlaser that overcomes these limitations.

At the heart of the system is a passively Q-switched Nd:YAG/Cr4+:YAG microchip laser developed by us. This laser uses a 4mm-thick, 1.1 at. % Nd:YAG as the laser crystal and a [110]-cut, 10% initial transmission, Cr4+:YAG for passive Q-switching to obtain a stable, linearly polarized output for efficient frequency conversion. The laser generates a 3 mJ, 13 MW peak power, 230 ps, 100 Hz pulse output at 1064 nm.

The high peak power of the fundamental beam enables us to perform frequency conversion without using any optics before the nonlinear crystals. A specially designed housing for the nonlinear crystals allows 3-axis orientation to achieve high conversion efficiency even in the critical phase matching (CPM) regime.

Using a LBO crystal, we obtain 1.7 mJ, 9.5 MW peak power, 177 ps, 100 Hz pulse output with 70% conversion efficiency. For the fourth harmonic generation we use a BBO crystal, placing it at a position designed to avoid two-photon absorption. We obtain 650 ?J, > 3 MW peak power, < 170 ps, 100 Hz pulses at 266 nm with 41 % conversion efficiency.

This first report of a palm-top size, MW peak power UV microlaser will be useful for many applications.

8604-5, Session 2

Generation of tunable visible picosecond pulses by frequency-doubling of a quantum-dot laser in a PPKTP waveguide

Ksenia A. Fedorova, Univ. of Dundee (United Kingdom); Grigorii S. Sokolovskii, Univ. of Dundee (United Kingdom) and Ioffe Physico-Technical Institute (Russian Federation); Daniil I. Nikitichev, Univ. of Dundee (United Kingdom); Philip R. Battle, AdvR, Inc. (United States); Daniil A. Livshits, Innolume GmbH (Germany); Edik U. Rafailov, Univ. of Dundee (United Kingdom)

Widely tunable compact laser sources emitting light with picosecond pulse duration in the visible spectral region are of considerable interest for various applications, such as biophotonics, photomedicine and laser-projection displays. An attractive method for the realization of portable visible laser sources is frequency-doubling of infrared light in a nonlinear crystal containing a waveguide. In this respect, the wide tunability offered by the quantum-dot external-cavity mode-locked diode lasers (QD-ECMLLs), due to the temperature insensibility and the broad gain bandwidth, is very promising for the development of a tunable visible picosecond source. Such sources can be based on a single laser device and a single crystal waveguide and can be realized by utilization of a significant difference in the effective refractive indices of the high-order and low-order modes in multimode waveguides. This concept enables one to shift the difference between the effective refractive indices of the fundamental and second-harmonic generation (SHG) waves to match the period of poling in a very broad wavelength range.

In this work we show a compact all-room-temperature laser source broadly tunable in the visible spectral region (600 nm - 627nm) in the picosecond regime. The tunable radiation is obtained by SHG in a periodically-poled potassium titanyl phosphate (PPKTP) waveguide using a tunable QD-ECMLL. The maximum SHG output peak power of 3.25mW at 613nm is achieved for 71.43mW of launched pump peak power at 1226nm, resulting in conversion efficiency of 4.55%. The demonstrated concept opens-up a new avenue for an order-of-magnitude increase in the wavelength tuning range for frequency conversion from a single crystal.

8604-6, Session 2

17 ps, 765 and 792.5 nm, MOPA using second-harmonic frequency conversion in a fiber-coupled PPLN bulk mixer

Youngjae Kim, Bryan Burgoyne, Alain Villeneuve Jr., Genia Photonics Inc. (Canada); Karin Wu, Jason Lin, Ryan Lai, HC Photonics Corp. (Taiwan)

Fiber lasers are very robust, versatile and cost-effective sources for many applications including biomedical imaging, diagnostic, chemical sensing and micro machining but they are limited in wavelength, and dp not cover some important wavelengths for biomedical applications between 700-1000 nm. To extend the tuning range, , we propose a fiber based MOPA at 765 nm using SHG in a pigtailed PPMgO:CLN bulk mixer. To pump the SHG mixer, we used our 25 ps tunable C+L band MOPA which delivers 1 W of average power at 80 MHz at 1530 nm. Details of tunable MOPA will be discussed in another paper. The 1 cm long crystal is fiber coupled with a PM 1550 at the input and a PM 680 at the output. The output coupling is estimated at between 40-50% due to the high quality beam profile of the fiber laser. We did the measurements at four repetition rates; 10, 20, 40, and 80 MHz. Maximum SHG power at each repetition rate is 14.2 mW, 15.2 mW, 59 mW and 136 mW, respectively at the fiber pigtail output. Conversion efficiency of 16.5 % was obtained at 80 MHz and it corresponds to 0.072 %/W. Peak power of 80 MHz SHG pulse train reaches 100 W. Pulse width of 765 nm pulse is ~ 17 ps and FWHM of the spectrum is 0.08 nm. Time-bandwidth product indicates the pulse chirp is about 1.2 greater than the transform limit. For applications where fiber solution is not mandatory, by use of collimated output from SHG mixer, we believe we can obtain ~ 50-70% more SHG power. Results for a MOPA at 792.5 nm will also be presented.

8604-7, Session 2

Several watts compact CW green laser head without cooling by using PPMgSLT

Yasuhiro Tomihari, Satoshi Makio, Masayuki Hoshi, Masami Hatori, Junji Hirohashi, Koichi Imai, Hiroshi Motegi, Yasunori Furukawa, Oxide Corp. (Japan)

Several watts compact CW green laser head without any cooling is demonstrated by combining CW fiber laser and PPMgSLT. Since the conventional high power visible laser has huge heat sources at its laser head, it requires air or water cooling. In addition, the optical system, which is mounted this type of head, has sometime problems of optical stability caused by those heat sources from the head. The laser head we demonstrated has three input and output ports of the laser light; fiber input of 1064 nm laser light from CW fiber laser, 532 nm output into free space, and fiber output of residual 1064 nm laser light. The size of laser head was 150mm X 90mm X 44mm (600cc). More than 25W of CW 1064 nm light from single mode fiber was focused into 30mm-long PPMgSLT device operated at 40 degree C. The linewidth of the laser was 0.15 nm at FWHM. 5W of 532 nm light was generated from PPMgSLT. Because of high power durability of PPMgSLT, it could be easily realized several watts of visible light generation by simple single-pass configuration. Residual 1064 nm light was split by harmonic separator and was coupled into large core multi-mode fiber. As a result, there are no remarkable heat sources at the laser head. The stable green light from this head was confirmed without any cooling. Since this configuration doesn't affect any thermal turbulence in surroundings, the stability of the optical system would be improved by using this laser head.

8604-8, Session 2

Pulsed picosecond 766 nm laser source operating between 1-80 MHz with automatic pump power management

Thomas Schönau, Torsten Siebert, Romano Haertel, Thomas Eckhardt, Dietmar Klemme, Kristian Lauritsen, Rainer Erdmann, PicoQuant GmbH (Germany)

The optical amplification and frequency conversion of a gain-switched 1532 nm distributed feedback (DFB) laser diode at a wide range of repetition rates are studied . The use of gain-switched laser diodes as

Return to Contents

seed laser allow for arbitrary repetition rates and a triggering of single pulses. The narrow emission spectrum of DFB laser diodes is ideally suited for nonlinear frequency conversion in quasi-phasematched crystals.

We present a two stage Erbium fiber amplifier setup pumped at 976 nm and operated at 1 – 80 MHz pulse repetition frequency. The seed pulse length is measured to (77 ± 3) ps FWHM and does not change during amplification or with repetition rate. In order to optimize the amplification process, the available pump power scales with repetition rate. Therefore the seed laser repetition rate is measured electronically and directly evaluated inside the pump driving electronics.

After amplification, the output light is focussed into a periodically poled lithium niobate bulk crystal for second harmonic generation to create 766 nm with a pulse energy greater than 3 nJ.

The beam profile is highly uniform and nearly diffraction limited. Beam shaping with an optional phase mask is possible to create a higher order mode with zero intensity in the center for stimulated emission depletion (STED) microscopy. There is a high demand of several hundred milliwatt of average laser power at certain visible wavelength matching utilized fluorophores.

8604-9, Session 2

Ultra-violet generation by third-harmonic conversion in conventional solid-core fibers

Yuichi Takushima, Yosuke Orii, Asa Higashitani, Takeshi Manabe, Spectronix Corp. (Japan)

We successfully demonstrated UV generation by launching 1040-nm picosecond pulses into a conventional step-index fused-silica fiber. In general, the phase-matching condition (PMC) for third-harmonic generation (THG) cannot be satisfied in solid-core fibers due to the material dispersion of fused silica. (Thus, the use of micro-fibers has been extensively studied so far.) However, we theoretically found that, in the step-index fiber with small core diameter and high index contrast, the relative phase mismatch between LP01 mode of the fundamental wave and higher-order mode of the third-harmonic wave can be reduced to be <1%. Thus, although the PMC is not satisfied rigorously, the THG can locally occur efficiently enough to observe the third-harmonic signal clearly at the output end. In the experiment, we used a 5-ps, 1040-nm fiber laser with a repetition rate of 50 MHz as a source of the fundamental wave and launched the pulses into a 30-cm commercially-available step-index fiber with high index contrast (~1.6%). Then, we measured optical spectra of UV and fundamental waves separately by using UV cold mirrors. As the power of the fundamental wave increased, its output spectrum was broadened (~110nm), and the center wavelength was shifted to around 1120 nm when the input power was 2.1 W. In UV spectrum, its third-harmonic components were observed at around 376 nm with conversion efficiency of 10^-6~10^-7. It should be noted that, we observed the uniform blue fluorescent along the fiber. Also, we observed the bright blue-light emission from the output end with a clear ring far-filed pattern, whose wavelength was centered at 480nm. We estimated that it was originated from the fluorescence due to the defect of SiO2/GeO2 radiated by UV light (generated by THG). In the presentation, we will report the experimental result of UV generation in detail and discuss the impact on the fiber's damage due to this UV generation.

8604-10, Session 3

High-power THz pulse generation and nonlinear THz spectroscopy *(Invited Paper)*

Hideki Hirori, Koichiro Tanaka, Kyoto Univ. (Japan)

The study of carrier multiplication has become an essential part of many-body physics and materials science since this multiplication directly affects nonlinear transport phenomena in ultra-high-speed transistors and plays a key role in designing efficient solar cells and electroluminescent emitters and highly sensitive photon detectors. Rapidly developing intense terahertz (THz) pulse sources have the potential to provide significant insights into ultrafast carrier multiplication through purely optical methods, because a THz pulse has a high electric field amplitude (>0.1 MV/cm) and lasts a picosecond. However, so far insufficient strength of THz pulse could induce a small amount of generated carriers and various phenomena simultaneously induced by the intense electric filed, i.e., phonon absorption, carrier mobility changes, and exciton dissociation1, has made the carrier multiplication behavior blur.

In this study, we highlight the extraordinarily efficient carrier multiplication in the typical semiconductor GaAs when it is subjected to a THz pulse of a strong electric field. We demonstrate for the first time that a THz pulse, unlike a DC bias, can generate a substantial number of excitons that emit near-infrared luminescence without any help of band-to-band photoexcitation. Our results imply that the carriers coherently driven by a strong electric field can efficiently gain enough kinetic energy to induce a series of impact ionizations that can increase the number of carriers by about three orders of magnitude on the picosecond time scale.

8604-11, Session 3

High-field THz pulses by efficient optical rectification in organic crystals *(Invited Paper)*

Carlo Vicario, Clemens Ruchert, Christoph P. Hauri, Paul Scherrer Institut (Switzerland)

We present our recent results on single-cycle THz pulse generation at MV/cm field strength covering the so-called THz gap (1-10 THz). Our recently developed table-top THz source is based on optical rectification of a powerful infrared femtosecond laser in organic stilbazolium salt crystals. We review the characteristics of the broadband, carrier-envelope phase stable THz radiation produced in various organic crystals like DAST, OH1 and DSTMS. Those relative new materials show high figure of merit as THz emitters when pumped by IR femtosecond laser. The collinear pump geometry paired with the very high OR nonlinear coefficient provides excellent focusing properties and efficient phase matching of the IR and the THz radiation, respectively. Finally we will discuss first applications of such unique THz pulses in condensed matter physics.

8604-12, Session 3

Comparative study on THz time-domain spectroscopy using 780-nm 1.3-ps laser pulses with different detections of LT-GaAs photoconductive antenna and ZnTe electro-optic sampling

Yuzuru Tadokoro, Osaka City Univ. (Japan); Yuma Takida, Osaka City Univ. (Japan) and Japan Society for the Promotion of Science (Japan); Hiroshi Kumagai, Osaka City Univ. (Japan) and Kitasato Univ. (Japan); Shigeki Nashima, Ataru Kobayashi, Osaka City Univ. (Japan)

Terahertz time-domain spectroscopy (THz-TDS) is a useful method in THz region (0.1-10 THz) because both amplitude and phase of THz waves can be obtained in a single measurement. Usually, the time-resolved detection of THz waveform in THz-TDS is based on photoconductive (PC) antenna or electro-optic (EO) sampling with femtosecond optical pulses. Although earlier studies with these detection techniques showed that their bandwidth could reached over 10 THz with probe pulses as short as 15 fs, comparison between them has not been done in depth with the pulses longer than 1 ps. Therefore, the present study was intended to investigate such a comparison, especially in the bandwidth limit of picosecond probe pulses. In order to make this comparison directly, we developed a picosecond THz-TDS system with a mode-locked

Ti:sapphire laser with the central wavelength of 780 nm, pulse duration of 1.3 ps, and repetition rate of 81.7 MHz. A bow-tie- or dipole- shaped PC antenna on low-temperature grown GaAs (LT-GaAs) and ZnTe were used for the PC antenna and EO sampling, respectively. As a result of our measurements, the sensitivity and SNR of obtained THz-wave pulse with the bow-tie antenna were higher than any other measurement with the dipole antenna and EO crystal. In addition, the obtained THz-wave pulses had different detection limits up to approximately 0.6, 0.9, and 1.2 THz with the bow-tie, dipole antenna, and EO crystal, respectively. The detailed results from these measurements will be presented in the conference.

8604-13, Session 3

The widely tunable THz generation in QPM-GaAs crystal pumped by a near-degenerate dual-wavelength KTP OPO at around 2.127 µm

Deggang Xu, Wei Shi, Kai Zhong, YuYe Wang, Pengxiang Liu, Jianquan Yao, Tianjin Univ. (China)

We report a widely tunable terahertz THz source by using QPM-GaAs crystals pumped by a near-degenerate dual-wavelength KTP OPO around 2.127 um, based on difference frequency generation (DFG). The near-degenerate dual-wavelength KTP-OPO has been achieved based on a walk-off compensated intracavity OPO pumped by Nd:YAG pulse laser. We use QPM-GaAs crystals with different pumping wavelength in order to achieve high power widely tunable THz generation. The coherence length of QPM-GaAs crystal is 650 um based on GaAs index dispersion. The tunable and coherent THz radiation from 0.06 THz to 3.34 THz can be achieved when the two pump waves are in the range of 2.101-2.127 um and 2.157-2.13 um by using the single QPM-GaAs structure with fixed period. The maximum output THz energy is 48.9 nJ with the peak power of 11 W at 1.68THz, corresponding to the energy conversion efficiency of 5.4?10-5 and the photon conversion efficiency of about 0.09%.

8604-14, Session 4

CW mid-IR OPO based on OP-GaAs *(Invited Paper)*

Peter G. Schunemann, Leonard A. Pomeranz, Scott D. Setzler, Casey W. Jones, Peter A. Budni, BAE Systems (United States)

Orientation-patterned GaAs (OP-GaAs) has grown in importance over the last decade as a quasi-phasematched (QPM) nonlinear optical (NLO) material for frequency conversion applications in the mid-infrared. OP-GaAs is attractive due to its very large second-order nonlinear susceptibility (d14 = 94 pm/V), high thermal conductivity (46 W/mK), and low absorption losses over most of its transparency range (~0.9-18 um). Since the first reports of pulsed (ns) SHG and OPO operation in OPGaAs, ns OPOs have improved in output power and efficiency and device demonstrations have expanded to broader spectral ranges (including THz generation) and temporal regimes (fs and ps). Continuous wave (cw) frequency conversion in OP-GaAs has been limited to DFG and, more recently, SHG demonstrations at relatively low power and efficiency. Despite attempts by several groups, cw OPO operation in OP-GaAs has not been previously achieved. OP-GaAs must be pumped at wavelengths > 1.73 um (~2 um for all practical purposes) to avoid two-photon absorption (and the even more severe free-carrier absorption which results), but to date a cw OPO has never been successfully demonstrated in any NLO material at a pump wavelength longer than 1.55 um. CW operation is increasingly challenging at longer wavelengths since the OPO threshold scales as the cube of the pump wavelength. Here we describe the first experimental demonstration of cw operation in an OP-GaAs OPO as well as the first cw OPO pumped at a laser wavelength longer than 1.55 um, achieving 5.3 W of mid-IR output from 24.7 W of Ho:YAG 2.09-um pump.

8604-16, Session 4

Intracavity phase interferometry and its application to magnetometry *(Invited Paper)*

Jean-Claude M. Diels, Ladan Arissian, Koji Masuda, The Univ. of New Mexico (United States)

Intracavity Phase Interferometry (IPI) is a technique in which a mode-locked laser with two intracavity pulses is used to detect a phase variation, by converting it into a frequency. Each of the two intracavity pulses produce two pulse train with the same repetition rate, but different carrier to envelope offset. As they are made to interfere, they produce a beat note, of frequency equal to the ratio of the phase to be measured by the cavity round-trip. Because it is a frequency that is being measured, the signal is not influenced by amplitude noise. A sensitivity to phase variation of 1 part in 10 million has been demonstrated. Different attempts to exploit this exquisite sensitivity to magnetometry will be demonstrated. IPI can be applied directly to the “SERF” magnetometer, by using direct intracavity probing of the circular polarization phase shift that lead to Faraday rotation. Another approach being pursued is to produce Coherent Population Trapping intracavity by repetition rate resonance of the mode-locked train. Interesting coherent effects have been observed in the experimental realization with rubidium and potassium vapors.

8604-17, Session 4

Narrow bandwidth tunable optical parametric generator

Brian D. Dolasinski, Univ. of Dayton (United States); Peter E. Powers, Univ. of Dayton (United States) and Univ. of Dayton (United States)

The output of a periodically poled lithium niobate (PPLN) optical parametric generator (OPG) is filtered using an off axis Fabry-Perot etalon. The filtered output is then parametrically amplified in the same PPLN crystal resulting in a tunable narrow-band infrared source. The PPLN OPG is pumped with a10 nsec pulse duration, 1.064 ?m single-frequency pump laser, with an output signal and idler determined by the PPLN periodicity. The polarization of the pump laser is rotated so that only a portion of it is phase matched on the first pass through the PPLN crystal. The portion that is phase matched generates a signal that is directed to an off-axis Fabry-Perot etalon, which, in the off-axis configuration has a narrow bandwidth reflection. The pump beam is transmitted through a quarter wave plate and reflected with a mirror so that when passed back through the PPLN crystal, its polarization is rotated 90 degrees with respect to the input. Hence the portion of the pump not phase matched on the first pass is now phase matched for the second pass. The reflected and filtered signal is co-aligned with the pump resulting in a narrow bandwidth amplified signal. This system is capable of generating narrow bandwidth over the tuning range of the PPLN crystal and is only restricted by the etalon reflectivity range. We demonstrate tunability in the 1.4 ?m -1.6 ?m signal range (3.2 ?m-4.4 ?m idler range), which is restricted by our etalon reflectivity.

8604-18, Session 4

Ho3+:LLF MOPA pumped RISTRA ZGP OPO at 3-5 µm

Georg Stöppler, Martin Schellhorn, Marc Eichhorn, Institut Franco-Allemand de Recherches de Saint-Louis (France)

High pulse energies in the mid-IR with a comfortable tuning possibility are required in a number of areas, including remote sensing, medicine and counter measure applications. Frequency converters based on the crystal ZnGeP2 (ZGP) are widely used for generating tunable IR radiation in the 2.5-12-?m region. ZGP possesses high nonlinearity, however, due to its limited transparency range it requires pump wavelengths longer

than 2 ?m. A significant drawback of ZGP and of most other IR non-linear crystals is a low damage threshold of ~ 1 J/cm2 for nanosecond pulses. Therefore nanoseconds OPOs at pulse energies in the 10–100-mJ range require large diameter pump beams to reduce the risk of optical damage to the crystal. We used the "Rotated-Image, Singly resonant, Twisted-RectAngle" (RISTRA) ring cavity concept to improve the beam quality of the OPO stage. A Tm3+ fiber laser pumped Ho3+:LuLiF4 (Ho3+:LLF) MOPA system was developed delivering > 100 mJ at 2053 nm in TEM00 operation at a repetition rate of 100 Hz. Using a RISTRA as a single OPO stage we demonstrated an overall OPO pulse energy of 21.8 mJ in the wavelength region 3-5 µm at a pump energy of about 46 mJ and a repetition rate of 100 Hz. The beam quality was measured to be M?~2.5.

8604-41, Session PTue

An efficient WDM-OTDM converter for spectrum interrogation based on nonlinear effects in electro-absorption modulator

Cuiqin Gao, Zhaoying Wang, Xuwei Qin, Tianhe Wang, Chunfeng Ge, Tianxin Yang, Tianjin Univ. (China)

In the modern intelligent fiber Bragg grating (FBG) sensing network, spectrum interrogation is the most challenging technique. Compared to those traditional techniques, modern spectrum interrogation should not only have high speed and wavelength resolution, but also use the limited spectrum resource efficiently.

In this paper, we propose a spectrum interrogation technique to improve utilization rate of spectrum in FBG sensing network. By using a wavelength-division multiplexing (WDM) to optical time-division multiplexing (OTDM) converter for spectrum interrogation, the sweeping WDM sensing signals reflected by multi-FBG sensors are converted into OTDM signals carried by a single wavelength. The mapping of the wavelength domain and the time domain in our spectrum interrogation can allocate the spectrum resource efficiently and dynamically.

The WDM-OTDM converter consists of an electro-optic switch, time delay unit and a multi-wavelength converter. The continuous WDM signals are converted into pulsed WDM signals by using a 10 GHz LiNbO3 intensity modulator as the electro-optic switch. Single-mode-fiber (SMF) is used as the time delay unit for delaying the WDM signals overlap in time at equal time interval precisely. Compared to conventional delay devices, such as array waveguide grating (AWG) that only delay fixed wavelengths, SMF can delay the sweeping multi-wavelength signals precisely. By using a high speed 40 GHz electro-absorption modulator (EAM) as the multi-wavelength converter, the delayed and pulsed WDM signals are converted into OTDM signals with the same wavelength one by one. Multi-wavelength conversion is achieved by the effects of cross-absorption modulation (XAM) and cross-phase modulation (XPM) in EAM.

8604-42, Session PTue

Terahertz generation in quasi-phase-matched GaAs wafers by pulse CO2 laser

Xingbing Wang, Duluo Zuo, Huazhong Univ. of Science and Technology (China); Zhiming Rao, Jiangxi Univ. of Traditional Chinese Medicine (China)

We report an efficient coherent terahertz (THz) source pumped by one CO2 laser with dual-wavelength output based on quasi-phase matched (QPM) different frequency generation (DFG) in a stacked GaAs wafers. We observed that the QPM-GaAs wafers can effectively increase the THz generation by increasing the number of GaAs wafers. The maximum single pulse energy of 12 nJ was generated at a frequency of 0.94 THz (319 ?m) by using ten GaAs wafers, corresponding to a peak output power 200 mW.

8604-43, Session PTue

Fourth-harmonic generation of the CO2 laser wavelength at 10.5910 ?m in BaGa4S7

Kiyoshi Kato, Chitose Institute of Science and Technology (Japan); Takayuki Okamoto, Takuya Mikami, Okamoto Optics Works (Japan); Valentin P. Petrov, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany); Valeriy V. Badikov, Dmitrii V. Badikov, Kuban State Technological Univ. (Russian Federation); Vladimir L. Panyutin, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany)

Owing to its high damage threshold at 1.0642 ?m and favorable birefringence, BaGa4S7 was found to be a useful material for the Nd:YAG laser-pumped OPO in the mid-IR [A. Tyazhev et al, in Digest of CLEO'2012, paper CTh1B4].

While, we have already generated the 7.6 W average output power at 5.2955 ?m by frequency-doubling of the 10.5910 ?m wave-guide CO2 laser operating with 18.3 W at 130 KHz in the 2 cm long AgGa0.63In0.37Se2 crystal [K. Kato et al, in Digest of CLEO'2001, paper CTuM14], we have attempted to use it for SHG of this mid-IR source.

The 1.4 cm long BaGa4S7 crystal used in this experiment is the same one that has been used for the above-mentioned Nd:YAG laser-pumped OPO, and was specified to be cut at ?=12.0° in the xz(=bc) plane. However, we have found ?=9.2° from the external 90° phase-matching angle for SHG of the Nd:YAG laser-pumped KTP/OPO tuned to 2.6588 ?m. This gave the phase-matching angle of ?pm=7.8° for SHG of 5.2955 ?m.

By focusing the 7.6 W, 5.2955 ?m pulses (peak power is 6 KW with 10 ns pulse duration) with the 5-7 cm focal length ZnSe lenses into the crystal, we have obtained the maximum average output of 0.3 W at 130 KHz without any damage to the crystal.

To determine what problems would occur when operating at 7 W pump power level, we have monitored the SHG output power without adjusting the crystal orientation for 1 h. No measureable degradation (less than 5 %) was observed.

8604-44, Session PTue

Frequency-doubled supercontinuum for scanning white-light interferometry

Piotr Ryczkowski, Goëry Genty, Tampere Univ. of Technology (Finland); Anton Nolvi, Ivan Kassamakov, Edward Hæggström, Univ. of Helsinki (Finland)

Scanning white-light interferometry is a high-resolution, non-contact imaging technique for cross-sectional mapping of samples, with applications ranging from imaging of biological tissue to materials research. Different types of sources have been traditionally used to perform scanning white-light interferometry including halogen lamps, LEDs, and supercontinuum. Halogen lamps and LEDs typically suffer from low spectral density and bright supercontinuum sources usually operates at a single repetition rate fixed by the pump laser.

Here, we demonstrate a broadband supercontinuum source operating in the visible/near-IR spectrum and with a continuously tunable repetition rate up to 1 MHz. Such compact, cost-effective and broadband source with large power density and tunable repetition rate at visible/near-infrared wavelengths source overcomes the limitation of fixed repetition rate typical fiber-based supercontinuum sources operating in this wavelength range. We demonstrate all the potential of the source in a scanning white-light interferometer to perform high-resolution dynamic imaging of micro-electro-mechanical systems oscillating at the MHz rate.

8604-45, Session PTue

Parametric gain analysis in tellurite/phospho-tellurite hybrid microstructured optical fibers with an engineered chromatic dispersion

Edmund P. Samuel, Tong Hoang Tuan, Meisong Liao, Zhongchao Duan, Takenobu Suzuki, Yasutake Ohishi, Toyota Technological Institute (Japan)

The tellurite/phospho-tellurite hybrid microstructured optical fibers (HMOFs) are emerging due to their capability of tailoring the dispersion. The dispersion and other related optical properties, such as optical mode confinement and effective index, have been deduced using the finite element method. Here, we have realized four zero dispersion wavelengths (ZDWLs) 1566nm, 1605nm, 1726nm and 1790nm and the parametric gain very near to each ZDWL. The pump wavelength have been chosen to be very close to each of the ZDWL with ??=0.2nm to achieve better accuracy along with the corresponding dispersion parameters ?¬2 and ?¬4. The gain bandwidth was deduced to be 780nm for the pump wavelength of 1727nm near to 3rd ZDWL. This paper reports the signal gain for the pump wavelength range from 1550nm to 1800nm. The propagation spectrum dependence on fiber length has also been studied for the third ZDWL (near 1726nm). The 60mW of the pump peak power has been assumed to deduce the simulation results and the fiber length is considered to be 1m.

8604-46, Session PTue

New acentric materials composed of 4-nitrophenol and pyridine derivatives for NLO and THz applications

Tatiana V. Timofeeva, Marina S. Fonari, Mikhail Y. Antipin, New Mexico Highlands Univ. (United States); Artem Masunov, Univ. of Central Florida (United States); Joel Zazueta, New Mexico Highlands Univ. (United States); Shannon Sullivan, Univ. of Central Florida (United States); Sergiu I. Draguta, New Mexico Highlands Univ. (United States)

To create efficient second-order nonlinear optical (NLO) organic materials for electrooptical and THz generation applications the optimization of orientation of non-centrosymmetrically packed donor–acceptor chromophores is needed. Despite the several focused approaches have been elaborated, the directed design of acentric materials still remains a challenge. A series of novel noncentrosymmetric adducts was obtained by co-crystallization of 4-nitrophenol (I) with several aminopyridines (4-aminopyridine (1), 2-amino,6-methyl-pyridine (2), 3,4-diaminopyridine (3), 2,3-diaminopyridine (4), 3-aminopyridine (5), and 4-[4-(dimethylamino) styryl]pyridine (6)). The final products have compositions 2(I)•1, 2(I)•2, 2(I)•3, 2(I)•4, I•5, and I•6, and crystallize in the acentric P2(1), Pca2(1) and Pna2(1) space groups. The proton transfer from 4-nitrophenol oxygen to the pyridine nitrogen was registered by X-ray and IR studies and confirmed by quantum-chemical calculations. In adducts with molar ratio 2:1 proton moves from 4-nitrophenol oxygen to pyridine nitrogen and in adducts with molar ratio 1:1 proton occupies approximately middle position between nitrogen and oxygen. The 4-nitrophenol-4-nitrophenolate anionic dimeric associates in the ternary compounds 2(I)•1, 2(I)•2, 2(I)•3, and 2(I)•4 are fixed by strong OH…O-(phenolate) hydrogen bonds, O…O distances are in the range 2.44-2.56 Å. The impact of intrinsic helicity imposed by the H-bonded 4-nitrophenol…4-nitrophenolate entity on crystal structure is discussed based on presented original results and statistical analysis of similar materials containing 4-nitrophenol…4-nitrophenolate entity found in literature. The quantum chemical calculations of first order molecular hyperpolarizability show that these new materials are good candidates for NLO applications.

8604-47, Session PTue

Generation of broadband infrared radiation in step index chalcogenide fiber

Satya P. Singh, Shailendra K. Varshney, Prasanta K. Datta, Indian Institute of Technology Kharagpur (India)

The simulation of dispersion characteristic of step-index fibers having chalcogenide as core and silica as cladding with core diameters 1.45?m and 6.5?m shows that the dispersion value of fiber with core diameter 6.5?m is almost flat and lower compared to the fiber with core diameter 1.45?m in a wavelength range of 2-4µm. In case of core diameter 1.45?m, zero dispersion wavelengths (ZDW) and nonlinear coefficient (?) are 1.55?m and 3950W-1km-1 while in case of 6.5?m core diameter, these are 2.94?m and 482W-1km-1, respectively. The effect of the variation of fiber length and detuning of pump wavelength with respect to ZDWs in both fibers have also been simulated and compared. It is observed that the signal gain increases and gain bandwidth decreases with the fiber length. In case of pump detuning around ZDW (or ZDW detuning around pump), the simulation results show that when the pump wavelength is detuned to lower wavelength side of the ZDW, the gain spectrum becomes broadened. If we detune the pump wavelength more and more lower side of the ZDW, a part of signal gain spectrum detached both side of the central gain spectrum due to the phase mismatch. By this approach, it is possible to create a gain region several hundred nanometers away from pump wavelength. Gain bandwidth of 1000nm and 600nm corresponding to core diameters 6.5?m and 1.45?m, respectively, are simulated in the fiber of length 20cm considering a single CW pump near zero-dispersion wavelength with input power of 20 W.

8604-49, Session PTue

Ultraviolet coherent light source by sum frequency generation with doubly-resonant external cavity

Norihiro Inoue, Hitachi Zosen Corp. (Japan); Kenta Mukoyama, Kazuhiro Tokuyama, Osaka City Univ. (Japan); Hiroshi Kumagai, Kitasato Univ. (Japan); Naoaki Fukuda, Kyoto Univ. (Japan); Toshio Takiya, Hitachi Zosen Corp. (Japan)

A high-power and tunable UV continuous wave laser has been developed through sum-frequency generation (SFG) by using a BBO nonlinear crystal. The output power of 160mW was detected in the developed laser whose wavelength was 312nm. Two-stage of frequency conversion system with two external cavities was adopted in order to enhance the continuous light source and to cause nonlinear optical phenomena. In the first stage, the coherent light of 532nm in wavelength was obtained by second harmonic generation (SHG) for the incident light of 1064nm in wavelength which was generated from a Nd:YAG laser. A bow-tie shaped external cavity incorporating four mirrors between which positions and distances were controlled by Haensch-Couillaud frequency stabilization method was constructed. In the second stage, the coherent light of 312nm in wavelength was successfully accomplished by mixing the light of 532nm from the first stage and the another light of 754nm from a Ti:Sapphire continuous wave laser with a single frequency. In these experiments, while the former light was resonated by adjusting the resonator length of the external cavity, the latter light was resonated by controlling the oscillation wavelength of the Ti:Sapphire laser. It was concluded that the high power UV continuous laser was obtained not only by the specific frequency stabilization but also by independently controlling the two incident lights in the SFG stage. The study is continuing to try to acquire higher output of power of the light of 312nm in wavelength by further stabilizing the external cavities.

8604-50, Session PTue

Linear and nonlinear refractive indices contributions on third-harmonic generation at materials interfaces using femtosecond pulses

Lino Misoguti, Emerson C. Barbano, Cleber R. Mendonca, Sergio C. Zilio, Univ. de São Paulo (Brazil)

The third-harmonic generation (THG) is one of the most fundamental nonlinear effects of the third-order nonlinearity on isotropic materials. Since the advent of femtosecond (fs) lasers, due to its natural high peak intensity, the third-order nonlinearity could be more explored and studied. Recently, we have observed that the THG in a slab is strongly affected by the input and output interfaces. Here, we report on new results on third harmonic (TH) generated by femtosecond laser pulses using Z-scan method at tightly focused condition in a quartz cell in order to explore their interfaces. As we know, the THG occurs on interfaces due to beam symmetry breaking which diminishing the Gouy phase shift contributions. Basically, using quartz cell filled with solvents we have four different interfaces which can be studied independently. Each interface presents its own TH intensity and spectrum. As light source we used pulses at IR (1400 nm), 1 kHz repetition rate with 120 fs-duration delivered by commercial optical parametric amplifier pumped by a amplified 150-fs Ti:sapphire laser at 775 nm. To detect the TH, we have used a high resolution portable UV-Vis spectrometer. We could observe that depending of solvents and laser propagation direction at interfaces, the TH signal changes. The TH signal can be enhanced or diminished by constructive or destructive interference, respectively, due to Fresnel reflection (linear refractive index). The TH spectrum bandwidth is determined mainly by cross-phase modulation and, consequently, it does depend of beam propagation, pulse intensity and material's nonlinearities.

8604-51, Session PTue

High-speed polygon-scanner-based frequency-swept optical beat source for continuous wave terahertz generation

Yong Seok Kwon, Myoung Ock Ko, Mi Sun Jung, Ik Gon Park, Chungnam National Univ. (Korea, Republic of); Namje Kim, Sang-Pil Han, Han-Cheol Ryu, Electronics and Telecommunications Research Institute (Korea, Republic of); Dae-Su Yee, Korea Research Institute of Standards and Science (Korea, Republic of); Kyung Hyun Park, Electronics and Telecommunications Research Institute (Korea, Republic of); Min Yong Jeon, Chungnam National Univ. (Korea, Republic of)

We demonstrate a high speed frequency-swept optical beat source for continuous wave (CW) THz generation using a polygon-scanner-based wavelength swept laser and a fixed distributed feedback (DFB) laser. A polygon-scanner-based wavelength swept laser consists of a semiconductor optical amplifier (SOA) as an optical gain medium, two optical isolators, two polarization controllers, an optical circulator, a 30 % output coupler, a collimating lens, a telescope lens, a diffraction grating, and a polygon scanning mirror. The 3 dB scanning bandwidth is about 60 nm around 1540 nm. A wide bandpass filter with 20 nm is employed in the laser cavity in order to obtain a flat intensity within the bandpass region from the wavelength-swept laser. The center wavelength of the DFB laser is 1560 nm. The output of the wavelength-swept laser is combined with the fixed DFB laser through a 3-dB fiber coupler. Therefore, a high speed frequency-swept optical beat source can be obtained. The measured instantaneous linewidth of the wavelength swept laser is less than 0.1 nm. The scanning frequency of the optical beat source is about 12 kHz, which is same as that of the wavelength swept laser. In order to confirm the feasibility of using our frequency swept optical beat source as the THz radiation for frequency-domain THz spectroscopy, a fiber-coupled CW THz measurement system is constructed. A single mode fiber coupled emitter and receiver made of low-temperature grown (LTG)-InGaAs photomixers are used to generate and detect THz radiation, respectively.

8604-52, Session PTue

Nonlinear optical properties of tungsten lead-pyrophosphate glass containing copper nanoparticles

Juliana Mara P. Almeida, Univ. de São Paulo (Brazil); Danilo Manzani, Univ. Estadual Paulista (Brazil); Leonardo De Boni, Univ. de São Paulo (Brazil); Marcelo Nalin, Univ. Federal de São Carlos (Brazil); Sidney J. Ribeiro, Univ. Estadual Paulista (Brazil); Cleber R. Mendonca, Univ. de São Paulo (Brazil)

The surface plasmon resonance (SPR) of metallic nanoparticles and the hyperpolarizabilities of the heavy-metal atoms have been investigated to improve optical nonlinearities in materials. In this study, we analyzed the effect of the cooper nanoparticles (NPs) in the third-order nonlinear optical properties of tungsten lead–pyrophosphate glass matrix (70Pb2P2O7-30WO3). The nonlinear refractive index (n2) and the excited state absorption spectrum were determined by the standard closed aperture and white-light continuum (WLC) Z-scan techniques, using ~150-fs pulses at 1 kHz repetition rate. The linear absorption spectrum of the copper doped matrix presents a broad absorption band centered at about 830 nm that is related to the absorption of Cu2+ ions. However, after the annealing at 400 ºC for 5 min the SPR band of the copper NPs was observed at ~570 nm. For longer annealing times, the position of the SPR band is shifted to smaller wavelengths. TEM images suggest that the average size of the produced copper NPs is approximately 10 nm.

The n2 of the glass matrix is about 2x10-19 m2/W for wavelengths between 1300 – 1500 nm and no significant enhancement effect was found for the samples containing copper NPs. Nonetheless, the presence of NPs in the glass promoted saturable absorption in the region of the SPR band, while reverse saturable absorption was observed for other spectral regions, as well as for the sample without NPs. Therefore, such material could be used in optical limiting applications in a wide spectral range and as saturable absorber in the SPR band.

8604-53, Session PTue

Tunable picosecond THz-wave generation based on trapezoidal MgO:LiNbO3 crystal in novel pentagram-shaped pump-enhancement cavity

Yuma Takida, Osaka City Univ. (Japan) and Japan Society for the Promotion of Science (Japan); Yuzuru Tadokoro, Osaka City Univ. (Japan); Hiroshi Kumagai, Osaka City Univ. (Japan) and Kitasato Univ. (Japan); Shigeki Nashima, Ataru Kobayashi, Osaka City Univ. (Japan)

It is well known that lithium niobate (LiNbO3) has excellent characteristics for efficient tunable/broadband THz-wave generation. Over the last few years, we have investigated novel THz-wave sources based on MgO-doped LiNbO3 (MgO:LiNbO3), and have succeeded in developing a tunable picosecond THz-wave source by using a novel pentagram-shaped pump-enhancement cavity.

One of the limiting factors in efficient THz-wave generation is the strong absorption by MgO:LiNbO3 in THz-wave region. To overcome this problem, we employ a surface-emitted configuration which consists of a trapezoidal MgO:LiNbO3 crystal and a pump-enhancement cavity folded in the shape of a pentagram. The pentagram-shaped cavity is designed for the noncollinear dual resonance of both pump and one of the down-converted waves. As a result, 1.5-ps pump pulses from a mode-locked

Ti:sapphire laser operating at 780 nm allow tunable THz-wave generation via parametric down-conversion resulting from stimulated phonon-polariton scattering in the MgO:LiNbO3 crystal. By slightly translating the position of one of the cavity mirrors, we experimentally find that the THz-wave peak frequency is tunable in the range from 0.9 to 3.5 THz with the average output power of dozens of nanowatts. The maximum THz-wave average power is up to 40 nW around 2 THz at the pump power of 800 mW, which is several times higher than the THz-wave output generated by using rectangular MgO:LiNbO3 crystals for Si-prism-coupled configuration under the same pump condition.

8604-54, Session PTue

Collinear THz parametric oscillator using QPM-GaAs structures pumped by 2.06 µm pulsed fiber laser

Wei Shi, Tianjin Univ. (China); Qiang Fang, HFB Photonics (China); Degang Xu, Jianquan Yao, Tianjin Univ. (China); Nasser N. Peyghambarian, College of Optical Sciences, The Univ. of Arizona (United States)

In this paper, we firstly propose and numerically investigate a collinear singly resonant THz parametric oscillator (TPO) in QPM-GaAs structures pumped by 2.06 um nanosecond fiber laser pulses. The QPM-GaAs was placed inside the bow-tie cavity to work as nonlinear medium to provide parametric gain. High energy 10 ns pulsed fiber laser at 2.06 um was used as the pump. The signal wave at 2.0966 um can be resonated in the cavity. The generated THz waves (idler) at 118 um can be extracted out of the cavity by an off-axis parabolic mirror placed inside the cavity. The process of the parametric mixing in the QPM-GaAs was described by the three-wave parametric mixing equations, which can be reduced in the plane-wave limit, and was resolved using split-step Fourier method (SSFM). The threshold of the TPO for different length of the QPM-GaAs was investigated and the lowest threshold of 145 uJ was achieved when the length of the QPM-GaAs is about 3 cm. The pulse energies of the generated THz waves at different pump levels were also investigated for 3-cm QPM-GaAs crystal. When the pulse energy of the pump laser was ~500 uJ at 10 kHz repetition rate, ~10 mW THz wave can be achieved and the power conversion efficiency is about 0.2%.

8604-55, Session PTue

Theoretical simulation on optical parametric oscillator based on LiInS2 crystals

Chao Ma, Sasa Zhang, Yang Liu, Shandong Univ. (China)

Theoretical simulation is performed on the nonlinear optical properties of LiInS2(LIS) crystals based on new Sellmeier equations: Refractivity of fast light and slow light in LIS crystal is calculated and analyzed; Walkoff angle of fast light and slow light is calculated and simulated; The effective nonlinear coefficient in three wave collinear interaction is calculated, simulated and analysed. Two directions are sellected(the XOY principal plane and the XOZ principal plane respectively), in which, the phase matching characteristics and ralating curves in three wave collinear interaction are theoretically computed and simulated.

8604-56, Session PTue

Second-harmonic generation in Hg0.35Cd0.65Ga2S4 and Hg0.52Cd0.48Ga2S4

Kiyoshi Kato, Chitose Institute of Science and Technology (Japan); Takuya Mikami, Okamoto Optics Works (Japan); Valentin P. Petrov, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany)

Hg0.35Cd0.65Ga2S4 and Hg0.52Cd0.48Ga2S4 have been found to be phase-matchable for type-1 second-harmonic generation (SHG) of the fundamental radiation at 2.907-5.453 ?m and 2.423-6.725 ?m, respectively. The Sellmeier equations for HgGa2S4 and CdGa2S4 that reproduce well these experimental results as well as the published data for the Cr:forsterite laser (1.25 ?m)-pumped Hg0.35Cd0.65Ga2S4 optical parametric generator (OPG) and the Ti:Al2O3 laser (0.820 ?m)-pumped Hg0.52Cd0.48Ga2S4 optical parametric amplifier (OPA) at 5.59-9.12 ?m are presented.

8604-57, Session PTue

Effects of nonlinear phase modulation on quantum frequency conversion using four-wave mixing Bragg scattering

Lasse Mejling, Technical Univ. of Denmark (Denmark); Colin J. McKinstrie, Alcatel-Lucent Bell Labs. (United States); Karsten Rottwitt, Technical Univ. of Denmark (Denmark)

For quantum information processing, a reliable device is needed to frequency convert the photons emitted from quan-tum memories, from 400-800 nm to the telecom band near 1550 nm. Furthermore, the long temporal wave-packets need to be shortened and reshaped to utilize existing communication infrastructure more effectively. These changes must be made without altering the other quantum properties of the photons. Recently, it was shown that Bragg scattering (BS), a four-wave mixing process in optical fibers, promises to fulfill both of these requirements. We have derived analytically the Green functions for BS, in both the low- and the high-conversion regimes; however in neither regime were the effects of nonlinear phase modulation (NPM) included.

In this paper we present solutions of the BS equations, which account for NPM, in the low- and moderate conversion regimes. The new Green functions are compared with the previously ones for both asymmetric and symmetric collisions (interactions centered at either the input and midpoint of the fiber, respectively). For weak interactions the effects of NPM are negligible and the two models agree, as expected. We show that NPM does not change the lowest-order con-version efficiency, but does prevent complete separability (freedom from temporal entanglement) and imposes chirps on the input and output modes. We find that by pre-chirping the pumps appropriately, we can reduce the effects of NPM. Hence, arbitrary reshaping of the input and output modes, and nearly complete separability of the Green function are still possible, even when the effects of NPM are included.

8604-58, Session PTue

Nd:YAG laser-pumped HgGa2S4 OPO

Fumihito Tanno, Panasonic Industrial Devices Nitto Co., Ltd. (Japan); Kiyoshi Kato, Chitose Institute of Science and Technology (Japan)

By pumping the 8 mm long HgGa2S4 crystal cut at ?=67.5° and ?=0° with the Nd:YAG laser operating at 30 Hz, we have generated 410 mW output power (110 mW at 4.180 ?m and 300 mW at 1.428 ?m) at 2.1W pmp power.

The HgGa2S4 crystal used in this experiment was the same one that had been reported in [E.Takaoka and K.Kato, Technical Digest CLEO'98, 1998, paper CWF39], and AR-coated at 1.06~1.47 ?m with T=97~99% on four side surfaces.

The OPO cavity consists of two flat mirrors separated by 2 cm. The fused silica input mirror has T=85% at 1.0642 ?m and R=90~97% at 1.24~1.46 ?m. The CaF2 output mirror has R=95% at 1.0642 ?m and R=90~92% at 1.24~1.53 ?m, and T=90~98% at 5.2~7.3 ?m.

Prior to the OPO experiments, we have measured the damage threshold of this crystal at 1.0642 ?m using the 22.5° cut side surfaces. The slight damage to the AR-coating was observed at the pump power levels of 0.3 J/cm2 (60 MW/cm2) at 30 Hz. Consequently, we were able to operate

this system at the pump power of 2 W for more than 10 hr without any decrease in the output power.

The OPO threshold measured with the 7 mm diameter pump beam was ~0.07 J/cm2 (14 MW/cm2), which is 1.8 times higher than that of the 2 cm long AgGaS2 crystal measured under the same experimental conditions. This gave d36 (HgGa2S4) =(2.2±0.2) x d36(AgGaS2).

By heating the HgGa2S4 crystal from 20? to 120? at normal pump incidence (?PM=67.5°), the signal and idler outputs were tuned from 1.428 to 1.400 ?m and from 4.180 to 4.438 ?m, respectively. These results agree well with the theoretical values calculated with the published Sellmeier and thermo-optic dispersion formulas [N.Umemura, T.Mikami, and K.Kato, Opt.Commun,285,1394-1396(2012)].

8604-59, Session PTue

Modeling ultra-broadband terahertz waveguide emitters through difference frequency generation using coupled mode theory

Felipe A. Vallejo, L. Michael Hayden, Univ. of Maryland, Baltimore County (United States)

We use coupled mode theory that adequately incorporates both terahertz (THz) and infrared (IR) losses, to model and design ultra-broadband terahertz waveguide emitters (0.1-15 THz) based on difference frequency generation of femtosecond IR optical pulses. We apply the theory to generic, symmetric, five-layer, metal/cladding/core waveguides using transfer matrix theory. Our expressions for the conversion efficiency and output THz power spectrum depend on the pump power, pulse width, beam waists, laser repetition rate, material optical properties, and waveguide dimensions. Using this approach we design waveguides with bandwidths greater than 15 THz and obtain high nonlinear conversion efficiencies up to 1.2?10-4 W-1. Our results reveal that a perfectly phase-matched structure is not necessarily the one with the highest conversion efficiency. The highest efficiency is obtained by balancing both the modal phase-matching and modal effective loss effects.

8604-19, Session 5

Cascaded generation of octave-spanning 2-5 µm frequency combs via subharmonic-supercontinuum process *(Invited Paper)*

Alireza Marandi, Charles W. Rudy, Konstantin L. Vodopyanov, Robert L. Byer, Stanford Univ. (United States)

Broad mid-IR frequency combs in the difficult-to-achieve 2-20 ?m range are greatly desirable for many applications, e.g. molecular spectroscopy, where they promise to dramatically improve precision and sensitivity [1]. Sub-harmonic generation using a degenerate optical parametric oscillator (OPO) has been shown to be an effective way to coherently translate a broad near-IR frequency comb to mid-IR [2]. In this paper, we use such a subharmonic OPO, pumped by a commercial 1.56-?m frequency comb source, to further broaden its spectrum: after passing the OPO output through a tapered fiber, an octave-wide mid-IR frequency comb is achieved, centered around 3.1 ?m. Optimum dispersion and nonlinearity in the fiber are achieved by in-situ tapering of a step index As2S3 fiber. The mid-IR output of the OPO was coupled in the fiber during the tapering process, and the spectral broadening was measured and used as the criteria for stopping the tapering process. To examine the coherence of the octave-wide mid-IR output, a c.w. laser at wavelength of 1564 nm with 3-kHz linewidth is interfered with the fiber laser and the second-harmonic of the mid-IR output. This experiment verifies that the coherence properties of the near-IR frequency comb are intrinsically transferred to the mid-IR.

References

[1] A. Schliesser, N. Picqué, T. W. Hänsch, Nature Photonics 6, 440–449 (2012)

[2] A. Marandi, N. C. Leindecker, V. Pervak, R. L. Byer, K. L. Vodopyanov, Optics Express 20, 7255 (2012).

8604-20, Session 5

Widely tunable parametric generation of picosecond visible and mid-infrared radiation in optical fibers

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

Widely tunable visible light sources are very interesting for several applications in the field of biophotonics, optical testing of components, etc. In a similar way, tunable mid-infrared sources are very useful for spectroscopy, LIDAR, etc. In this work, we demonstrate a widely tunable visible and mid-infrared picosecond light source. An efficient generation of widely separated signal and idler is possible via degenerate four-wave mixing if an endlessly single-mode photonic crystal fiber pumped at a wavelength far from the zero dispersion wavelength is used. The use of a tunable near-infrared pump coming from an Yb-doped fiber opens the door to a widely tunable source with a theoretical tuning range of ~50nm in the visible and ~400nm in the mid-infrared.

In this work a tunable picosecond seed laser is amplified to ~40KW peak power by using Yb-doped fibers. The high repetition rate of the laser is reduced to 250KHz by using an acousto-optic modulator. By launching this amplified radiation into a 1.6m long LMA-10 PM photonic crystal fiber, it was possible to obtain a visible source with up to 25% conversion efficiency over more than 25nm. Thus, in the visible range the source is tunable from 628nm to 654nm and in the mid-infrared range it can be tuned from ~2.7µm to ~2.9µm simply by tuning the pump from 1030nm to 1050nm. We believe that this source, given its simplicity and high efficiency, apart from the applications mentioned above, can be an ideal seed for Thulium/Holmium doped active fiber systems.

8604-21, Session 5

Polarization stabilization of vector solitons in circularly birefringent fibers induced by Raman effect

Evgeny A. Kuzin, Nikolay A. Korneev, Balder-Arturo Villagomez-Bernabe, Baldemar Ibarra-Escamilla, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); Olivier J. Pottiez, Centro de Investigaciones en Óptica, A.C. (Mexico); Andres González-García, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); Manuel Durán-Sánchez, Univ. Tecnológica de Puebla (Mexico)

Common optical fibers are randomly birefringent, and solitons traveling in them develop random polarization states upon propagation. However it is desirable to have solitons with a well-defined polarization. We analyzed the two coupled propagation equations in a circularly birefringent fiber. Our equations included the soliton self frequency shift. For our best knowledge this set of equation was analyzed for the first time. We performed a transformation of equations which reduces them to a form of perturbed Manakov task. The difference between our equations and the integrable Manakov case was considered as a perturbation. The perturbation method gives us an equations for evolution of the polarization state of pulse. The evaluation equation shows that in a circularly birefringent (twisted) fiber the cross–polarization Raman term leads to unidirectional energy transfer from the slow circularly polarized component to the fast one. The magnitude of this effect is

determined by the product of birefringence and amplitudes of both polarization components. Thus, solitons with any initial polarization state will eventually evolve stable circularly polarized solitons. We also solved equations using a split-step Fourier method. The parameters of a standard fiber were used with delay between left- and right- circular polarizations of 1 ps/km that corresponds a fiber twisted by 6 turns/ meter. Initially solitons with elliptical polarization were generated by pulse break-up process, than we investigated their evolution in the fiber. Numerical results confirmed analytical approximation.

8604-22, Session 5

Design of microstructured optical fibers for supercontinuum generation

Silvia Rodrigues, Margarida Facão, Sofia C. Latas, Mário F. Ferreira, Univ. de Aveiro (Portugal)

The only way to achieve very high values of index contrast using silica fibers as a basic material is by incorporating air as one component of the fiber cladding. This can be done using a tapered fiber, or through the use of various designs of microstructured optical fiber (MOF). In order to achieve a higher nonlinearity, we can consider also other materials instead of silica.

In this paper we look for an optimum design of microstructured optical fibers for supercontinuum generation. To achive this goal, we perform an accurate numerical modelling of MOFs by applying the finite element analysis and using the commercial software COMSOL Multiphysics. The dependence of the dispersion parameters and nonlinear parameter on wavelength is analyzed.

A new design is proposed and analysed, corresponding to a layered spiral microstructured optical fiber (LS-MOF). By changing appropriately its three parameters, it is possible to shift the zero dispersion wavelength to visible and near-infrared regions, as well as to achieve very high nonlinearity close to the zero dispersion wavelengths. Numerical results will be presented concerning the dispersion and nonlinear characteristics of the LS-MOF using silica and arsenic trisulphide, as well as the generation of supercontinuum on those optimized fiber designs.

8604-23, Session 5

Experimental and theoretical investigations of single-frequency Raman fiber amplifiers operating at 1178 nm

Iyad Dajani, Christopher L. Vergien, Craig Robin, Air Force Research Lab. (United States); Benjamin G. Ward, Shadi A. Naderi, U.S. Air Force Academy (United States)

We present a detailed study of power scaling in Raman fiber amplifiers (RFAs) operating at 1178 nm and pumped at 1120 nm. This wavelength is of interest as it can be frequency doubled into 589 nm for sodium guide star applications. We consider power scaling using two types of fiber: a commercial off the shelf (COTs) fiber and, also, an acoustically tailored fiber with an enhanced Raman gain. For the former, 10.5 W of single-frequency output in a single-stage counter-pumped RFA was obtained through the application of two temperature steps along the fiber in order to suppress stimulated Brillouin scattering (SBS). For the latter, 18.3 W of single-frequency output was obtained. We discuss how the design of the acoustically tailored fiber can be improved to accommodate the full benefit of the thermal gradient; thus allowing for power scaling to >30 W from a single-stage RFA. We also present experimental results confirming that the optimized output signal at SBS threshold scales linearly with the pump power and show excellent agreement with our numerical simulations. Furthermore, we show experimental results confirming that four-wave mixing (FWM) is a limiting factor in a co-pumped configuration and suggest two techniques to mitigate it including the utilization of a novel fiber. The design of this fiber is performed using a finite element method (FEM). Finally, we present preliminary results from a two-stage RFA whereby various seed powers are investigated and discuss generating two lines corresponding to the D2a and D2b through proper phase modulation.

8604-24, Session 6

Precision mid-infrared frequency combs and spectroscopic applications *(Invited Paper)*

Marco Marangoni, Politecnico di Milano (Italy)

Frequency combs have brought new life into the field of high-resolution spectroscopy, allowing cw lasers to be referenced to a highly repeatable, precise and absolute frequency axis. Repeatability is a key feature to obtain high quality measurements of absorption profiles and thus accurate determination of spectroscopic parameters, while absolute frequency calibration makes it possible the comparison of spectroscopic data acquired in different laboratories and at different times, as well as comparison with theoretical predictions or existing databases. In this work a special emphasis is given to the field of comb-assisted spectroscopy in the mid-infrared spectral region, whose interest is motivated by the occurrence of the most intense rovibrational transitions of all molecular compounds. The lack of commercial mid-infrared combs can be overcome by means of a sum frequency generation process enabling mid-infrared probe lasers, and specifically quantum cascade lasers (QCLs), to be referenced to near-infrared frequency combs. The referencing method will be discussed with the help of two significant examples at 4.3 and 9.1 um, starting from an Erbium and a Thulium comb respectively. The discussion will encompass the application of the method to precision spectroscopy in the mid-infrared and the strategy to achieve coherent phase-lock of the QCL to the comb.

8604-25, Session 6

Ultrafast Tm fiber lasers: frequency combs and applications to nonlinear optics *(Invited Paper)*

Ingmar Hartl, IMRA America, Inc. (United States)

We demonstrate the recent advance in ultrafast Tm-fiber laser technology.

First a 500 MHz ultra-low noise 58fs Tm fiber soliton laser centered at 1.95 µm is presented. This laser can be amplified to the 2.5W output power level, sufficient to pump a low-threshold doubly resonant degenerate OP-GaAs OPO for coherent mid-infrared generation and to generate a octave-spanning supercontinuum in a highly nonlinear fiber. An intracavity electro-optic graphene modulator is used for fast carrier phase control, enabling fully stabilized frequency comb operation. The system can be long-term stabilized to a narrow-linewidth cw-reference laser around 1550nm.

Secondly we demonstrate a tunable mid-infrared source based on a Tm-fiber laser. Part of the Tm-fiber-lasers output is Raman self-frequency shifted in a fluoride fiber to a center wavelength of up to 2.5-µm. Difference frequency generation of the Raman shifted pulse and the 1.95-µm Tm-laser output in OP-GaAs results in a tunable pulse from 6.7-12.7 µm with 1.3 mW output power.

Finally we demonstrate spectral narrowing and optical referencing of a room-temperature 9.1 µm DFB quantum cascade laser (QCL) using sum-frequency generation (SFG) of the QCL and a Tm-fiber-laser frequency comb. SFG results in a blue-shifted comb centered at 1.6 µm which is heterodyned with a supercontinuum generated by the Tm-comb. The resulting beat-signal is used to narrow the QCL linewidth via feedback to the QCL current driver.

8604-26, Session 6

Broad-band cascaded four-wave mixing frequency comb centered around 1 μm

Mateusz Wysmolek, Hakan Sayinc, Laser Zentrum Hannover e.V. (Germany) and Ctr. for Quantum Engineering and Space-Time Research (Germany); Jose Manuel Chavez Boggio, Roger Haynes, Martin M. Roth, Leibniz-Institut für Astrophysik Potsdam (Germany); Uwe Morgner, Laser Zentrum Hannover e.V. (Germany) and Ctr. for Quantum Engineering and Space-Time Research (Germany) and Leibniz Univ. Hannover (Germany); Jörg Neumann, Dietmar Kracht, Laser Zentrum Hannover e.V. (Germany) and Ctr. for Quantum Engineering and Space-Time Research (Germany)

The mode-locked laser based frequency comb (FC) technology is well established, but their mode-spacing is limited to several GHz directly from the oscillator. Since there are numerous applications requiring a line spacing of hundreds GHz to several THz, like astrophotonics, spectrograph calibration and THz-technology, a different approach is needed. Furthermore, the possibility of covering the visible optical frequencies with such a FC would stimulate the development in many scientific areas for example in the search of Earth-like planets.

To cover the visible spectral range centring the FC at 1 μm seems to be the most reasonable approach. Despite the unfavourable dispersion profile of standard fibres we demonstrate a broad-band cascaded four-wave mixing frequency comb (CFWM FC) centred around 1060 nm generated in photonic crystal fibres (PCF).

The two-tone seed is amplitude modulated at a frequency of multi-hundred kHz producing pulses of several nanoseconds. The seed wavelengths are then separately amplified and filtered prior to coupling into CFWM FC generation stage consisting of PCFs with appropriate dispersion profiles. The resulting FC is covering 600 nm consisting of 44 idler-waves with a line spacing of 3.6 THz. The complete characterization of the comb is carried out, i.e. RF and optical spectrum and pulse length evolution in every stage of the system.

To the best of our knowledge it is the first demonstration of broad-band CFWM FC centred around 1 micron with a great potential of frequency doubling for covering the visible wavelengths.

8604-27, Session 6

Multispectral mid-infrared imaging using frequency up-conversion

Nicolai Sanders, Jeppe S. Dam, Ole B. Jensen, Christian Pedersen, Peter Tidemand-Lichtenberg, DTU Fotonik (Denmark)

It has recently been shown that it is possible to up-convert infrared images to the near visible region with high quantum efficiency and low noise by three-wave mixing with a laser field. If the mixing laser is single-frequency, the up-converted image is simply a band-pass filtered version of the object, however with a bandwidth corresponding to the acceptance parameters of the conversion process and a center frequency given by the phase match condition.

Tuning of phase matched wavelength has previously been demonstrated by changing the temperature or angle of the nonlinear material, however, temperature tuning is slow, and angle tuning typically results in alignment issues. We present here a novel approach where the wavelength of the mixing field is used as a tuning parameter, allowing for fast tuning and hence fast imaging acquisition paving the way for real time multispectral imaging.

In the present realization the converter consists of an external cavity tapered diode laser in a Littrow configuration with computer controlled motorized grating feedback, ECDL. The output from the ECDL is used as a seed for a fiber amplifier system, boosting the power to approx 5 W over the tuning range of 1020 to 1080 nm.

Using a PP:LN crystal with 5 different poling periods ranging from 21 to 23 μm, any spectral component from 2.8 μm to well above the transparency limit of the PP:LN can be phase matched for sum-frequency mixing.

8604-28, Session 6

High resolution mid-infrared spectroscopy based on frequency up-conversion

Jeppe S. Dam, Qi Hu, Peter Tidemand-Lichtenberg, Christian Pedersen, DTU Fotonik (Denmark)

We present high resolution up-conversion of incoherent infrared radiation by means of sum-frequency mixing with a laser followed by simple CCD Si-camera detection. Noise associated with up-conversion is, in strong contrast to room temperature direct mid-IR detection, extremely small, thus very faint signals can be analyzed. The obtainable frequency resolution is usually in the nm range where sub nm resolution is preferred in many applications, like gas spectroscopy.

In this work we demonstrate how to obtain sub nm resolution when using up-conversion.

In the presented realization one object point is imaged through the up-converter. Assuming homogeneous spherical emission from the object point, the up-converted radiation will carry the spectral information as concentric rings. From the optical path length and dispersion properties of the nonlinear material, the acceptance bandwidth of the up-conversion process is calculated. It is then straightforward to deduce the spectral information of the light emitted from the object point by a simple analysis of the up-converted radiation.

In order to increase resolution, a scanning Fabry-Perot etalon is inserted in a collimated geometry of the up-converted light generated by the crystal. The etalon is designed with a free-spectral range larger than the bandwidth of the up-conversion process. Hence, the spectral resolution is now set by the finesse of the etalon. Based on this approach a spectral resolution of 0.2 nm has been reached around 3 μm.

We demonstrate high resolution spectral performance by observing emission from hot water vapor in a butane gas burner.

8604-29, Session 6

Intracavity molecular spectroscopy in the mid-IR using ultra-broadband optical parametric oscillator

Magnus W. Haakestad, Norwegian Defence Research Establishment (Norway) and Stanford Univ. (United States); Nicholas C. Leindecker, Alireza Marandi, Konstantin L. Vodopyanov, Tobias P. Lamour, Stanford Univ. (United States)

Laser sources in the mid-IR 'fingerprint' region of > 3 μm have great potential for such applications as precision spectroscopy, trace gas detection, and human breath analysis. Synchronously pumped optical parametric oscillators (OPOs) operating around degeneracy point, represent an attractive way of generating ultra-broadband mid-IR radiation suitable for coherent spectroscopy in the Fourier domain. We have performed molecular spectroscopy using two such sources. One source was a periodically-poled lithium niobate (PPLN) based OPO pumped by a femtosecond Er-doped fiber laser, and the other source was an orientation-patterned GaAs based OPO pumped by a Tm-doped fiber laser. Both OPOs operate near degeneracy to obtain the broadest bandwidth, which reached more than one octave (2.5-6.1 μm) in the case of Tm-pumped OPO. Intracavity spectroscopy of water vapor, isotopic carbon dioxide, methane, acetylene, carbon monoxide, and formaldehyde was performed by injecting gas directly into the OPO enclosure, or by using an intra-cavity gas cell with a volume ~30 cm?. The absorption spectra were measured using a commercial FTIR-instrument. We observed significant effective path length and

sensitivity enhancement due to the intracavity effect. In addition, we found that the measured spectral line shapes may show derivative-like features, resembling the real part of the refractive index of the gasses. The measured spectra were compared to a simple model, based on the intracavity round-trip dispersion, and excellent agreement between theory and measurements was found. Detection limits in the ppb-range were demonstrated.

8604-30, Session 7

Periodically oriented GaN for nonlinear frequency conversion *(Invited Paper)*

Jennifer K. Hite, Mark E. Twigg, Jaime A. Freitas Jr., Michael A. Mastro, Igor Vergaftman, Jerry R. Meyer, Shawn P. O'Connor, Nicholas J. Condon, Francis J. Kub, Steven R. Bowman, Charles R. Eddy Jr., U.S. Naval Research Lab. (United States)

Periodically oriented (PO) structures of III-V semiconductors such as gallium arsenide (GaAs) and gallium phosphide (GaP) have made considerable progress toward efficient quasi-phase matching for second harmonic generation and optical parametric oscillation applications. Gallium nitride (GaN), an alternate III-V, is widely used in optoelectronic and electronic devices, but has not been rigorously investigated for non-linear optics due to a historical lack of native substrates and challenges in selectively controlling GaN polarity on such substrates. In this work we demonstrate lateral and vertical polarity inversion of GaN on GaN substrates. A one-dimensional PO GaN stripe grating was achieved in areas as large as a square-centimeter. The boundaries between lateral polarity changes are both sharp and vertical, and growth conditions have been optimized to provide equal growth rates of both polarities. Chemical etching of the material confirms the polarity of the material. Transmission electron microscopy (TEM) rules out the presence of alternating polar inclusions in the inverted material and shows a strong inversion domain boundary at the vertical interfaces. Dislocation density and grain size were determined through the use of electron channeling contrast imaging and were consistent with high quality epitaxy. The MOCVD-grown PO GaN structures have been extended in thickness by HVPE growth. TEM and photoluminescence imaging confirms that the PO GaN structure is maintained throughout the extended growth of thicknesses up to 80um. This method of GaN polarity inversion offers a means of fabricating heterostructures with both lateral and vertical polarities, opening the potential for novel engineered polarity-based devices.

8604-31, Session 7

Progress in orientation-patterned GaP for next-generation nonlinear optical devices *(Invited Paper)*

Vladimir Tassev, Michael Snure, Rita D. Peterson, Robert G. Bedford, Air Force Research Lab. (United States); William D. Goodhue, Univ. of Massachusetts Lowell (United States); Shivashankar R. Vangala, Solid State Scientific Corp. (United States); Angie Lin, James S. Harris Jr., Martin M. Fejer, Stanford Univ. (United States); Peter G. Schunemann, BAE Systems (United States)

The need for high-brightness tunable coherent mid-IR sources has led to the development of frequency conversion techniques based on quasi-phase matching (QPM) in patterned semiconductors. We compare existing QPM materials with some new candidates from the point of view of their suitability for this application. Due to its broad transparency and small two-photon absorption in the convenient 1.0-1.7 µm pumping region, OPGaP has been recently recognized as one of the most promising QPM materials.

Progress in developing a simple, cost effective OPGaP template preparation technique as well an epitaxial process for a subsequent thick patterned GaP growth is described. The experiments are conducted in a hot-wall horizontal quartz reactor using low-pressure hydride vapor phase epitaxy. The goal was increasing growth rate and layer thickness, while maintaining rectangular domain mesas, equalizing the deposition rates of the two opposite crystallographic orientations, and controlling optical properties by optimizing process parameters. Growth was done on bare GaP wafers and on half-patterned (HP) and orientation-patterned (OP) templates. The latter were fabricated on (100) GaP wafers by a sub-lattice inversion MBE assisted process, and by a wafer fusion technique. Up to 370 µm thick layers with high optical, surface and structural quality were grown on bare wafers in 8-hour long experiments. Growth on HP templates helped to determine the best substrate and pattern orientation, and provided essential feedback to the OP template fabrication process. Growth on OP templates achieved stable deposition rates of 50-70 µm/h with vertically propagating domain walls, following the periodicity of the initial pattern. We produced the first 350 µm thick device quality OPGaP. Specific optical characterizations are in progress.

8604-32, Session 7

Surface plasmon enhanced second harmonic generation in periodically poled whispering gallery resonator

Ardhendu Saha, Nabamita Goswami, Priyanka Dey, National Institute of Technology Agartala (India)

First time we observed analytically the surface plasmon resonance (SPR) enhanced very low threshold second harmonic generation (SHG) in periodically poled MgO doped whispering gallery resonator (WGR). With our survey of generating second harmonic, the range of threshold power has watt and milliwatt ranges. But with our proposed configuration first time SHG will be possible at low threshold input power of microwatt range. This microwatt power is amplified upto milliwatt range through SPR at off resonance condition in Kretschmann configuration which is formed by a BK7 prism (refractive index=1.50066), a 29nm thin gold layer (refractive index=0.38+i10.75) and a 20nm thin GaAs layer (refractive index=3.377-i0.75534) at 25 degree centigrade. This reflected amplified optical radiation enters to a WGR for SHG with a high quality factor. The amplification of incident laser radiation through SPR can be found from electric field enhancement effect which is one of the side effects of SPR phenomenon only in the presence of P-polarized light as incident light & metal-dielectric interface as plane of incident. In our proposed configuration fundamental radiation comes from a mode locked laser, lasing at 1550nm with an input power of 1.53?W which will incident in metal-dielectric interface at an angle 41.5o and an amplified light of 25mW generated through SPR. This reflected power incident in the WGR which is periodically poled for SHG. Then from WGR second harmonic of 14.76mW will be generated. Thus first time with an incident power of microwatt range generation of second harmonic of milliwatt range can be possible.

8604-33, Session 7

Study and design of fractal two dimensional second-order nonlinear photonic crystals

Mohamed Lazoul, Univ. Paris 13 (France)

Recent advances in engineered domain inverted optical lattices have made possible the achievement of multiple quasi-phase-matching (QPM) in second order nonlinear crystals. The designed structures offer multiple solutions for simultaneous nonlinear processes associated with the reciprocal lattice vectors involved in the phase matching.

In the case of two dimensional nonlinear photonic crystals (2D-NLPC), the QPM can be performed by a multitude of reciprocal lattice vectors but in general higher order vectors are less efficient and the overall efficiency is reduced compared to the 1D case.

Many solutions have been suggested in order to quasi phase match more than one nonlinear process in a single crystal. The most important

criterion that must be satisfied is to design photonic structures with substantial Fourier components associated with equalized and maximized generation efficiencies. Structures such as quasi-periodical optical superlattice and aperiodical optical superlattice can satisfy multi-wavelength generation criteria.

The aim behind this work is the design of 2D-NLPC with a new fractal-type reciprocal lattice. The design consists in a fractal-based duplication of square 2D lattices, with different periods associated with the desired nonlinear processes. The new architecture contains more than one reciprocal lattice primitive vectors. Compared to the previous methods, the proposed approach is quite simple to implement and the resulting lattice is substantially rich in significant Fourier components. Simulation results show that the calculated efficiencies for each phase matching order are much more similar and they can be easily maximized by means of optimization algorithms.

8604-34, Session 7

Difference frequency generation in strained silicon waveguides

Federica Bianco, Massimo Cazzanelli, Univ. degli Studi di Trento (Italy); Mher Ghulinyan, Georg Pucker, Fondazione Bruno Kessler (Italy); Lorenzo Pavesi, Univ. degli Studi di Trento (Italy)

Silicon is a centro symmetric crystal with a zero second order nonlinear coefficient. One way to circumvent this intrinsic limitation is to break the centro-symmetry by using interfaces. Another possibility is to strain silicon and, therefore, to induce a bulk second-order nonlinearity. Following this approach, we have experimentally demonstrated that strained silicon waveguides can be mechanically modified within a CMOS-compatible growth technology and that second harmonic generation can be observed with a second order susceptibility chi(2)>40 pm/V. The strain field was caused by a stressing cladding layer made of silicon nitride thin films.

In this work we report on the growth of high optical quality periodically-poled waveguides with micrometric-sized longitudinal poling-period. In this structure we mixed two high-power fs-pulsed near infrared laser beams and demonstrate difference frequency generation. A clear mid-infrared nonlinear conversion is observed. Additionally we observed second-harmonic generation coming from the longer-wavelength single propagating pump beam. The origin of these second-order nonlinear down-conversion effects is attributed to the bulk nonlinear susceptibility induced in the strained silicon waveguides and its enhanced conversion efficiency to the amplification effects due to the quasi-phase matching between the propagating pump and DFG beams achieved in the periodically-poled waveguides. Possible applications in the field of silicon nonlinear optical devices as well as in the on-chip quantum optical devices are described.

8604-35, Session 7

Tapered nanowire waveguide layout for rapid optical loss measurement by cut-back technique

M. Firdaus A. Muttalib, Univ. of Southampton (United Kingdom); Ruiqi Y. Chen, Stuart J. Pearce, Martin D. B. Charlton, Univ. of Southampton (United Kingdom)

Tantalum pentoxide (Ta2O5) is a promising material for both linear and nonlinear integrated optical device fabrication due to its high refractive index, low absorption over a wide wavelength range, high nonlinear refractive index, large value of chi 3 and high optical damage threshold. In particular Ta2O5 rib and ridge waveguides provide an interesting platform for solid state Laser applications. Waveguide surface roughness and sidewall slope profile can induce significant scattering loss reducing the efficiency of the device. Optimization of these parameters is key to obtain ultimate performance of the final device.

In this paper, we present a method and photolithographic mask layout suitable to allow easy measurement of optical propagation loss for planar rib or ridge waveguides equivalent to the standard ‘cut back’ method, but not requiring devices to be cleaved and polished multiple times.

The mask incorporates a set of narrow nano-wire waveguides coupled by tapered waveguide sections to wide input / output guides. The lengths of the central nano-wire section is determined precisely by the lithographic mask. The layout is designed to allow losses of each sub-component such as taper sections and input waveguides to be removed from the measurement, giving accurate measurement of loss in the central nanowire section of the guide.

Optical loss measurements are presented for Tantalum Pentoxide (Ta2O5) nanowire rib waveguides. Loss was found to be dependent on lengths and widths of nanowire waveguide sections. Measured propagation losses for the rib waveguides are found to be just slightly higher than loss of a Ta2O5 slab waveguide as measured by a commercial Metricon system, validating the low loss nanowire waveguide fabrication processes. Propagation losses of 400nm and 2000nm width nanowire waveguides are 6.597dB/cm and 1.515dB/cm respectively.

8604-36, Session 8

Tailorable stimulated Brillouin scattering in silicon nanophotonics *(Invited Paper)*

Peter T. Rakich, Sandia National Labs. (United States) and Yale Univ. (United States); Heedeuk Shin, Sandia National Labs. (United States); Wenjun Qiu, Massachusetts Institute of Technology (United States); Robert L. Jarecki, Jonathan A. Cox, Roy H. Olsson III, Andrew Starbuck, Sandia National Labs. (United States); Zheng Wang, The Univ. of Texas at Austin (United States)

While nanoscale modal confinement has been shown to radically enhance nonlinear light-matter interactions within silicon waveguides, traveling-wave stimulated Brillouin scattering nonlinearities have never been observed in silicon nanophotonics. Through a new class of hybrid photonic-phononic waveguides, we demonstrate traveling-wave forward stimulated Brillouin scattering in nanophotonic silicon waveguides for the first time, yielding thousands of times stronger forward stimulated Brillouin response than any previous waveguide system. Simulations reveal that a coherent combination of electrostrictive forces and radiation pressures are responsible for greatly enhanced photon-phonon coupling at nano-scales. The highly tailorable Brillouin nonlinearities are produced by engineering the structure of the suspended waveguides and observed over wide frequency range 1 – 18 GHz with high quality-factors (>1000). This wideband and tailorable on-chip SBS in silicon nano-structures could enable practical realization of on-chip slow-light devices, RF-photonic filtering and sensing, and ultra-narrow-band laser sources by using standard semiconductor fabrication and CMOS technologies.

8604-37, Session 8

Large second-harmonic generation in silicon nitride films and silicon nitride resonant waveguide gratings

Tingyin Ning, Henna Pietarinen, Outi Hyvärinen, Janne Simonen, Martti Kauranen, Goëry Genty, Tampere Univ. of Technology (Finland)

Large efficiency in nonlinear frequency conversion is paramount for many applications of photonic devices. For integrated nano-photonic applications that require materials with reduced dimensions, enhancing the local fields in sub-wavelength structures is the most promising route to increase the efficiency of nonlinear processes. In addition, it would be highly beneficial to develop nonlinear materials that are compatible with the complementary metal-oxide-semiconductor (CMOS) technology. In

this context, silicon nitride (SiN), with high and tunable refractive index as well as low loss at visible and infrared wavelengths, is a good candidate for on-chip applications.

Here, we first report on the fabrication of amorphous silicon nitride SiN films by plasma-enhanced chemical vapor deposition, where the particular fabrication conditions (ratio of reacting gas, temperature, gas pressure) give rise to a strong second-harmonic response. The value of the dominant tensor component of the second-order susceptibility was found to be as high as 2.5 pm/V, which is comparable to that measured in typical nonlinear crystals. Using this material, we then fabricated an optimized resonant waveguide grating that allows for large enhancement of second-harmonic generation. We demonstrate the emission of a significant second-harmonic signal enhanced by as much as a factor 10^3 compared to a flat SiN film and with a conversion efficiency exceeding 10^-8. Our results show great potential for nonlinear applications of SiN resonant waveguide gratings as nano-photonic devices.

8604-38, Session 8

Giant optical nonlinearity of graphene in a magnetic field

Xianghan Yao, Alexey A. Belyanin, Texas A&M Univ. (United States)

We show that graphene in a magnetic field exhibits an extremely strong optical nonlinearity in the mid- or far-infrared range, perhaps the strongest among known materials. We apply a rigorous quantum-mechanical density matrix formalism to calculate the nonlinear frequency conversion due to the four-wave mixing and Raman scattering processes in strong magnetic and optical fields (X. Yao and A. Belyanin, Phys. Rev. Lett. 108, 255503 (2012)). The bulk third-order nonlinearity per monolayer turns out to be of the order of 0.1 esu in a magnetic field of several Tesla. The high nonlinearity originates from unique electronic properties and selection rules for the transitions between the Landau levels near the Dirac point. These selection rules enable strong allowed transitions with a large change of the principal quantum number, e.g. from n = -1 to n = 2, giving rise to a fully resonant cascade of the optical transitions involved in a multi-wave mixing. As a result, even one monolayer of graphene gives rise to appreciable four-wave mixing efficiency of about 10^-5 for incident infrared radiation. The Raman gain for just one monolayer of graphene can be as high as 0.02. The nonlinear signal can be enhanced by employing multilayer graphene. The nonlinearity is expected to be ultrafast, enabling response to THz modulation. These properties of graphene may have important implications for coherent nonlinear generation and detection in the mid-infrared and THz range.

8604-40, Session 8

Low loss OPGaAs waveguides for quasi-phasematched infrared devices

Izaak V. Kemp, Air Force Research Lab. (United States); Dan Botez, Univ. of Wisconsin-Madison (United States); Rita D. Peterson, Kenneth L. Schepler, Air Force Research Lab. (United States)

The mid-IR frequency band (? = 2-5 ?m) contains several atmospheric transmission windows making it a region of interest for a variety of medical, scientific, commercial, and military applications. Recently there has been a growing interest in using orientation-patterned semiconductors such as OPGaAs to achieve frequency tuning in this region since GaAs has a well developed fabrication technology allowing for the manufacture of devices such as waveguides. By confining the pump beam throughout the length of a waveguide one can achieve very high field intensities while at the same time overcoming the diffraction normally associated with tight focusing of Gaussian beams. However, device performance in OPGaAs waveguides has been limited by large waveguide losses resulting from the unique nature of the material.

In this paper we report an OPGaAs/OPAlxGa1-xAs embedded ridge waveguide which, combined with a new growth process using alternating MOCVD growth and chemical mechanical polishing (CMP), is capable of achieving the low losses necessary to function effectively as a nonlinear gain material. Our waveguide was designed to be single mode from 2-10 ?m, based upon a series of numerical simulations to determine the effective indices of the waveguide across the mid-IR band, which was crucial for accurate calculation of the grating period ? needed for quasi-phasematching. Record low RMS surface roughness values of 8 nm were obtained using this new growth process. In addition, record low OPGaAs waveguide losses of 1.0 dB/cm were measured in an OPA experiment, confirming our theoretical predictions.

8605-1, Session 1

Advances in power-delivery and loss-handling capabilities of small connectors for fiber-optic launching of high-power diode lasers

Stuart Campbell, Magnus Pålsson, Optoskand AB (Sweden)

Constant advancement in laser sources leads to commercial and industrial lasers with ever higher output powers and brilliance. The increasing capabilities of diode laser sources in particular produces extreme challenges for fibre launching. The difficulties arise due to the nature of the diode lasers, which are often designed with a numerical aperture (NA) exceeding the optical fiber's NA and a spot size overfilling the fiber core so as to maintain the best possible brilliance. In addition to these properties, the spot imaged onto the fibre facet is typically rectangular. The combination of these properties result in an imperfect launch efficiency, forcing the connector built around the optical-fibre to cope with the radiation which is "lost" from the core of the fibre.

Improvements in the Optoskand SMAQ connector are discussed, along with the presentation of results showing the increased power- and loss-handling capabilities when used with a variety of diode laser sources at 976nm. The sources used in the tests are optimised for an optical-fibre of core diameter (Ø) 200µm and NA of 0.22. The sources range in maximum power from 150W to 1000W with a coupling efficency of between 80 and 90%.

Additional complimentary results are shown for a Ø=400µm fibre guiding light of NA=0.12 where launch efficiency is 90 to 95%.

8605-2, Session 1

Characterization of laser diodes under short-pulsed conditions with high pulse energies

Tobias Koenning, Evan Hale, Kim Alegria, Steve Patterson, DILAS Diode Laser, Inc. (United States)

New applications require diode lasers to be driven at ultra short pulses in the sub-micro second range. The goal is to minimize both cost and size of the diode laser module by reducing the amount of laser bars to the minimum required number while maintaining a lifetime that is desired for the application. Products demanded by the market range from QCW stacks to fiber coupled modules.

Three key parameters need to be known in order to design a diode laser module that is suited for high peak powers. First is the damage threshold of the facet. The damage threshold determines the maximum power level at which the laser can be operated safely. The damage threshold is a function of the pulse width. The second parameter that is influenced by the drive current is the slow axis divergence of the diode laser. This parameter is critical when laying out optical designs like slow axis collimation optics. The third parameter is the emitter size which may increase with operating current. An increase in emitter size will lead to larger divergence after collimating optics or may result in a larger spot when coupling into an optical fiber. All these parameters have to be considered when designing a new product.

Results for different chip materials will be presented. The data includes damage thresholds, near field and far field data at various operating currents. A design study for fiber coupled modules with high pulse energies based on the test results will be shown for various wavelengths.

8605-3, Session 1

Micro-optics and beam shaping the inconspicuous key elements for highly efficient and brilliant high power diode laser systems

Thomas Mitra, Udo Fornahl, Jana Fründt, Oliver Homburg, Waleri Imgrunt, Manfred Jarczynski, Jens Meinschien, Michael Voss, LIMO Lissotschenko Mikrooptik GmbH (Germany)

Nowadays, almost all semiconductor lasers contain optical elements like simple aspherical collimators or acylindrical fast axis and slow axis collimators. This is due to the fact that light radiating from the emitter is rather lamp light – it is highly divergent and cannot be used commonly without beam conditioning. Opportunities for significant improvement of laser performance by means of well-designed micro lenses and lens arrays were investigated and will be presented. Such optics seem to be non-exciting due to its familiar and wide range use of off the shelf parts. Nevertheless, there is large playground to discriminate high performance optics from standard optics which are worth to be considered in sophisticated laser concepts. Lenses and lens arrays designs need to be reviewed specially to utilize recent progress in in high power diode laser systems which was mainly achieved by intensive efforts in squeezing power and brightness from the light source itself, i.e. from the semiconductor element.

The characteristic of the light source (emitter) and the requirements on the beam thereafter lead to very specific and unique lens designs. This paper evaluates with respect to the beam shaping performance, a wide range parameters e.g. refractive index, focal length, numerical aperture, thickness. A series of examples will be presented, were the optics are compared with respect to key parameters like divergence, beam size and beam parameter product. It is adviced to describe these parameters preferentially in terms of power content values (e.g. 95% power content) compared to form factor parameters (e.g. FWHM or FW1/e2).

8605-4, Session 1

Brightness-doubled high-power single emitters in ultra-compact external cavity for fiber laser pumping

Dan A. Yanson, Moshe Levy, Ido Amrani, Moshe Shamay, Noam Rappaport, Yaroslav Don, Ophir Peleg, Shalom Cohen, Yuri Berk, Genadi Klumel, Renana Tessler, Yoram Karni, SCD Semiconductor Devices (Israel)

Laser diode single emitters offer multi-watt output for fiber laser pumping and direct energy applications. However, their combination and coupling into low-NA delivery fiber is limited by the highly multimode emission in the slow axis (parallel to the p-n junction), with M-squared > 20.

We report a novel brightness improvement scheme by selective optical feedback in a compact external resonator < 2cm long. The scheme is based on non-blocking lateral mode filtering with weak optical feedback and enables spatial mode locking of an anti-reflection-coated single emitter with minimal power penalty.

Optical simulation results are presented showing the lateral mode selection rules in the external cavity and their optimization. Using purpose-fabricated external reflectors with a specific size and reflectivity combination, we demonstrate a brightness doubling with an M-squared reduction from 23 to 12 for an output power of over 10W at 975nm wavelength emitted from a 90 micron laser facet with ultralow AR coating. The doubled brightness is achieved with a wall-plug efficiency of 48% and only a 10% power penalty compared to a typical free-running single emitter.

We present a high-brightness multi-emitter fiber laser pump module with 40W output at 808nm and 55W output across the 900nm – 1100nm wavelength range. The facet-passivated single emitters developed for these pumps reach a rollover-limited power of 20W. Integration of emitters with lower M-squared values in fiber-coupled pump modules allows brightness scaling with a tangible reduction of the fiber NA and/or core diameter with minimal degradation in the coupled power.

8605-5, Session 1

High brightness fiber coupled pump modules optimized for optical efficiency and power

Kirk Price, Marty Hemenway, Ling Bao, John G. Bai, Kylan Hoener, Kevin Shea, David Dawson, Manoj Kanskar, nLIGHT Corp. (United States)

We report on the continued development of high performance fiber coupled laser diode modules at nLIGHT. We show that by optimizing the laser resonator design single emitter diode lasers can be tailored for high brightness or for reduced $/W applications. For instance, a fiber laser pump module based on 6 single emitter diode lasers couples efficiently into a 105um, 0.15 NA fiber with peak operating efficiency >59% and output power > 65W. These results are made possible by optimizing the diode laser slow axis brilliance and by increasing the optical to optical efficiency to 90%. We will also report on the development of tailored laser resonator that meets the power, brightness, and cost targets for industrial applications. For instance, a wider emitter has reliable performance of >18W of output power while maintaining the slow axis divergence required for coupling into a fiber with a 11 mm-mrad beam parameter product. The corresponding 50% increase in output power significantly improves the $/W performance. nLIGHT will also report on volume holographic grating stabilized devices for a variety of pumping applications. These results of high brightness, high efficiency, and wavelength stabilization demonstrate the pump technology required for next generation solid state, fiber lasers, and materials processing applications.

8605-6, Session 2

Monolithic fast-axis collimation of diode laser stacks

Roy McBride, Natalia Trela, Matthew O. Currie, Jozef J. Wendland, PowerPhotonic, Ltd. (United Kingdom)

Commercially-available QCW diode laser stacks with bar pitch below 0.5mm deliver can now deliver source power densities exceeding 10kW/cm^2. An increasing number of applications for these sources also specify high brightness, with collimation requirements ranging from equalisation of fast and slow axis divergence to achieving fast-axis divergence within a small multiple of the diffraction limit. While collimation can be achieved by mounting an array of rod lenses in a frame with a suitable v-groove array, the resulting optical assembly has a large number of elements and associated adhesive bonds, and the size of the mounting frame limits the density at which stacks can be packed together. We present results exploiting an alternative approach using monolithic fast-axis collimator arrays. This approach greatly reduces the component count and minimises the number of adhesive bonds required, providing a compact and rugged assembly well-suited to demanding applications. The monolithic collimator array also simplifies package design, and maximises the achievable device stack packing density. Lens array properties may be tailored to generate application-specific divergence profiles or to match the geometry of individual stacks in order to achieve low divergence. Direct-write fabrication of these components allows mass-customisation, offering a scalable, low-cost route to high volume collimation for fusion applications.

8605-7, Session 2

Optimization of fiber coupling in ultra-high power pump modules at l = 980 nm

Boris N. Sverdlov, Hans-Ulrich Pfeiffer, Evgeny Zibik, Stefan Mohrdiek, Michele Agresti, Norbert Lichtenstein, Oclaro, Inc. (Switzerland)

This work is based on results from our development of ultra-high power single-mode pump modules at ??= 980 nm for erbium-doped fiber amplifiers. The laser diodes for these modules achieve more than 3 W of output power and more than 2 W of kink-free power in CW regime at room temperature. With the laser differential quantum efficiency approaching 90% and laser power conversion efficiency already at 65%, the problem of overall module efficiency shifts more and more to improving the optical coupling between the laser and the output fiber of the pump module. We performed investigation of various laser waveguide structures directed towards improving the fiber coupling efficiency. The so called integrated fiber wedge lens was used as a coupling element in the present investigation. Numerical estimates show that between the two most widely used laser waveguide types: large optical cavity (LOC) and separate confinement (SCH or GRICC) heterostructures the difference in coupling efficiency can be as high as ten percent. We achieved experimental coupling efficiencies of? 93 percent for LOC-like laser structures. The SCH-based lasers showed a maximum coupling efficiency of 83 percent. However in spite of much better coupling efficiency the general performance of LOC-based laser modules is rather poor due to lower power conversion efficiency of LOC lasers in comparison with SCH lasers. To improve the situation we had to find a reasonable compromise between the two structures. Lasers from this approach gave coupling efficiencies around 90 percent. The pump modules built on these lasers showed linear wavelength-stabilized output up to 1.8 W CW at room temperature. We will also discuss in more detail the operating characteristics of these modules.

8605-8, Session 2

Micro-lens arrays for laser beam homogenization

Volker R. Sinhoff, Stefan Hambuecker, Olaf Ruebenach, Christian Wessling, Klaus Kleine, INGENERIC GmbH (Germany)

For a long time, micro-optics have been an indispensable component of the system design for shaping the beam of high power semiconductor lasers – whether in the form of fast and slow axis collimation optics in order to collimate or symmetrize the laser beam, or in the form of beam transformation optics for efficient fiber coupling. For many innovative applications a significant improvement in the homogeneity of the laser beam is a critical requirement when using semiconductor lasers. Likewise, for the next generation of laser diode types, appropriate collimation optics need to be developed and be manufacturable on a large scale.

There are several different methods for the homogenization of laser radiation. For example, homogenization of a specified beam profile, for example a Gaussian beam, can be achieved using specially shaped aspheres. The disadvantage of this solution is the high sensitivity of the homogenization result in terms of fluctuations in the initial beam profile and the assembly accuracy. Another method for homogenization of laser radiation is the use of waveguides or optical fibers. However, this method requires a sophisticated assembly process and sufficient installation space.

Homogenization using micro-cylinder lens arrays is a considerably more elegant and compact solution. In this case the incident laser beam is separated into partial beams by one or more micro-lens arrays. These partial beams are then overlaid in the homogenization plane by the downstream optics. Depending on the arrangement and geometry of the micro-lenses, this enables homogeneously illuminated lines, rectangles or squares to be generated. The major advantage of this solution lies in the increased freedom of adjustment to account for the initial beam profile,

as well as the extremely compact design.

In addition to a comparison of different homogenization principles the paper describes new approaches of homogenization via micro-lens arrays and compares the impact on the array performance by different manufacturing approaches.

8605-9, Session 2

Power scaling to high-brightness kW systems using semiconductor bars in water-cooled stacks

David A. Schleuning, Keith Guinn, Serguei Kim, Krishna Kuchibhotla, Calvin Luong, Yu Zhang, Bruno Acklin, Coherent, Inc. (United States)

The scalability of semiconductor diode lasers to multi-kWatt power levels has increasing importance in applications of direct diode material processing. These applications require hard-pulse on-off cycling capability and the high brightness achieved by low fill-factor bars mounted with a tight vertical pitch. Coherent uses 20%FF bars operated at >80W/bar packaged on water-cooled packages with a vertical pitch of 1.65mm in the Highligh D-series which achieves up to 10kW of power in a line beam of less than 1mm x 8mm with a working distance of roughly 300mm. We present thermal results compared to fluid flow modeling to show that each emitter is cooled individually to a low junction temperature with minimal thermal cross-talk similar to single emitter packaging. The good thermal performance allows for scaling to operation at higher power and brightness. We present accelerated life-testing results in both CW and hard-pulse on-off cycling conditions.

8605-10, Session 2

Multi-kW high-brightness fiber coupled diode laser

Bernd Köhler, Armin Segref, Paul Wolf, Andreas Unger, Heiko Kissel, Jens Biesenbach, DILAS Diodenlaser GmbH (Germany)

Fiber coupled diode laser devices are attractive light sources for applications in the area of solid-state laser pumping and materials processing. The ongoing improvement in the brightness of diode lasers, which means power per beam quality, makes more and more industrial applications accessible to diode lasers. For many applications in materials processing multi-kW output power with a beam quality of better than 30 mm x mrad is needed.

Previously we have reported on a modular diode laser platform based on a tailored bar design (T-Bar) and have demonstrated an output power of up to 785 W out of a 200 µm NA 0.22 fiber at a single wavelength of 976 nm. We have now extended that tailored bar platform to different wavelengths in the range from 900 nm to 1100 nm. At each single wavelength efficient fiber coupling into a 200 µm NA 0.22 fiber will be demonstrated.

One important concept for power scaling is coarse wavelength multiplexing with a spectral separation of typically about 40 nm. Combining of different wavelengths enables scalable multi-kW high-brightness diode laser units. Further power scaling can be achieved by dense wavelength multiplexing with a spectral separation of only about 5 nm.

In this paper we report on a diode laser unit with 3.5 kW output power and a beam quality of 25 mm x mrad.

8605-11, Session 3

Laser bars and single emitters in the 9xx emission range optimized for high output powers at reduced far field angles

Martin Zorn, Ralf Huelsewede, Agnieszka Pietrzak, Olaf Hirsekorn, Haike Schulze, Juergen Sebastian, JENOPTIK Diode Lab GmbH (Germany); Petra Hennig, JENOPTIK Laser GmbH (Germany)

High-power single emitters and laser bars are used as light sources in many industrial applications such as material processing or as pump sources for solid state or fiber lasers.

Those applications require laser devices with high optical power, high efficiency and high brightness. To fulfill the requirements the laser design in both directions, vertical and lateral, is continuously improved. We have optimized an epitaxial structure, emitting at 940nm, for a strongly reduced vertical carrier leakage, lower thermal and electrical resistance resulting in high electro-optical efficiency even at high currents. Furthermore the vertical divergence angle containing 95% power was reduced to 40°. 200W CW-power was reached from the improved laser design when processed as high fill-factor bars and mounted on passively cooled sub-mounts. There were no signs of the laser degradation observed. The knowledge gained from the development of 9xx-devices was utilized for the optimization of laser structures emitting at 880 nm, founding application in laser fusion.

The Jenoptik's technology of 12W 940nm single emitters with operating efficiency of 65% (peak efficiency >70%) has been currently extended to emission wavelengths of 915nm and 976nm. The epitaxial design was slightly adjusted for these two wavelengths and laser structures having comparable electro-optical parameters to those emitting at 940nm were grown. Therefore a high output power with an excellent efficiency is to be expected from the mounted devices as well.

8605-12, Session 3

Higher brightness laser diodes with smaller slow axis divergence

Wenyang Sun, Science Research Lab., Inc. (United States); Rajiv Pathak, Coherent, Inc. (United States); Mehmet Dogan, Geoff Campbell, Henry Eppich, Jonah H. Jacob, Science Research Lab., Inc. (United States); Aland K. Chin, Somerville Laser Technology, LLC (United States); Jack Fryer, Micro Cooling Concepts, Inc. (United States)

We will present experimental measurements of the slow axis (SA) divergence of 20% fill-factor, 980nm, laser diode (LD) bars that were operated at powers of > 300W/bar, well above the state-of-the-art 60-80W/bar. The LDs had gain lengths ranging from 4 to 7mm. Under CW operation, the SA divergence was essentially a function of the power per emitter. The SA divergence had a very slow variation with gain length. The full angle SA divergence, for 95% of power containment, was ~ 5° just above threshold and as large as 13° at the highest power of > 300W/bar, corresponding to > 17W/emitter. Most of the increase in the SA divergence, as the power increased from near threshold to the highest power, was the result of a spatial temperature gradient across the 100µm stripe width. By attaching the LD chips to appropriately designed coolers, that eliminated the temperature gradient, the SA divergence increase with power/emitter was much slower. The SA divergence at > 300W/bar was 7.5°, resulting in an increased brightness of 2X at the highest power levels.

8605-13, Session 3

Liquid metal heat sink for high-power laser diodes

John Vetrovec, Drew A. Copeland, Amardeep S. Litt, Aqwest, LLC (United States); Jeremy Junghans, Roger Durkee, Northrop Grumman Cutting Edge Optronics (United States)

We report on an active heat sink cooled by a liquid metal offering very low thermal resistance, electronic temperature control, and compact packaging. This self-contained heat sink uses a liquid metal coolant flowing in a miniature, closed, and sealed flow loop. The flow is energized without any moving components by a miniature magneto-hydrodynamic pump integrated with the unit. The high thermal conductivity of the liquid metal in combination with a high flow velocity enables very efficient removal of waste heat from the laser diodes. Testing at laser powers at up to 120 W shows that the liquid metal heat sink offers major advantages over traditional technologies for thermal management of laser diodes. This paper discusses the results of parametric testing of laser diodes with various configurations of the heat sink.

8605-14, Session 3

Optimizing performance of 808 nm diode laser bars for efficient high-temperature operation

John G. Bai, Ling Bao, Zhigang Chen, Weimin Dong, Xingguo Guan, Shiguo Zhang, Jason Patternson, Mike Grimshaw, Mark DeVito, Manoj Kanskar, Rob Martinsen, Jim Haden, nLIGHT Corp. (United States)

Both high-temperature and high-efficiency epitaxial materials emitting in the 780-820 nm range were optimized for continuous wave (CW) operation. Refined phenomenological modeling of diode lasers allowed tailoring of device parameters to obtain optimized bar performance. In other words, we adjusted modeling inputs such as bar layout, facet coating, and thermal resistance, etc., to optimize modeling outputs such as operation current and wall plug efficiency as the operational indicators. Thus, both time and cost were saved without the need of extra experimental runs. We demonstrated that both high-temperature and high-efficiency epitaxial designs can support centimeter bars with power ratings well beyond 100W/bar. At the standard power rating of 100W/bar, the high-efficiency designs show advantages in both operating current and efficiency as compared to the high-temperature designs. Higher power ratings such as 250W/bar are achievable with newly released high-efficiency epitaxial designs. It is expected that the development of these high power and highly efficient semiconductor laser bars will enable new commercial applications in the areas of defense as well as the consumer markets which demand high-power and high-efficiency lasers.

8605-15, Session 4

High power high beam quality laser source with narrow stable spectra based on truncated-tapered semiconductor amplifier

Xiaozhuo Wang, Götz Erbert, Hans Wenzel, Paul Crump, Bernd Eppich, Steffen Knigge, Peter Ressel, Arnim Ginolas, Andre Maassdorf, Guenther Tränkle, Ferdinand-Braun-Institut (Germany)

High power diode lasers are increasingly important in many industrial applications. However, an ongoing challenge is to simultaneously obtain high output power, diffraction-limited beam quality and narrow spectral width. One approach to fulfill these requirements is to use a “master oscillator - power amplifier (MOPA)” system. We present recent data on MOPAs using PA designs that have low confinement factor (1%), leading to low modal gain, and low optical loss (<0.5cm-1). Quantum barriers with low refractive index are used to reduce the optical waveguiding due to the active region, which should decrease susceptibility to filament formation. A truncated tapered lateral design was used. Conventional tapered designs have a ridge waveguide (RW) at the entrance of the devices with etched beam spoilers at the transition to the tapered gain region. Our truncated amplifier design has no RW entrance section. We show that for this design beam spoilers are not necessary, and achieve improved performance when they are omitted, which we attribute to the filament insensitivity of our structure. High beam quality was achieved from 970nm amplifier with M2 (1/e2) = 1.9, with efficiency of >48% in QCW condition, and >17W diffraction-limited beam maintained in the central lobe. The impact of the in-plane geometrical design was assessed. Large surface area is advantageous for device performance. The spectral properties of the amplifier replicated that of the DBR-tapered laser, which is used as the master oscillator, with a spectral width of <30pm (FWHM). Design options for further increases in power will also be presented.

8605-16, Session 4

Novel opto-mechanical platform for line generators of high-power diode lasers

Jens Meinschien, Melanie Brodner, Udo Fornahl, Dirk Hauschild, Ulrich Jentsch, Thomas Mitra, Stephan Schneider, Detlef Stöhr, LIMO Lissotschenko Mikrooptik GmbH (Germany)

Novel configurations for line generators of high power diode lasers are presented which take into account high demands particularly for three key parameters: high power density per line length (20…60 W/mm), small line width (50 µm … 200 µm) and scalability to real long line lengths (1 m and more). These parameter sets are proven on small scale test systems to be vital for surface processing applications which can only be reasonably implemented by laser technology.

The approach followed here is to extrapolate requirements on the entire laser concept (optics, mechanics, beam shaping, laser diodes as light source) starting from the target parameters of the application and tracing back to the beam shaping, to the light source and the mechanics, respectively. A configuration of passively cooled laser diode bars is chosen to address high brightness and high compactness of the assembly. The beam shaping approach allows firstly a beam quality in one axis (fast axis) with M2 smaller than 5, secondly a uniform intensity distribution in the other axis (slow axis) with an inhomogeneity smaller than 5% and thirdly true scalability to line lengths in the range of several meters without the need of optical elements of such unrealistic large size. The mechanical concept takes into account a modular approach which addresses production and supply chain aspects with a significant number of identical sub-units.

The herewith presented approach is feasible for a large range of applications were surfaces or thin films are treated by scanning processes in large scale, e.g. photovoltaics, flat panel displays production, drying and annealing surfaces. Such a laser system can be implemented into inline-processes. It avoids the circumstances for oven processes and is much more energy efficient. The energy consumption for thermal processes on surfaces can be reduced to 25% or less compared to standard heat treatment procedures.

Green Photonics:

The herewith presented approach is feasible for a large range of applications were surfaces or thin films are treated by scanning processes in large scale, e.g. photovoltaics, flat panel displays production, drying and annealing surfaces. Such a laser system can be implemented into inline-processes. It avoids the circumstances for oven processes and is much more energy efficient. The energy consumption for thermal processes on surfaces can be reduced to 25% or less compared to standard heat treatment procedures. It is even possible to treat thin films to temperatures exceeding 1000 °C on top of sensitive substrate materials, e.g. melting silicon layers on glass substrates.

8605-17, Session 4

High-power and high-efficiency distributed feedback (DFB) lasers operating in the 1.4-1.6 mm range for eye-safe applications

Toby J. Garrod, Christian Galstad, Michael Klaus, Don Olson, Yan Xiao, Francois Brunet, Alfalight, Inc. (United States)

Incorporating monolithic distributed feedback (DFB) gratings in broad area (BA) diode lasers results in a ten times narrower spectral width and four-to-five times lower thermal shift in emission wavelength. We report on our progress to obtaining a high-power, high-efficiency DFB diode pump in the 1.4 – 1.6 um range for use in industrial and military, eye-safe applications.

High power diode laser bar technologies emitting at 9xx nm have made significant progress in terms of reliable power (>100W), efficiency (>70%) and brightness (HFF ~ 10°) over the last decade. This level of power and efficiency has not been demonstrated for long wavelength diode pumps emitting around 1.4 – 1.6 um, a range useful for pumping solid-state laser systems and direct-diode applications. It is evident that all diode-pumped laser systems will benefit from pumps that have high efficiency, high brightness, high temperature operation (20°C to 80°C), a stable spectrum, and a narrow line-width that overlaps with the gain absorption spectrum. Alfalight is an industry leader in pushing the performance envelope of diode lasers with these attributes. Diode pumps used in Er:YAG solid-state lasers require a wide operating temperature range and narrow, stable emission spectrum. Conventional broad area (BA) laser diodes emitting light around 1.5 um have a spectral width of 6 – 8 nm. This is not sufficient for efficiently pumping solid-state lasers with absorption features less than 1 nm. The ability to incorporate a monolithic distributed feedback (DFB) grating into a BA laser results in a high power, high efficiency diode source with a narrow (<0.5 nm), stable spectrum (dl/dT = 0.1 nm/°C). We report on the design and fabrication progress of a high power, high efficiency DFB laser emitting around 1.5 um.

8605-18, Session 4

High brightness laser systems incorporating advanced laser bars

Stephan G. Strohmaier, TRUMPF Photonics (United States)

The performance of high power and high brightness systems has been developing and is developing fast. In the multi kW regime both very high spatial and spectral brightness systems are emerging. Also diode laser pumped and direct diode lasers are becoming the standard laser sources for many applications. The pump sources for thin disk laser systems at TRUMPF Photonics enabled by high power and efficiency laser bars are becoming a well established standard in the industry with over two thousand 8 kW disc laser pumps installed in TruDisk systems at the customer site. These systems have proven to be a robust and reliable industrial tool. A further increase in power and efficiency of the bar can be easily used to scale the TruDisk output power without major changes in the pump source design.

This publication will highlight advanced laser systems in the multi kW range for both direct application and solid state laser pumping using specifically tailored diode laser bars for high spatial and/or high spectral brightness. Results using wavelength stabilization techniques suitable for high power CW laser system applications will be presented.

These high power and high brightness diode laser systems, fiber coupled or in free space configuration, depending on application or customer need, typically operate in the range of 900 to 1070 nm wavelength.

8605-19, Session 4

High-power fiber-coupled 100 W visible spectrum diode lasers for display applications

Andreas Unger, Bernd Köhler, Matthias Küster, Jens Biesenbach, DILAS Diodenlaser GmbH (Germany)

Diode lasers in the blue and red spectral range are the most promising light sources for upcoming high-brightness digital projectors in cinemas and large venue displays. They combine improved efficiency, longer lifetime and a greatly improved color space compared to traditional xenon light sources. The availability of high-power red diode bars and GaN-based blue emitters makes this long dreamed of sources now feasible.

In this paper we report the development of high-power visible diode laser sources to serve the demands of this emerging market. We show fiber-coupled and free-space red diode laser units based on the previously published T-Bar approach. A unique electro-optical platform enables scalable fiber coupled sources at 638 nm with an output power of up to 100 W from a 400 µm NA 0.22 fiber in a small footprint. For the blue diode laser source we demonstrate a modular coupling concept based on 450 nm single emitters. This concept enables scalable sources from 5 W to 100 W from a 400 µm NA 0.22 fiber. We present a newly designed set up which enables dense 2-dimensional stacking for generating a collimated beam or fiber coupling of multiple single emitters, avoiding individual lens alignment.

8605-20, Session 5

The impact of external optical feedback to the degradation behavior of high-power diode lasers

Martin Hempel, Forschungsverbund Berlin e.V. (Germany); Mingjun Chi, Paul M. Petersen, Technical Univ. of Denmark (Denmark); Ute Zeimer, Ferdinand-Braun-Institut (Germany); Jens W. Tomm, Forschungsverbund Berlin e.V. (Germany)

We investigate early stages of gradual device degradation that took place under external optical feedback in commercial 808 nm emitting AlGaAs-based high-power diodes. For this purpose accelerated aging tests at high current levels of 200 h duration have been made. Almost linear gradual power losses of 5.4 and 2.4 percent have been observed with and without external feedback, respectively. Subsequently these devices (an pristine reference devices from the same batch) have been analyzed with respect to alterations that are responsible for the gradual power losses observed. Photoluminescence (PL) and electroluminescence (EL) spectroscopy at the facet revealed that the changes took place underneath the front facet (i.e. not in the bulk) without producing any signatures being detectable by external inspection. Preparative opening allowed for the inspection of the layers forming the 'active region' of the lasers. Within the cladding layers clear signatures of (point) defect creation are observed by Raman spectroscopy. These layers are also the ones containing the highest Al-content. Spatial intensity fluctuations and dark spots in the waveguide CL maps pinpoint alterations also at this layer. At the same time, CL and PL mapping proved the quantum well, which doubtlessly experiences the highest total optical load, to be not affected by any detectable aging effects. We conclude that under external optical feedback waveguide and cladding layers represent bottlenecks. Thus hardening of diode lasers against effects implemented by external feedback must necessarily involve them.

8605-22, Session 5

Catastrophic optical bulk damage (COBD) processes in aged and proton-irradiated high power InGaAs-AlGaAs strained quantum well lasers

Yongkun Sin, Stephen LaLumondiere, Brendan Foran, Nathan Presser, William Lotshaw, Steven C. Moss, The Aerospace Corp. (United States)

Unprecedented characteristics of broad-area InGaAs-AlGaAs strained quantum well (QW) lasers include optical output powers of over 20 W and power conversion efficiencies of over 70%. Leading manufacturers have recently demonstrated encouraging reliability in these lasers, but their long-term reliability has never been demonstrated for satellite communication systems. Furthermore, the dominant failure mode of these lasers is catastrophic optical bulk damage (COBD), which is a new failure type requiring physics of failure investigation to understand its root causes.

We investigated reliability, radiation effects, and the root causes of COBD processes in MOCVD-grown broad-area InGaAs-AlGaAs strained QW lasers using various FMA techniques. Two different approaches were taken to degrade lasers: accelerated life-testing and proton irradiation. We studied the growth of point defects introduced during crystal growth as well as those induced by proton irradiation with different energies and fluences in the lasers during degradation processes. Deep level transient spectroscopy and time-resolved photoluminescence techniques were employed to study trap characteristics and carrier dynamics in pre- and post-stressed lasers and these characteristics are compared with those in pre- and post-proton irradiated lasers to study the role that non-radiative recombination centers play in COBD. During entire accelerated life-tests, time-resolved electroluminescence 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. Lastly, we employed EBIC, FIB, and high-resolution TEM to study dark line defects and crystal defects in both post-aged and post-proton irradiated lasers at different stages of degradation.

8605-23, Session 5

Reliability of high power/brightness diode lasers emitting from 790 to 980 nm

Ling Bao, John G. Bai, Kirk Price, Kevin Bruce, Mark Devito, Mike Grimshaw, Weimin Dong, Xingguo Guan, Shiguo Zhang, Hailong Zhou, David Dawson, Manoj Kanskar, Rob Martinsen, Jim Haden, nLIGHT Corp. (United States)

This paper presents nLIGHT's recent progress in the development of high power single emitter laser diodes from 790 to 980 nm for reliable use in industrial and pumping applications.

A newly released laser design demonstrates near-penalty-free efficiency on 5 mm long laser cavity diodes at 915-980 nm. 5 mm long laser cavity single emitters can be reliably operated from 12 W to 20 W in different optimized fiber-coupled modules to meet different power/brightness/cost requirements. The output power of these devices is thermally limited without catastrophic optical damage (COD) even at higher current operation. The ongoing highly accelerated life-test has accumulated over 100000 raw device hours, with extremely low failure rate observed to date. More reliability experiments are underway to compare this chip design to the 3.8 mm, 95 um device design that demonstrated FIT rates < 1000 at a rated power of 12W, as evaluated in a two-year long multi-cell life-test.

High performance and reliability designs have also been extended to the 790 to 880 nm ranges, with a corresponding peak efficiency value in excess of 65%. We will present reliability studies for these single emitters under highly accelerated conditions (14-16A) and single emitter based fiber-coupled modules (reasonably accelerated at 8-10A). Two failure modes following random and wear-out failure statistics will be analyzed and discussed in detail.

Reliability study of lensed diode lasers and VBG locked diode lasers also reveal back-reflection related results for detailed discussion at different emitting wavelengths.

8605-24, Session 5

High power 405 nm diode laser fiber-coupled single-mode system with high long-term stability

Cornell P. Gonschior, Karl-Friedrich Klein, Technische Hochschule Mittelhessen (Germany); Tong Sun, Ken T. V. Grattan, The City Univ. (United Kingdom)

Fiber-coupled 405 nm diode laser systems are rarely used with fiber output powers higher than 50 mW. A quick degradation of fiber-coupled high power modules with wavelengths in the lower range of the visible spectrum is known for several years. Meanwhile, the demand for high power fiber-coupled violet laser systems is increasing, but this issue remained unexplained. The typical power of single-mode diode lasers around 400 nm is in the order of 100 to 300 mW. When coupling with single-mode fibers power densities in the 1 MW/cm? range are achieved. This is three magnitudes of order below the known threshold for optical damage. Our profound investigations on the influence of 405 nm laser light irradiation of synthetic silica fibers with undoped core and fluorine-doped cladding found the growth of periodic surface structures in the form of ripples responsible for the power loss. The ripples are found on the proximal and distal fiber end-faces, negatively impacting power transmission and beam quality, respectively. Important parameters in the generation of the surface structures are power density, surface roughness and polarization direction. Following our investigations we developed a fiber-coupled high-power 405 nm diode laser system that exhibits a high long-term stability which will be introduced and described here. Several 1000 h irradiation tests with power densities higher than 1 MW/cm? in the fiber core were executed and proved its reliability.

8605-25, Session 5

Laser-bar stack using ELF heat-sinks mounted kinematically for double-sided cooling

Aland K. Chin, Somerville Laser Technology, LLC (United States); Jeff G. Manni, JGM Associates, Inc. (United States); Richard H. Chin, Science Research Lab., Inc. (United States); Joe Levy, Northrop Grumman Cutting Edge Optronics (United States); Mehmet Dogan, Jonah H. Jacob, Science Research Lab., Inc. (United States); Rajiv Pathak, Coherent, Inc. (United States); Christian Wessling, INGENERIC GmbH (Germany); Keith D. Lang, Henry Eppich, Science Research Lab., Inc. (United States); Jay Fryer, Micro Cooling Concepts, Inc. (United States); Tobias Haverkamp, INGENERIC GmbH (Germany)

Single laser-diode (LD) emitters for fiber coupling are well developed and manufactured in high volume. Less-developed LD-bars, ~1cm wide, are inherently more suited for high-power applications due to their compact size. However, even though the wall-plug efficiency exceeds 60%, high power bars must be water-cooled to remove the waste heat and vertically stacked to efficiently couple the power of multiple bars into the round aperture of a fiber. To compete effectively with single LD-emitters, LD-bars for fiber coupling must have high brightness, high reliability and low cost in terms of dollars per watt. For reliable operation of LD-bars at high optical power, it is important to minimize the junction temperature and the mechanical stress. High brightness implies low smile; low cost implies a simple method of stacking while maintaining single-bar performance-features. We have developed the long lifetime, enhanced lateral-flow (ELF) heat-sink whose low thermal-impedance allows the realization of high-power LD-bar operation. By adding mounting screws to the ELF, the heat-sink becomes a kinematic mount that improves LD lifetime by transmitting low mechanical-stress and also providing beneficial, double-sided cooling to the LD-bars. We demonstrate a CW, 480W, 6-bar stack of collimated, 20% fill factor (FF), 976nm bars with a beam-parameter product (BPP) of <10 mm-mrad by <91 mm-mrad. In our initial attempt, using a polarization multiplexer to fold the beam along the slow axis (SA), we are able to couple 250W of the light from the stack directly into a 250µm, 0.46NA double clad fiber (BPP ~57 mm-mrad) typically used in high power fiber lasers. The power limitation is due to unexpected ghost images along the SA that will be removed with an aperture in the future.

8605-26, Session 6

Compact high brightness diode laser emitting 400W from a 0.1mm fiber

Stefan W. Heinemann, Benjamin Lewis, Torsten Schmidt, Fraunhofer USA, Inc. (United States); Ulrich Pahl, Wolfgang Gries, DirectPhotonics Industries GmbH (Germany)

Single emitter diodes allow highest brightness, excellent reliability and simple cooling. Optical stacking and dense spectral combining are deployed for power scaling. The core technologies for low cost, high power multiple single emitter diode lasers are automated manufacturing with real time quality control, efficient optical stacking and spectral combining with minimum channel spacing.

We will present our modular product design that optically stacks about 50 single emitters in a compact package for coupling into a 100?m fiber with 0.15 NA. We leverage our next generation, flexible, automated manufacturing line for cost effective production. A precision robotic system handles and aligns the individual fast axis lenses within less than 90 seconds and tracks all quality relevant data. Dense spectral combining uses external Volume Bragg Grating or dichroic filters. The impact on diode reliability, power scalability and manufacturing will be discussed for these two approaches. Three channels are combined within the 5nm fitting the absorption bandwidth of many laser crystals. The narrow, stabilized spectrum and the high brightness enable advanced pumping.

Individual modules emit 400W from a 100?m fiber with 0.15 NA and are the basic building block for multi kilowatt systems with identical beam quality. Integrated power supplies and control enable pulsing with more than 500 kHz repetition rate. Such diode laser systems open the door for laser cutting, welding and ablation.

8605-27, Session 6

Suppression of mode switching noise in wavelength stabilized laser diodes by external Bragg gratings

Karl Häusler, Ralf Staske, Goetz Erbert, Ferdinand-Braun-Institut (Germany)

Wavelength stabilized laser diodes are applied in many technical fields, such as spectroscopy, atomic clocks, or pumping of fiber lasers and solid state lasers. Whenever a small thermal drift of wavelength is required, external Bragg Gratings are the preferred devices instead of monolithically integrated gratings. Some applications, such as optical free space communications based on Nd:YAG lasers require a pump source with very low noise in the range of the relaxation oscillation frequency of the YAG, which is several 100 kHz. Typically, broad area (BA) laser diodes are used as pump laser. The disadvantage of external feedback is the onset of intensity noise at low frequency in the range of few Hz up to several MHz originating from switching of higher order optical modes in the BA laser.

We studied a configuration using single mode 808 nm emitting lasers where the relative intensity noise in the low frequency range was reduced by several orders of magnitude compared to multimode emitters. The influence of external optical feedback by volume holographic gratings on the optical intensity, mode switching and intensity fluctuations was examined. Quantum well lasers with different optical cavity width and different anti reflecting coatings were characterized dependent on the phase difference between emitted and reflected radiation by variation of the distance between Bragg grating and laser facet at high resolution of few nm. For higher power applications the single mode emitters were assembled as laser bars. Measurements of laser bar characteristics demonstrate an excellent stability of wavelength over a large temperature range of typically +-10 K around the working temperature, small thermal drift of the wavelength of less than 25 pm/K and suppression of mode switching noise in the low frequency range up to 10 MHz at several Watts of optical powers.

8605-28, Session 6

Multi-wavelength operation of an unstructured broad area diode laser using spectral beam combining

Christof Zink, Antonio Saghati, Ronny Schmidt, Danilo Skoczowsky, Axel Heuer, Ralf Menzel, Univ. Potsdam (Germany)

An experimental realization of a multiline broadband diode laser for measurement applications is presented. It is based on an external cavity setup where the optical components of the cavity maintain distinct gain channels in a single broad area diode laser (BAL). The combination of a dispersive element and an aperture inside the cavity provides laser light channels in the unstructured active region of the diode laser. Each channel lases at a distinct wavelength and therefore mode competition is suppressed and crosstalk reduced.

The setup of the external cavity is based on spectral beam combining schemes developed for laser arrays. The cavity consists of a fast axis collimator (FAC), a cylindrical lens, a diffraction grating, a mirror, a slit aperture and an outcoupling mirror. The cylindrical lens transforms the position of the active region at the front facet into the angle of incidence onto the grating. To ensure spatial overlap the grating is placed in the focal plane of the cylindrical lens. Codirectional propagation is forced by the second pass of the cylindrical lens. In this configuration the double pass through the lens forms a telescope, which images the front facet of the BAL on the outcoupling mirror. Thus the size of the slit aperture, directly adhered to the mirror, defines the size of the induced gain channels inside the BAL. Because of the different incident angles of the BAL beams at the grating they will operate at different wavelengths.

We examined a commercial BAL with a width of 1000 µm operating around 780 nm. Different setups with diverse gratings and different widths of the mode selective aperture were analyzed. The number of the induced channels visible in the near field corresponds to the measured spectrum of the laser.

8605-29, Session 6

Low-loss smile-insensitive external frequency-stabilization of high power diode lasers enabled by vertical designs with extremely low divergence angle and high efficiency

Paul Crump, Steffen Knigge, Andre Maassdorf, Frank Bugge, Ferdinand-Braun-Institut (Germany); Stefan Hengesbach, Ulrich Witte, Hans-Dieter Hoffmann, Fraunhofer-Institut für Lasertechnik (Germany); Bernd Köhler, Ralf Hubrich, Heiko Kissel, Jens Biesenbach, DILAS Diodenlaser GmbH (Germany); Götz Erbert, Guenther Traenkle, Ferdinand-Braun-Institut (Germany)

Broad area lasers with narrow spectra are required for many pumping applications and for wavelength beam combination. Although monolithically stabilised lasers show high performance, some applications can only be addressed with external frequency stabilisation, for example when very narrow spectra are required. When conventional diode lasers with vertical far field angle, VFF95 ~ 45° (95% power) are stabilised using volume holographic gratings (VHGs), optical losses are introduced, limiting both efficiency and reliable output power, with the presence of any bar smile compounding the challenge. Diode lasers with designs optimized for extremely low vertical divergence (ELoD lasers) directly address these challenges. The vertical far field angle in conventional laser designs is limited by the waveguiding of the active region itself. In ELoD designs, quantum barriers are used that have low refractive index, enabling the influence of the active region to be suppressed, leading to narrow far field operation from thin vertical structures, for minimal electrical resistance and maximum power conversion efficiency. We review the design process, and show that 975nm diode lasers with 90µm stripes that use ELoD designs operate with VFF95 = 26° and reach 58% power conversion efficiency at a CW output power of 10W. We demonstrate directly that VHG stabilised ELoD lasers have significantly lower loss and larger operation windows than conventional lasers in both divergent and collimated feedback regimes, even in the presence of significant (≥1µm) bar smile. We review also the influence of ELoD designs on reliable output power and discuss options for further performance improvement.

8605-30, Session 7

Advances in high power and high brightness laser bars with enhanced reliability

Haiyan An, John Jiang, Yihan Xiong, Aloysius Inyang, Qiang Zhang, Alexander Lewin, Stephan G. Strohmaier, Georg Treusch, TRUMPF Photonics (United States)

High power and efficiency laser bars with high fill factor have been used to build the pump sources for thin disc laser systems at TRUMPF Photonics. With over 1,500 high power disk lasers installed, the disc laser system – powered by our pump sources – has proven to be a robust and reliable industrial tool. We have further optimized bar design for this application.

In addition, we use the low fill factor bars to build the fiber-coupled, direct diode laser systems. Higher reliable output power, higher efficiency, and better slow axis beam quality of the high power laser bars are needed to further increase the brightness. We have optimized the bar epitaxial structures as well as the lateral design in order to improve the slow axis beam quality. The detailed near field and far field studies of the slow axis for each individual emitter on the bar allow us to understand the dependency of beam quality as function of the drive current. We have optimized the high brightness bar designs at 900-1070nm wavelengths based on these study results for direct diode application.

In this paper, we will give an overview of our recent advances in high power and high brightness laser bars with enhanced reliability. We will present the beam quality study and reliability test results of our laser bars in the 900-1070nm wavelength region for coarse wavelength multiplexing. The performance and reliability results of the 200W/bar for our next generation thin disk laser pump source will be presented as well.

8605-31, Session 7

Reliable QCW diode laser arrays for operation with high duty cycles

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

Quasi-continuous wave (QCW) laser bars and arrays have found a wide range of industrial, medical, scientific, military and space applications with a broad variety in pulse energy, pulse duration and beam quality. New applications require even higher duty cycles, increased operating temperatures and less or no cooling.

We present performance and reliability data of two novel high-brightness QCW arrays with a custom, compact and robust design for an operation with high duty cycles. Both designs are based on single diodes consisting of a 1cm laser bar that is AuSn soldered between two CuW submounts.

In design 1, an array of eight diodes is connected to a 28x14x5 mm^3 DCB macro-channel cooler suitable for an operation with tap water. The available optical output power is shown to be strongly depending on the wavelength and fill factor of the laser bars as well as on the duty cycle, e.g. at 808nm, we can reach 850 W at 120A for 15% duty cycle using laser bars with 50% fill factor.

In design 2, an array of 15 diodes is connected to a 39x28x0.6 mm^3 DCB submount. The complete array soldered to a copper block can be driven without additional water or thermo-electrical cooling. This design is of particular interest for mobile applications demanding a compact package and ordinary air cooling. Using 980nm bars with 20% fill factor, we can reach an optical output power of 1.150 W at 45°C base plate temperature without additional cooling operating the array with 15Hz and 15% duty cycle.

8605-32, Session 7

Increased power density QCW arrays

Jeremy Junghans, Joseph Levy, Ryan Feeler, Northrop Grumman Cutting Edge Optronics (United States)

Northrop Grumman Cutting Edge Optronics (NGCEO) has developed a new epitaxial design for increased power which maintains efficiency at higher temperatures. The laser diodes manufactured from this material can be combined with NGCEO's High Density Stack (HDS) or tight-pitched, hard soldered package designs to provide increased power density capability and proven reliability across a wide range of QCW operating conditions. Efficiencies greater than 53% have been demonstrated at 70°C and currents up to 200A. NGCEO expects to demonstrate upon completion of this project greater than 400 W/cm (per bar) at greater than 50% efficiency at 70°C.

Multiple bar geometries were processed by NGCEO, including 2 mm CL in both 1 cm wide (standard bar) and 3 mm wide (mini-bar) configurations. The bars were then packaged into HDS and Golden Bullet packages and fully characterized using NGCEO's automated test station. The arrays were tested at both short pulse, low duty factor, and long pulse, high duty factor conditions. Operational thermal testing was also completed on the arrays to simulate the harsh environmental conditions required for many industrial and military applications. Life test samples were made and stepped stress analysis was conducted to determine the reliability of the new epitaxial material at high currents. This work contains a detailed description of the results of each of these tests. A comparison with the results from other bar and epitaxial designs is also presented. Finally, recommended operating conditions for each design are discussed.

8605-33, Session 7

14xx nm and 15xx nm laser diodes with 50% power-conversion-efficiency

Manoj Kanskar, Ling Bao, Zhigang Chen, Mark DeVito, Weimin Dong, Sandrio Elim, Mike Grimshaw, Xingguo Guan, Shiguo Zhang, nLIGHT Corp. (United States)

Applications such as resonant end-pumping of Er- doped solid-state and fiber lasers and direct-diode medical and industrial lasers are driving the development of high brightness diode modules operating in the 1400 nm to 1600 nm band. To serve these applications, nLight has extended its high-brightness, Pearl platform, a conductively-cooled fiber-coupled package format based on arrays of single-emitters, to this wavelength regime. In this work, we report on recent advancements in the chip development based on reducing the loss due to Auger by reducing the carrier density in the quantum well. We have also further optimized the photonic and electronic structure of our epitaxial layers to produce, for the first time, laser diodes in the 14xx to 15xx nm wavelength range with 50% electrical-to-optical power conversion efficiency. In this wavelength range, power in excess of 30 W is demonstrated as measured from the distal end of a 105 µm, 0.15 NA fiber. A similar package (with more emitters) designed for efficient coupling to a 200 µm, 0.22 NA fiber delivers >50W at the same wavelength. In some cases, the naturally broad, temperature-sensitive, spectrum offered by long-wavelength diode laser sources is undesirable. To mitigate this effect, nLight has developed a wavelength locking approach, based on external wavelength-locking optical component, which offers a greater-than order-of magnitude improvement in the spectral bandwidth and spectral stability over temperature, without compromise to the power or efficiency of the module. Application of this approach to the aforementioned modules is also presented.

8605-34, Session 7

Next generation 9xx/10xx nm high power laser diode bars for multi-kilowatt industrial applications

J. Paul Commin, René Todt, Martin Krejci, Rainer Bättig, Reinhard Brunner, Norbert Lichtenstein, Oclaro, Inc. (Switzerland)

Reliable and efficient epitaxial structures, the E2 facet passivation technology and established AuSn solder processes for large die footprint have formed the robust baseline of OCLARO 9xx/10xxnm high power bars used in multi kilowatt laser systems for industrial applications. The continuous improvement of high filling factor bars on micro channel cooler (MCC) has resulted in a power increase from 50W (2002) to 200W (2009). In addition, extending from the 9xxnm into the 10xxnm wavelength region has widened the options for coarse wavelength multiplexing in direct diode systems. We will present the electro-optical and reliability characteristics of our latest 900-1060nm bar designs, demonstrating the continuation of this trend.

Moving on from our 2009 Oclaro 200W 9xx/10xxnm bar on MCC, our new design is able to provide 250W optical power with ~65% power conversion efficiency (PCE) across the entire 900-1060nm wavelength range with roll-over far beyond 350W, representing a significant step forward. Higher PCE and improved assembly enables reduced values for slow axis divergence, junction temperature and spectral width, required for higher system operation levels. Latest reliability data recorded during 5300h on-off operation at 250W show less than 0.5%/1000h mean power degradation. Electro-optical and reliability results of bars, based on our new design and assembled on the OCLARO BLM conductive cooler, suggest reliable operation up to 70mW/um stripe width. This new cooler has a small footprint of 12.6mmx24.8mm and is therefore designed for lateral or vertical stacking of diodes in multi kilowatt systems, offering the benefits associated with a conductive cooler.

8605-35, Session PTue

Laser assisted sheet metal working in series production

Markus Eckert, Michael Emonts, Christian Brecher, Fraunhofer-Institut für Produktionstechnologie (Germany)

Based on the demand for a responsible use of natural resources and energy the need for lightweight materials is increasing. The most common materials for lightweight production are high and highest strength steel. These materials are difficult to machine using conventional sheet metal working processes because the high strength leads to a limited formability and high tool wear.

The Fraunhofer IPT developed the laser-assisted sheet metal working. Selective laser based heating of the part directly before machining softens the material locally. Thus the quality of the following cut can be increased, for example for shearing 1.4310 the clear cut surface ratio can be increased from 20% up to 100% using a shearing gap of 10% of the sheet thickness.

Because of the softening of the material and thus the increased formability, parts with a higher complexity can be produced. For example 1.4310 can be bent laser-assisted with a radius of 0.25 mm instead of 2-3 mm using the conventional process. For the first time spring steel can be embossed with conventional tools up to 50% of the sheet thickness.

For the implementation in series production a modular system upgrade "hy-PRESS" has been developed to include laser and scanner technology into existing presses. For decoupling the sensitive optical elements of the machine vibrations an active-passive damping system has been developed.

The combination of this new hybrid process and the system technology allows to produce parts of high strength steel with a high complexity and quality.

8605-36, Session PTue

20.8W TM polarized GaAsP laser diodes of 808nm wavelength

Peixu Li, Shandong Huaguang Optoelectronics Co., Ltd. (China); Kai Jiang, Xin Zhang, Qingmin Tang, Wei Xia, Shuqiang Li, Zhongxiang Ren, Shandong Huaguang Optoelectronics Co., Ltd. (China); Xiangang Xu, Shandong Univ. (China)

High-power semiconductor lasers of 808nm wavelength are widely used as pumping sources for solid state lasers, printing and numerous medical applications. In this paper, we investigate high-power broad waveguide tensile strained GaAsP quantum well laser diodes of 808nm. To decrease the absorption and reduce thevertical far field angle,an asymmetry broad waveguide structure was used.The laser structures were grown by low-pressure metalorganic chemical vapor deposition and broad area lasers with 150-?m-wide stripe and 2000-?m-long cavity were fabricated. The threshold current and the slop efficiency of the LD are 745mA and 1.31W/A, respectively. At the driving current of 20A, the optical output power reaches 20.86W. Furthermore the LD has a maximum wall-plug efficiency of 58%. The vertical far field angle is 27°, and the horizontal one is 7°.At last ,the lifetime of the LDs was tested and an only very low degradation rate was found.

8605-37, Session PTue

Latest developments in high brightness diode lasers and their applications

Waldemar Sokolowski, TRUMPF Laser- und Systemtechnik GmbH (Germany); Alexander Hangst, Matthias Buehler, Alexander Killi, TRUMPF Laser GmbH & Co. KG (Germany); Tracey Ryba, TRUMPF Inc. (United States)

The latest developments of high brightness diode lasers of TRUMPF with output power below 1kW as well as their applications in such advanced material processing techniques as welding of plastics, selective soldering and welding of thin metal sheets will be presented.

8605-38, Session PTue

Speckle characteristics of laser diodes for SWIR and NIR active imaging

Lew Goldberg, U.S. Army RDECOM CERDEC NVESD (United States); Stephen R. Chinn, U.S. Army Night Vision & Electronic Sensors Directorate (United States); Jeffrey H. Leach, U.S. Army RDECOM CERDEC NVESD (United States)

Laser illumination makes it possible to perform high resolution imaging when ambient light level is insufficient to overcome camera noise. The relatively long coherence length of most lasers, however, causes coherent speckle in the camera image plane, which can result in a significant decrease of the image quality and the maximum effective imaged object resolution. We characterized image plane speckle properties for several types of NIR and SWIR laser diode sources. Image plane speckle contrast was measured by illuminating the imaged Lambertian surface with narrow-band single mode laser, multi-mode narrow-stripe laser, wide-stripe laser diodes with broad-band emission, and NIR and SWIR vertical cavity surface emitting laser (VCSEL) arrays. The impact of various imaging system parameters, including pixel size, imaging lens focal length and IFOV on the contrast and characteristic size of the speckle intensity distribution were determined. Speckle contrast dependence on the polarization properties of various reflecting surfaces was measured. The reduction of speckle contrast with increasing source spectral width, and increasing size of spatially incoherent VCSEL emitter arrays will be described. We show that image plane speckle contrast of <5% is achievable for a typical imaging system.

8605-39, Session PTue

High power 840nm AlGaAs-InGaAsP GRIN-DBSCH laser diodes with extremely small vertical divergence beam

Chih Tsang Hung, Tien-Chang Lu, National Chiao Tung Univ. (Taiwan)

High power AlGaAs-based laser diodes (LDs) are critical components of diode pumped solid state laser systems, constraining their performance and reliability. Hence, these LDs require mainly high output power and narrow beam divergence to achieve high conversion and coupling efficiencies.

In this report, high power AlGaAs/InGaAsP single quantum well (SQW) LDs which adopt optimized double barrier separate-confinement heterostructure (DBSCH) waveguide layers demonstrated low vertical divergence angle and low threshold current density (Jth) simultaneously. Compared to the conventional DBSCH LDs, we modify the double-barrier profile by adding parabolic-like grading layers with graded AlGaAs composition into the interfaces between the SCH layers. This design can keep reducing the vertical divergence beam, which attenuating the optical confinement and extending the optical field into cladding layer significantly. Besides, it is also workable to enhance the carrier confine around the active layer and prevent current leakage.

For the GRIN-DBSCH LDs, vertical beam divergence can be reduced to 12.5? FWHM and the Jth of 450 A/cm2 and Slope efficiency of 0.99 W/A has been obtained at room temperature. The LDs can be driven at the maximum power density of 7.5 MW/cm2 with high characteristic temperatures sensitivity of threshold current (T0) and slope efficiency (Ts) to be 450K and 1750K, respectively.

8606-1, Session 1

Design of high-efficiency semiconductor disk lasers *(Invited Paper)*

Peter Unger, Univ. Ulm (Germany)

The design of optically pumped semiconductor disk lasers is discussed with emphasis on the optimization for high power conversion efficiencies. Main topics are the compensation of strain in the epitaxial layer sequence, the realization of a low-absorption Bragg reflector which has a high reflectivity for pump and laser wavelength and a low thermal resistance, and the effect of a surface coating reducing optical losses inside the semiconductor disk. As an alternative concept, quantum-well pumping may be more efficient because of the reduced quantum defect. Efficient intra-cavity second-harmonic generation can be obtain in folded cavity setups.

8606-2, Session 1

Development of next generation OPS laser products *(Invited Paper)*

Juan L. Chilla, Coherent, Inc. (United States)

Starting with the first commercially available solid state laser at 488 nm in 2001, we have translated the advantages of the OPS technology into products. These advantages include wavelength flexibility, broad pump tolerance, efficient spectral and spatial brightness conversion and high power scaling. Examples of the first generation of commercial lasers based on OPS technology are being used in a wide range of applications, including scientific, bio-instrumentation, medical, military and entertainment.

An active development program is required in order to compete favorably and displace alternative laser technologies in this broad array of markets. Our group is embarked in several programs to develop OPS technology in different directions, including: high power scaling, both at the single chip level and aggregation efforts; expansion of the spectral coverage, in particular toward wavelengths beyond the coverage of our traditional InGaAs material system for SHG red emission; novel cavity designs and packaging techniques, smaller and more efficient lasers to facilitate integration and adoption in different applications.

We will present a summary of our latest developments, taking examples and results from all these programs

8606-3, Session 1

High power (23 W) vertical external cavity surface emitting laser emitting at 1180 nm

Tomi Leinonen, Sanna Ranta, Miki Tavast, Tampere Univ. of Technology (Finland); Ryan J. Epstein, Gregory J. Fetzer, Arete Associates (United States); . Sandalphon, Cinnabar Optics LLC (United States); Neil R. Van Lieu, Arete Associates (United States); Mircea Guina, Tampere Univ. of Technology (Finland)

Frequency-doubled VECSELs offer a cost-effective solution to generate high-brightness light in the visible wavelength range. Furthermore, they can be made wavelength tunable and to exhibit narrow emission linewidth (< 1 MHz). Competing laser technologies at this wavelength range tend to be significantly more expensive, and suffer from technical limitations such as need for frequent maintenance or lack of wavelength tuning.

Frequency-doubled VECSELs for the blue–green part of the visible spectrum exploit optical gain provided by well established InGaAs/GaAs quantum well (QW) which exhibit moderate lattice strain. On the other hand for the yellow-red part of the spectrum, the strain becomes high making the implementation of InGaAs/GaAs gain mirror difficult. The high strain can be alleviated by employing low temperature growth and strain compensation techniques. However, these solutions have so far limited the power scaling ability of VECSELs to levels much lower than what has been demonstrated by using close to lattice matched InGaAs QWs.

Here we report a breakthrough concerning the high power operation of VECSELs with emission around 1180 nm based on strain-compensated InGaAs/GaAs QWs. In free-running operation (i.e. without intra-cavity optics to control the emission wavelength), we have obtained an output power slightly higher than 23 W and in single-frequency operation we have generated more than 10 W of output power at 1178 nm.

8606-4, Session 2

Passively mode-locked femtosecond VECSELs with high average output power *(Invited Paper)*

Maik Scheller, College of Optical Sciences, The Univ. of Arizona (United States); Stephan W. Koch, Philipps-Univ. Marburg (Germany); Jerome V. Moloney, The Univ. of Arizona (United States)

Vertical-external-cavity surface-emitting lasers (VECSELs) combine the advantages of semiconductor devices with key features of solid-state lasers such as ideally TEM00-beam quality and high output power. As the design of the quantum wells (QWs) as active medium can be customized, it is possible to adjust the emission wavelength continuously in a wide range of the electromagnetic spectrum as well as to vary the gain bandwidth. Thus, a growing number of practical and scientific applications are actively pursued. In particular, the potential of passively mode-locking of VECSELs is of high interest. Pulse durations below 100 fs have been reported and high average output powers in the femtosecond regime above 1W.

To maximize the performance of our VECSEL devices, we enhanced the thermal management of the chips as well as the homogeneity of the epitaxial growth. Moreover, we employed microscopic modeling of the VECSELs to optimize the design of the semiconductor structure. Recently, we demonstrated continuous wave (cw) VECSELs emitting above 100 W of cw radiation centered at an emission wavelength of 1030 nm. We probed the width of the QW gain of these structures and showed that simultaneous emission of two-wavelengths spaced by 12 nm is possible. Thus, the gain bandwidth is more than sufficient to support pulses in the femtosecond regime.

In this work, we present results of passively mode-locking of our efficient VECSELs and demonstrate femtosecond operation with record output powers and pulse energies. At average output powers exceeding 5 W, we achieved nearly transform-limited pulses with 682 fs duration.

8606-5, Session 2

Characterization of nonlinear gain parameters in VECSELs to optimize femtosecond high average power operation *(Invited Paper)*

Mario Mangold, Valentin J. Wittwer, Oliver D. Sieber, Martin Hoffmann, Matthias Golling, Thomas Südmeyer, Ursula Keller, ETH Zurich (Switzerland)

With optically-pumped (OP) VECSELs we have generated 1.05 W average power with 784 fs pulse durations. We have obtained shorter pulses with 364 fs only at the expense of average output power. Numerical simulations have been successfully used to gain a better understanding, but initially have not predicted the average output power correctly. Only after we directly determined the correct gain parameters we got very good agreement. Numerical pulse forming simulations for SESAM modelocked VECSELs show that weak gain saturation is beneficial for high-power operation in the femtosecond regime. With a high-precision reflectivity measurement setup we measured the nonlinear change in reflectivity of the OP-VECSEL gain chip as function of the incident pulse fluence, pump intensity, and heat-sink temperature. For OP-VECSELs with an emission wavelength around 960 nm, we obtain saturation fluences in the range of 30-80 ?J/cm2 for InGaAs quantum well (QW) and InAs quantum dot (QD) active regions, which are considerably lower than previously assumed. We measured the gain saturation behavior and the small-signal gain for two structures with QD and QW active regions and different flip-chip bonded heat-spreader materials (diamond and copper). The characterization was performed both with 130-fs and 1.4-ps pulses from an 80-MHz Ti:sapphire laser. Small-signal gain up to 5% was measured, strongly depending on the pump power and the heat-sink temperature. In addition, we determined the spectral dependence of the gain using a tunable continuous-wave probe beam. For both structures, gain bandwidths of over 26 nm FWHM were measured.

8606-6, Session 2

Towards VECSEL frequency combs *(Invited Paper)*

Keith G. Wilcox, Univ. of Southampton (United Kingdom)

Significant progress has been made over the last year towards generating frequency combs using VECSELs. Here, I will discuss recent progress made generating > 4kW peak power femtosecond pulse VECSELs, where we have achieved 3.3 W average power with 400 fs pulse duration at 1.7 GHz repetition rate. This has been achieved by exploiting the rapid power scaling progress made in the field of CW VECSELs [1]. The gain structure used here is grown and processed by the University of Marburg, and the window layer is etched for anti-resonance to increase the gain bandwidth and reduce the dispersion [2].

We have used this to generate supercontinuum, achieving 45 % throughput in a 2.2 micron core photonic crystal fibre when the VECSEL produced 1 W average output power. A continuum with a width of 130 nm is generated. At higher average powers heating of the fibre tip reduces coupling efficiency which limits the supercontinuum bandwidth and we will discuss measures to avoid this. Finally, I will outline approaches to further reduce the pulse length, whilst maintaining the average power, to a point where generating coherent octave spanning supercontinuum, suitable for F-2F stabilisation should become a reality.

[1] B. Heinen et. al. Electronics Letters, 48, 9, 516-517, (2012)

[2] A. C. Tropper et. al. Semiconductors and Semimetals 86, 269-300, (2012)

8606-7, Session 2

Supercontinuum generation with femtosecond pulse fiber amplified VECSELs

Christopher R. Head, Ho-Yin Chan, James S. Feehan, David P. Shepherd, Shaif-ul Alam, Anne C. Tropper, Jonathan H. Price, Keith G. Wilcox, Univ. of Southampton (United Kingdom)

We present a mode-locked VECSEL emitting 400-fs pulses at a 3 GHz repetition rate at 1040 nm, amplified by a cascaded ytterbium doped fiber amplifier system to an average power of 40 W. The 3-ps duration amplified pulses are recompressed to their original 400-fs duration using a high-throughput transmission grating compressor. The recompressed pulses are used to generate supercontinuum with two different photonic crystal fibers (PCF); an all-normal dispersion PCF with a dispersion minimum at 1050 nm, and a standard PCF with a ZDW at 1040 nm.

For both PCFs ~50% power transmission is achieved, however the maximum incident power is limited by thermal effects in the non-actively-cooled PCF tip. The supercontinuum produced with all-normal dispersion PCF exhibits a flat-topped 205-nm broad spectrum with average power of 3.9 W. Due to the all-normal dispersion the supercontinuum created is temporally coherent and should be compressible with appropriate dispersion compensation [1]. The supercontinuum obtained from the PCF (ZDW=1040 nm) has a spectral width of 540 nm and an average power of 2.5 W.

The current system exhibits weak nonlinear spectral broadening. With an optimized final amplifier the parabolic pulse regime could be reached, where near-transform-limited compressed pulses with durations of ~100fs can be achieved[2]. This VECSEL seeded fiber amplifier system is well suited for applications including materials processing and generating high power continuum with wide-comb spacing for ultra-short pulse and metrology applications.

References:

[1] J. Opt. Soc. Am. B, 27, 3 (2010) 550-559

[2] Opt. Express 14, 21 (2006) 9611-9616

8606-8, Session 3

Semiconductor disk lasers: a flexible intracavity power platform *(Invited Paper)*

John-Mark Hopkins, Univ. of Strathclyde (United Kingdom); David J. M. Stothard, Malcolm H. Dunn, Univ. of St. Andrews (United Kingdom); David Burns, Univ. of Strathclyde (United Kingdom)

The ubiquitous applicability and flexibility of the semiconductor disk laser is now widely accepted and commercially exploited for the production of compact, high-power and high-brightness sources. A second revolution is occurring in the intracavity pumping of secondary linear and non-linear colour conversion resonators based around the significant advantages the SDL brings to such systems. The planar gain medium and short carrier lifetimes crucially provide a flexible intracavity power platform for stable conversion and subsequent application.

This talk will concentrate on the properties of SDLs which distinguish them for intracavity exploitation. The potential advantages for linear conversion using intracavity laser gain medium will be presented and discussed. This will be followed by an in depth review and analysis of non-linear intracavity conversion techniques that have been reported. The presentation will then focus on SDL pumped optical parametric oscillators, their prospects and potential applications.

Specific review topics will include:-

- Semiconductor disk laser properties advantageous for intracavity pumping
- Linear laser conversion exploiting high intracavity fields
- Intracavity second harmonic generation
- Difference frequency generation to the THz
- Intracavity Raman conversion
- Optical parametric oscillators utilising 1um and 2um SDLs
- Future prospects for intracavity techniques

Reported examples will be presented and discussed for each of the above while emphasis will be placed on the SDL pumping of OPOs. The presentation will conclude with a roadmap of devices and applications in this rich field and some challenges to the principal researchers in this field.

8606-9, Session 3

Intracavity-enhanced solid-state laser cooling using high power VECSELs at 1020 nm *(Invited Paper)*

Mansoor Sheik-Bahae, Mohammad Ghasemkhani, Alexander R. Albrecht, The Univ. of New Mexico (United States); Denis V. Seletskiy, Univ. Konstanz (Germany); Jeffrey G. Cederberg, Sandia National Labs. (United States); Seth D. Melgaard, The Univ. of New Mexico (United States)

Laser cooling of solids (or optical refrigeration) relies on resonant anti-Stokes fluorescence: pump laser tuned to below mean luminescence photon energy creates "cold" population in both ground- and excited state manifolds in a rare-earth doped system. Subsequent interaction with phonons establishes quasi-equilibrium by removing heat from the lattice. In the final step, the fluorescence carries the excess energy (heat) away from the medium resulting in net cooling of the system. Recently, cooling from room temperature to 118K have been demonstrated in Yb:YLF crystals, thus realizing the long-sought all-solid-state cryocooler. One engineering challenge in achieving a high wall-plug efficiency is maximizing the fraction of absorbed laser pump power. Previous attempts have relied on external cavity enhancements (resonant and non-resonant). With the recent advances in high power VECSEL technology, an intracavity absorption scheme using such lasers is quite practical and promising. For this purpose, we developed high power InGaAs MQW VECSELs at 1020 nm (linewidth<0.3 nm) for intracavity laser cooling of Yb:YLF crystals. The laser gain chip consists of 12 resonant periodic gain InGaAs quantum wells and high reflecting DBR grown by MOCVD in a bottom emitter geometry, and bonded to a CVD diamond for thermal managment. The laser (without the cooling sample) can be tuned from 1010 to 1030 nm using an intracavity birefringent filter. The laser CW output power exceeded 18W when pumped with 70 W laser diodes at 810 nm. Initial experiments have demonstrated cooling by about 80K in a vacuum. Efforts are now underway to optimize the sample geometry for a minimal thermal load in combination with the maximum power extraction at cryogenic temperatures.

8606-10, Session 3

30 W peak-power 3 ns pulse-width operation of a 2 µm electro-optically cavity-dumped VECSEL

Sebastian Kaspar, Marcel Rattunde, Tino Töpper, Christian Manz, Klaus Köhler, Joachim Wagner, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany)

In recent years, vertical-external-cavity surface-emitting laser (VECSEL) [1] have attracted a great deal of interest due to their capability of simultaneously delivering a high output power and an excellent beam quality. The modular design of SDLs allows a straightforward insertion of optical elements into the laser cavity in order to achieve, e.g., narrow-linewidth single-frequency emission [2] or non-linear frequency conversion [3].

Short pulse operation of 2-µm VECSELs has been achieved via pulsed current injection into the pump diode laser [4], resulting in a rather long pulse length of 180 ns at 16-W peak output power. Cavity-dumped VECSELs have not yet been demonstrated at wavelengths above 2 µm, however at 1 µm [5] with an intra-cavity acousto-optic modulator. In order to achieve ns pulses by this technique, tight focusing is required as the beam-transit time through the acoustic wave traveling through acousto-optic modulator (AOM) employed determines the pulse length, resulting in a minimum pulse length of 24 ns at 41 W peak power at a beam waist of 52 µm [5]. Given the damage threshold of acousto-optic materials suited for cavity dumping at 2-µm, only output powers <1 W at a 10 ns pulse can be expected to be reached prior to optically damaging the AOM.

By contrast, employing electro-optic modulation (EOM) for cavity dumping, tight focusing is not required for short-pulse operation. In the present study a Pockels cell and a birefringent polarizer were inserted in the cavity, such that ns pulses are coupled out of the cavity sideways by means of internal total reflection. This way we demonstrate an electro-optically cavity-dumped VECSEL that emits at a wavelength of 2 µm at a peak power of 30 W and a pulse length of 3 ns at repetition rates adjustable between 90 kHz and 1 MHz. The present EOM cavity-dumped VECSEL delivers the shortest pulses achieved so far with any cavity-dumped VECSEL and constitutes the first realization of a cavity-dumped VECSEL setup at 2 µm. It is well suited for high-precision LIDAR (depth resolution <1 m) or materials processing.

References

[1] M. Kuznetsov et al., IEEE J. Sel. Topics In Quantum Electron. 5, pp. 561-573 (1999).

[2] S. Kaspar et al., Appl. Phys. Lett. 100, 031109 (2012).

[3] T. Schwarzbäck et al., Appl. Phys. Lett. 99, 261101 (2011).

[4] D. Burns et al., Proc. SPIE 7193, 719311 (2009).

[5] V. G. Savitski et al., Opt. Express, 18, 11933 (2010).

8606-11, Session 4

VECSEL-pumped infrared and visible Raman lasers *(Invited Paper)*

Daniele C. Parrotta, Peter J. Schlosser, Alan J. Kemp, Martin D. Dawson, Jennifer E. Hastie, Univ. of Strathclyde (United Kingdom)

Continuous wave (CW) VECSELs are commercially-attractive lasers with broad wavelength flexibility. Watt-level fundamental emission ranges from red to mid-infrared via bandgap and strain engineering, while ultraviolet and other visible wavelengths are obtained via efficient harmonic generation. The spectral coverage of VECSELs may be further extended via intracavity stimulated Raman scattering with scope for additional cascaded nonlinear conversion. Here we will present our recent work in the development of VECSEL-pumped Raman lasers: power scaling to near diffraction-limited multi-Watt output; investigation of the evolution of emission spectra; analysis of mode-matching, brightness and efficiency; and up-conversion to the visible.

In this work, a diamond Raman laser was pumped in a CW, high-finesse, diode-pumped InGaAs-based VECSEL with wavelength ~1055nm. Both resonators were co-aligned to produce a focus within a 6.5-mm-long synthetic single-crystal diamond cut for propagation along <110>. With 2.2% output coupling, the Raman laser emitted up to 4.4W at 1228nm, with 14.2% diode-to-Stokes conversion efficiency, and was tuned from 1209-1256nm. Visible emission was realised by placing an LBO crystal in the Raman laser resonator. Up to 1.5W at 614nm with 5.4% diode-to-visible conversion efficiency, M2~1.2 and emission linewidth of ~0.1nm were achieved. The visible emission was tuned from 604.5-619.5nm, with output power exceeding 1W from 613-618nm.

We have also demonstrated a diamond Raman laser intracavity-pumped by an AlGaInP-based VECSEL with wavelength ~670nm. Tunable Raman laser operation from 738-748nm is observed, with further optimization of this laser, including output coupling, to be implemented. Further details on design, characterization and future directions will be presented.

8606-12, Session 4

Investigation of InAs quantum dashes for 1.45-2.1 µm vertical external cavity surface emitting laser active regions

Thomas J. Rotter, Pankaj Ahirwar, Darryl M. Shima, Christopher P. Hains, L. Ralph Dawson, Ganesh Balakrishnan, Ctr. for High Technology Materials (United States); Saima Husaini, Robert G. Bedford, Air Force Research Lab. (United States)

Lasers with emission wavelength around 2 ?m have been traditionally based on InGaSb quantum wells grown on GaSb. An alternative is to use self assembled InAs Quantum Dashes grown on InP by the Stranski—Krastanov growth mode. More specifically, InAs quantum dashes embedded in strained InGaAs quantum wells, grown in InAlGaAs waveguides lattice matched to InP substrates have been successfully used as active medium in edge emitting lasers with wavelengths in the range from 1.45 ?m to 2.1 ?m. Advantages of this material system compared to the GaSb based system include easier lattice matching; i.e. only one group V element is involved. Many optoelectronic properties of the InAs/InP quantum dash material system are similar to those of InAs quantum dots grown on GaAs substrates. The latter material system has been very successfully used for VECSELs in the wavelength region around 1 µm, leading to the highest power VECSEL at this wavelength, modelocking, wide range tunability as well as intracavity SHG to generate red light. A challenge in the material system based on InP substrates is to fabricate a DBR. A lattice-matched DBR can consist of GaAsSb/AlAsSb. Alternatively one can grow a metamorphic DBR based on either GaAs/AlAs or GaSb/AlSb. The latter requires the DBR to be grown after the active region. The resultant VECSEL is then a “bottom emitter”, where the substrate has to be removed. This can be achieved by introducing an etch stop layer between substrate and active region. Lastly, the DBR can be grown separately and subsequently wafer bonded to the active region. This presentation will discuss details of these technologies and present results.

8606-13, Session 4

TEM based analysis of III-Sb VECSELs on GaAs substrates for improved laser performance

Pankaj Ahirwar, Darryl M. Shima, Thomas J. Rotter, Stephen P. R. Clark, Christopher P. Hains, L. Ralph Dawson, Ganesh Balakrishnan, Ctr. for High Technology Materials (United States); Robert G. Bedford, Air Force Research Lab. (United States); Yi-Ying Lai, Alexandre Laurain, Jörg Hader, College of Optical Sciences, The Univ. of Arizona (United States); Jerome V. Moloney, The Univ. of Arizona (United States)

The antimonide based vertical external cavity surface emitting lasers (VECSELs) operating in the 1.8 to 2.8 µm wavelength range are typically based on InGaAsSb/AlGaAsSb quantum wells on AlAsSb/GaSb distributed Bragg reflectors (DBRs) grown lattice-matched on GaSb substrates. The ability to grow such antimonide VECSEL structures on GaAs substrates can take advantage of the superior AlAs based etch-stop layers, mature DBR technology based on GaAs substrates and improved heat extraction capability due to better thermal conductivity of III-As DBRs when compared to III-Sb DBRs. The growth of such III-Sb VECSELs on GaAs substrates is non-trivial due to the 7.8% lattice mismatch between the antimonide based active region and the GaAs/AlGaAs DBR. The challenge is therefore to reduce the threading dislocation density in the active region without a very thick metamorphic buffer and this is achieved by inducing 90º interfacial misfit dislocation arrays between the GaSb and GaAs layers. In this presentation we make use of cross section transmission electron microscopy to analyze a variety of approaches to designing and growing III-Sb VECSELs on GaAs substrates to achieve a low threading dislocation density. We shall demonstrate the failure mechanisms in such growths and we analyze the extent to which the threading dislocations are able to permeate a thick active region. Finally, we present growth strategies and supporting results showing low-defect density III-Sb VECSEL active regions on GaAs.

8606-14, Session 5

Recent progress in wafer-fused VECSELs emitting in the 1310 nm and 1550 nm bands *(Invited Paper)*

Alexei Sirbu, Alexandru Mereuta, Andrei Caliman, Vladimir Iakovlev, Nicolas Volet, Ecole Polytechnique Fédérale de Lausanne (Switzerland); Jari Lyytikainen, Jussi Rautiainen, Oleg G. Okhotnikov, Tampere Univ. of Technology (Finland); Jaroslaw Walczak, Michal Wasiak, Tomasz Czyszanowski, Technical Univ. of Lodz (Poland); Elyahou Kapon, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

Wafer fusion approach proved to be very successful in demonstrating state of the art optically pumped vertical cavity surface emitting lasers (VECSELs). The gain mirror structures in these VECSELs are formed by direct bonding of InAlGaAs/InP active cavities to AlGaAs/GaAs DBRs. Thanks to excellent thermal properties of these gain mirrors, optically pumped VECSELs are capable of producing multi-Watt level diffraction limited beams in the 1310 nm and 1550 nm wave-bands. This wavelength agility represents an important advantage compared with existing solid-state and fiber lasers, opening new perspectives in the development of Raman fiber lasers and amplifiers.

Even optical pumping of high power VECSELs is well accepted in the industry, electrically pumped devices are expected to offer a considerable cost and size reduction. One important challenge in the quest for high performance electrically pumped VECSELs consists in reaching uniform pumping of large apertures that are several orders of magnitude larger than in VCSELs. This objective becomes even more challenging in long wavelength VECSELs that are based on un-doped DBRs. We have introduced novel designs of electrically pumped gain mirrors fabricated by a modified wafer-fusion technique that produced state of the art 1500 nm electrically pumped VCSELs.

Over the last years we have demonstrated continuous improvements of 1310 nm and 1550 nm bands long-wavelength VECSELs in terms of maximum output power and beam quality. These results open new possibilities of applications in the photonics industry that will be discussed in the talk.

8606-15, Session 5

Passively mode-locked electrically pumped VECSELs

Christian A. Zaugg, Wolfgang P. Pallmann, Mario Mangold, Valentin J. Wittwer, ETH Zurich (Switzerland); Holger Moench, Stephan Gronenborn, Philips Technologie GmbH (Germany); Michael Miller, Philips Technologie GmbH U-L-M Photonics (Germany); Bauke W. Tilma, Thomas Südmeyer, Ursula Keller, ETH Zurich (Switzerland)

Optically pumped vertical external cavity surface emitting lasers (OP-VECSELs) passively modelocked with a semiconductor saturable absorber mirror (SESAM) have already generated pico- and femtosecond pulses at gigahertz repetition rates with multi-Watt average output power. This makes them highly interesting for many scientific and commercial applications. Electrical pumping is the next step to reduce size and cost of such sources, increasing the commercial attractiveness further.

The design of an electrically pumped VECSEL (EP-VECSEL) requires a more critical tradeoff between electrical and optical properties, such as losses, beam quality and group delay dispersion. For modelocked operation, it is also essential to consider certain gain properties, particularly the gain saturation of such a resonant device. Semiconductor lasers experience strong gain saturation, which considerably influences the pulse formation process.

Here we present the first detailed gain characterization of three EP-VECSEL structures, each exhibiting a different field enhancement in the

quantum-well gain layers and thus different saturation characteristics. The spectral gain distribution and the gain saturation behavior of the devices is measured and the spectral bandwidth, small-signal gain and saturation fluence is compared for different heat-sink temperatures and driving currents. Based on this characterization, we chose the most suitable design for passive modelocking experiments. Using an appropriate low-saturation fluence SESAM, we have generated 9.5-ps pulses with an average output power of 7.6 mW at a repetition rate of 1.4 GHz in a Z-type cavity. This has been the shortest pulse duration obtained from a modelocked EP-VECSEL to date.

8606-16, Session 5

Analysis of single-mode efficiency of electrically-pumped VECSELs

Thomas Schwarz, Michael Berens, RWTH Aachen (Germany); Stephan Gronenborn, Johanna Kolb, Philips Technologie GmbH (Germany); Peter Loosen, RWTH Aachen (Germany); Michael Miller, Philips Technologie GmbH U-L-M Photonics (Germany); Holger Moench, Philips Technologie GmbH (Germany); Rolf Wester, Fraunhofer-Institut für Lasertechnik (Germany)

We present a model and results of simulations and experiments investigating the L-I characteristics of electrically pumped (EP) VECSELs in the single- and multi-mode regime. In our model we use a mode expansion ansatz to treat the electromagnetic field inside the VECSEL cavity. The eigenmodes of the passive cavity are computed using the bidirectional beam propagation method (BDBPM) to solve the Helmholtz equation. The BDBPM allows us to account for the complex refractive index distribution within the semiconductor heterostucture, composed of approximately thousand interfaces along the optical axis in addition to lateral refractive index variations in oxide-confined devices as well as the macroscopic external cavity. We simulate the time evolution of the modal powers of several transverse modes and the spatial distribution of the inversion carriers in the quantum well plane. Therefore we solve an differential equation system composed of multimode rate equations and the carrier diffusion equation. With this ansatz we are able to identify cavity geometries suitable for single-mode operation assuming typical current profiles that are taken from photoluminescence measurements of the devices under investigation. Furthermore, we identify effects limiting the single-mode efficiency, such as poor gain and mode matching, reabsorption in unpumped regions of the quantum wells or enhanced carrier losses due to strong spatial hole burning. Critical parameters of the equations, such as optical losses, injection efficiency, carrier recombination constants and gain parameters are obtained from experiments, microscopic models and literature.

The simulation results are compared to experimental results from EP-VECSELs from Philips Technologie GmbH U-L-M Photonics.

8606-17, Session 5

Automated assembly of VECSEL components

Christian Brecher, Nicolas Pyschny, Sebastian Haag, Fraunhofer-Institut für Produktionstechnologie (Germany)

Due to the architectural advantage of an external cavity architecture that enables the integration of additional elements into the cavity (e.g. for mode control, frequency conversion, wavelength tuning or passive mode-locking) VECSELs are a rapidly developing laser technology. Nevertheless they often have to compete with direct (edge) emitting laser diodes which can have significant cost advantages thanks to their rather simple structure and production processes. One way to compensate the economical disadvantages of VECSELs is to optimize each component in terms of quality and costs and to apply more efficient (batch) production processes.

In this context, the paper presents recent process developments for the automated assembly of VECSELs using a new type of desktop assembly station with an ultra-precise micromanipulator. The core concept is to create a dedicated process development environment from which implemented processes can be transferred fluently to production equipment.

By now two types of processes have been put into operation on the desktop assembly station: 1.) passive alignment of the pump optics implementing a camera-based alignment process, where the pump spot geometry and position on the semiconductor chip is analyzed and evaluated; 2.) active alignment of the end mirror based on output power measurements and optimization algorithms.

In addition to the core concept and corresponding hardware and software developments, detailed results of both processes are presented explaining measurement setups as well as alignment strategies and results.

8606-18, Session 6

Characteristics of thermal resistance in (GaIn)As-based near-infrared VECSEL *(Invited Paper)*

Wolfgang Stolz, Bernd Heinen, Philipps-Univ. Marburg (Germany); Tsuei-Lian Wang, College of Optical Sciences, The Univ. of Arizona (United States); Bernardette Kunert, Philipps-Univ. Marburg (Germany); Jörg Hader, College of Optical Sciences, The Univ. of Arizona (United States); Martin Koch, Stephan W. Koch, Philipps-Univ. Marburg (Germany); Jerome V. Moloney, The Univ. of Arizona (United States)

Near infrared (GaIn)As-based VECSEL-structures have been grown by a specific metal organic vapour phase epitaxy (MOVPE) process using less toxic and thermally more efficiently decomposing MO-group-V-sources like tertiary butyl arsine (TBAs) and tertiary butyl phosphine (TBP). For the efficient optimization of these complex laser devices a closed-loop-design concept of detailed microscopic modelling and experimental realization as well as laser characterization has been applied. In particular, the efficient heat spreading and heat sinking is of key importance for high-power VECSEL structures. A simplified but more precise method has been developed to obtain the thermal resistance in VECSEL. The implications for improved laser properties with continuous wave output powers in excess of 100 W will be presented and discussed.

8606-19, Session 6

2-µm single-chip VECSEL overcoming the 10-W benchmark by means of 1.5-µm barrier pumping

Marcel Rattunde, Sebastian Kaspar, Tino Töpper, Andreas Bächle, Rolf Aidam, Joachim Wagner, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany)

In recent years, vertical-external-cavity surface-emitting laser (VECSEL) [1] have attracted considerable interest due to their capability of simultaneously delivering high output powers and a high quality output beam. High-performance VECSELs have been realized at wavelengths ranging from the UV [2] to the near-to-mid IR [3,4].

High-performance GaSb-based VECSELs emitting in the 1.9-2.8-µm range using 980 nm barrier pumping have been demonstrated, exhibiting at 2 µm lasing wavelength a maximum output power of 4.1 W and a differential power efficiency of 26% at 20°C heatsink temperature [5]. These structures were barrier-pumped with standard 980 nm diode lasers. This, however, leads to a high quantum deficit (~50%) and hence a high thermal load. Therefore, a key element to improve the performance of GaSb-based VECSELs is to reduce the quantum deficit and thus the thermal load on the active region.

One approach to achieve this goal are in-well pumped GaSb-based VECSELs, for which a differential power efficiency of 32 % has been demonstrated for a 2.3 µm emitting VECSEL pumped at 1.97 µm [6]. A serious drawback of this approach is, however, the rather low power

efficiency of state-of-the-art 2 µm pump diode lasers and the complex dual band epitaxial DBR in combination with pump recycling optics needed to achieve sufficient pump absorption.

Here we present a new GaSb-based VECSEL structure emitting at 2.0 µm, optimized for barrier-pumped at 1.5 µm to reduce the quantum-deficit compared to 980 nm-pumped VECSELs. Samples of this structure were bonded to an intracavity heatsink out of SiC using the method of liquid capillary bonding. They were operated in a single-chip linear cavity and pumped with a fiber coupled diode laser module with 1.47 µm pump wavelength. This way we achieved an output power of over 6.5 W CW at 20°C and over 10 W CW at -10°C heatsink temperature for a simple single-chip linear cavity. The differential power efficiency reaches 30 % at 20 °C.

References

[1] M. Kuznetsov et al., IEEE J. Sel. Topics in Quantum Electron. 5, pp. 561-573 (1999).

[2] T. Schwarzbäck et al., Appl. Phys. Lett. 99, 261101 (2011).

[3] B. Rösener et al., Optics Lett. 36, 319 (2011)

[4] Khiar et al, Appl. Phys Lett. 97, 151104 (2010)

[5] T. Töpper et al., Appl. Phys. Lett. 100, 192107 (2012).

[6] N. Schulz et al., Appl. Phys. Lett., 93, 181113-3 (2008) .

8606-20, Session 6

Effects of cryogenic temperatures on the performance of CW and mode-locked VECSELs

Oliver J. Morris, Keith G. Wilcox, Christopher R. Head, Andrew P. Turnbull, Univ. of Southampton (United Kingdom); Ian Farrer, Harvey E. Beere, David A. Ritchie, Univ. of Cambridge (United Kingdom); Anne C. Tropper, Univ. of Southampton (United Kingdom)

VECSEL gain chips typically operate between 220 K and 290 K as this range is readily accessed by Peltier temperature elements. We report the effects of cryogenic temperatures on the performance of CW and mode-locked VECSELs. Our experiments use unprocessed, short micro-cavity, anti-resonant gain chips pumped with a 120-µm diameter spot.

A helium flow cryostat is used to demonstrate that a gain chip held at 20 K accepts twice as much incident pump power at rollover and exhibits a doubling of the optimum output coupling when compared to operation at 293 K. More extensive studies are achieved by housing the entire VECSEL within the vacuum space of a cold-finger, liquid nitrogen cryostat. This eliminates the cryostat window acting as an unwanted intracavity element. In this configuration we report a CW VECSEL, constructed with a gain chip held at 110 K, that exhibits a 2-fold reduction in the lasing threshold and a 3.7 times increase in the output power when compared to operation at 293 K. This VECSEL is pump power limited. Using a gain chip held at 140 K, we also demonstrate a semiconductor saturable absorber mirror (SESAM) mode-locked VECSEL that produces picosecond pulses at a centre wavelength of 1005.7 nm and a fundamental repetition rate of 0.97 GHz.

Mode-locked operation of a VECSEL is readily achieved through the use of a SESAM. The enhanced performance found at low temperatures should enable a more diverse range of mode-locking techniques to be employed in these lasers.

8606-21, Session 7

Self mode locked OPSL *(Invited Paper)*

Hsing-Chih Liang, Yi-Chun Lee, Jung-Chen Tung, Kuan-Wei Su, Yung-Fu Chen, Kai-Feng Huang, National Chiao Tung Univ. (Taiwan)

The occurrence of self-mode locked is an intriguing phenomenon observed in a laser system without any saturable absorber. The first demonstration of self-mode locking in the Ti-sapphire laser by Spence et al., the phenomena of Kerr-lens mode locking (KLM) has been explored widely both experimentally and theoretically. Recently, the self-mode-locked operation with a linear cavity has been also observed in the optically pumped semiconductor laser (OPSL). However, the underlying exploration for spatio-temporal dynamics in modelocking operation remains incomplete.

In this work, we employed a platform of a commercially available OPSL from Coherent Inc. to demonstrate a picosecond high-power self-mode-locked operation with GHz oscillation at 1060 nm in a vertical-external cavity surface-emitting laser. With an incident pump power of 20 W, the compact laser cavity produces the average output power greater than 6.2 W with a pulse width as short as 1.1 ps in a pulse repetition of 1.2 GHz. Moreover, it is experimentally found that the laser beam displays a phenomenon of complex spatio-temporal dynamics. To confirm the origin of the spatio-temporal dynamics, we verify that the experimental observation can be explained in terms of total mode locking of TEM00 and high-order modes. All the experimental results are found to agree very well with the theoretical calculations.

8606-22, Session 7

Advances in mode-locked semiconductor disk lasers *(Invited Paper)*

Lukasz W. Kornaszewski, Nils Hempler, Craig Hamilton, Gareth T. Maker, Graeme P. A. Malcolm, M Squared Lasers Ltd. (United Kingdom)

Nonlinear microscopy techniques, such as two-photon excited fluorescence and second harmonic Generation provide advantages over conventional confocal laser scanning microscopy. A key element in a nonlinear microscope is an ultrafast laser which produces short pulses with the high intensities needed for exciting nonlinear processes. Semiconductor disk lasers potentially offer an alternative to expensive Ti:Sapphire lasers. The reported 200MHz operation of a mode-locked semiconductor disk laser is to our knowledge the lowest repetition rate as yet demonstrated.

8606-23, Session 7

Generation of 200 fs pulses with a short micro-cavity VECSEL

Andrew P. Turnbull, Keith G. Wilcox, Christopher R. Head, Oliver J. Morris, Univ. of Southampton (United Kingdom); Ian Farrer, David A. Ritchie, Univ. of Cambridge (United Kingdom); Anne C. Tropper, Univ. of Southampton (United Kingdom)

We report a 1-µm mode-locked VECSEL emitting 200 fs pulses. The pulses were generated using two different semiconductor saturable absorber mirrors (SESAMs) designed for 1000 nm and 1030 nm respectively. The first SESAM generated 200 fs pulses with an average power of 2 mW, the second 240 fs pulses with an average power of 13 mW.

The gain structure used in the VECSEL was a 4.5?/2, 4 QW structure designed at 1 µm. Due to the broad gain bandwidth the laser was spectrally agile therefore careful active temperature control using peltier elements was essential to ensure spectral overlap of the gain and SESAM.

With the 1 µm SESAM at 90 °C and the gain sample at -23 °C 200 fs pulses were observed with an average power of 2 mW, a cavity repetition rate of 1 GHz and a FWHM spectral bandwidth of 6 nm. The low power is attributed to temperature dependent non-saturable loss in the SESAM QW.

By cooling the both the gain and the 1030 nm SESAM to -12 °c in the same cavity, 240 fs pulses with an average output power of 13 mW were

generated and a FWHM spectral bandwidth of 8 nm. In this regime the output power was not significantly changed by cooling the SESAM, but the enhanced gain provided by the cooled gain structure was necessary to overcome SESAM insertion loss.

8606-24, Session 7

Exploring spatio-temporal dynamics of an optically pumped semiconductor laser with intracavity second harmonic generation

Yi-Chun Lee, Hsing-Chih Liang, Jung-Chen Tung, Kuan-Wei Su, Yung-Fu Chen, Kai-Feng Huang, National Chiao Tung Univ. (Taiwan)

Since the first demonstration of self-mode locking in the Ti-sapphire laser by Spence et al., the phenomena of Kerr-lens mode locking (KLM) has been explored widely both experimentally and theoretically. Recently, KLM experiments have been demonstrated for the Yb-doped and Nd-doped solid-state lasers. More recently, the self-mode-locked operation with a linear cavity has been also observed in the optically pumped semiconductor laser (OPSL). However, the underlying exploration for spatio-temporal dynamics in the GHz remains incomplete.

In this work, we employed a platform of a commercially available OPSL from Coherent Inc. to demonstrate the dynamics with intracavity second harmonic generation (SHG) for 532-nm emission in the time scale corresponding to the cavity round trip. Experimental measurements reveal that the laser beam displays a phenomenon of complex spatio-temporal dynamics. To confirm the origin of the spatio-temporal dynamics, the cavity configuration is used to calculate the tangential and sagittal mode sizes and mode spacings. With the calculated parameters, we verify that the experimental observation can be explained in terms of total mode locking of TEM00 and high-order modes with significant astigmatism. The overall scenarios are found to be similar to the observation of spatio-temporal dynamics in soft-aperture Kerr-lens mode locked Ti:sapphire lasers.

8606-25, Session 8

Noise properties of NIR and MIR VECSELs *(Invited Paper)*

Mikhaël Myara, Univ. Montpellier 2 (France)

Owing to their cavity geometry and quantum-well semiconductor gain medium, optimised Vertical External Cavity Surface Emitting Lasers (VECSELs) can select a single coherent state - i.e. single polarisation direction, single transverse mode, and single frequency - without the need for intracavity filter. This results in low losses inside the cavity, which permits to reach high photon lifetime in a compact design. This high finesse feature boosts the coherence properties, leading to a diffraction limited beam and reducing the fundamental noise limits (quantum noise) down to extremely low levels (sub-Hz linewidth). Moreover, the short electron lifetime gain medium permits A-class dynamics with low cut-off frequency, leading to shot-noise limited emission over a wide frequency range.

Unfortunately, high power emission relies on noisy optical pumping and induces thermal effects, which impact this high quality light state : the coherence properties of VECSELs are thus the association of ultra-low physical limits polluted by technical elements (thermal, mechanical, ...).

This work aims at showing, thanks to modelisations and measurements, that in spite of these technical limits, optimised optically-pumped VECSELs can reach low noise operation, demonstrating multiwatt emission at 1 µm with beams close to the diffraction limit (M2<1.2) with narrow linewidth (<40 kHz 1 ms !) and shot noise limited operation. These properties define today the state of the art, compared to traditionnal solid-state lasers or to conventional laser diodes.

These properties are also compared to the ones of Electrically-Pumped VeCSELs, which can easily take benefit on ultra-quiet (sub-shot noise) electrical pump.

8606-26, Session 8

Optically-pumped external-cavity semiconductor lasers for precision spectroscopy and laser cooling of atomic Hg *(Invited Paper)*

R. Jason Jones, Justin R. Paul, Yushi Kaneda, Tsuei-Lian Wang, Christian R. Lytle, College of Optical Sciences, The Univ. of Arizona (United States); Jerome V. Moloney, The Univ. of Arizona (United States)

The coherent excitation, measurement, and control of atomic and molecular systems places demanding requirements on the spectral purity, stability, and wavelength accessibility of tunable single frequency laser sources. Optically pumped semiconductor lasers (OPSLs) offer many attractive properties that make them well suited for these types of applications. The flexibility of their operational wavelength in the near-IR and high power single frequency performance allow them to access almost any transition of interest down to the UV, either directly or through efficient harmonic conversion. Furthermore, the low intracavity loss of the OPSL provides an intrinsically narrow quantum limited laser linewidth. In this work we report single-frequency and rapidly tunable operation of an OPSL-based system generating > 100 mW of light at 254 nm. We demonstrate the tunability and intrinsically narrow linewidth of this source through saturated absorption spectroscopy of the 61S0-63P1 Hg transition and a beat note measurement (< 50 kHz FWHM) between the high power OPSL (> 1.5 Watt) and a low power narrow linewidth reference laser operating at 1014 nm. Finally, we demonstrate laser cooling and trapping of over 1 million Hg atoms. OPSL sources are ideal for many future applications in atomic, molecular, and optical physics experiments.

8606-28, Session 8

Tunable high-purity microwave signal generation from a dual-frequency VECSEL at 852 nm

F. A. Camargo, Lab. Charles Fabry (France); N. Girard, Thales Research and Technology (France); J.-M. Danet, LNE-SYRTE, Systèmes de Référence Temps-Espace, Observatoire de Paris, CNRS (France); G. Baili, L. Morvan, D. Dolfi, Thales Research & Technology (France); David Holleville, LNE-SYRTE, Systèmes de Référence Temps-Espace, Observatoire de Paris, CNRS (France); S. Guérandel, Observatoire de Paris (France); I. Sagnes, Lab. de Photonique et de Nanostructures (France); Patrick Georges, Lab. Charles Fabry (France); G. Lucas-Leclin, Lab. Charles Fabry, Institut d'Optique , CNRS (France)

We describe the dual-frequency operation of an optically-pumped vertical external cavity semiconductor laser (VECSEL) stabilized onto an Cs atomic transition. It is based on the simultaneous emission of two cross-polarized adjacent longitudinal modes inside the same laser cavity, which provides a strong correlation between the two laser lines. The frequency difference, in the GHz range, is fixed by the intracavity phase anisotropy, and precisely tuned with an electro-optic modulator (EOM). For this work, we additionally take benefit of the class-A dynamical behaviour of VECSEL which results in a shot-noise limited relative-intensity-noise on a wide spectral range.

The GaAs/AlGaAs active structure is pumped with a 1W-fiber coupled laser diode at 670 nm. The laser cavity has been carefully designed for improved thermal and mechanical stability, and compactness. It consists in a 15-mm concave output coupler, a glass Fabry-Perot etalon, a YVO4 birefringent plate and a MgO:SLT EOM. The output power at

each frequency reaches 20 mW. The frequency difference is phase-locked to a microwave reference source through the EOM voltage with a MHz bandwidth, resulting in a high-purity optically-carried microwave signal. Simultaneously, one laser line is locked on a Cs atomic hyperfine transition at 852 nm through a low-bandwidth servo-loop on the cavity length. The performance of our laser source is thus fully compatible with the excitation of Cs atoms in coherent population trapping atomic clocks.

8606-27, Session PTue

Efficient thermoelectric cooling of concentrated heat loads

Jeff Hershberger, Robert Smythe, Xiaoyi Gu, Richard Hill, Laird Technologies (United States)

An efficiency improvement of 83% is demonstrated in cooling of concentrated heat loads when using thermoelectric coolers (TECs) constructed with thermally conductive printed circuit boards (TCPCBs) as compared to traditional ceramic-based TECs. Laser diodes and infrared detectors must be actively cooled but are smaller than typical TECs. As a result, heat spreading must occur between the optical component and the semiconductor pellets near the edge of the TEC. Typically, TECs based on aluminum nitride circuit boards are chosen and in some cases an AlN plate is added between the optical component and the TEC. To address this, TECs have been developed that replace the ceramic circuit boards with laminated TCPCBs containing a thick copper backing. The copper backing improves heat spreading within the TEC.

A study was conducted to quantify differences in coefficient of performance (COP, heat pumped divided by electrical power consumed) when cooling concentrated heat loads. A heat source 3 mm wide was cooled by TECs ~12 mm wide, comparing ceramic-based and TCPCB-based TECs of otherwise identical design. With a fixed hot side temperature and heat load, each TEC was powered to achieve a desired temperature at the heat source. Ceramic-based and TCPCB-based TECs exhibited COPs of 0.24 and 0.44 respectively, an 83% improvement. A case with an interposing ceramic plate is also presented. Further improvements are achievable: adding a thick copper plate between the heat source and the TEC resulted in a COP of ~0.59 for both TEC types.

Conference 8607: Laser Applications in Microelectronic and Optoelectronic Manufacturing (LAMOM) XVIII

Monday - Thursday 4 –7 February 2013 • Part of Proceedings of SPIE Vol. 8607 Laser Applications in Microelectronic and Optoelectronic Manufacturing (LAMOM) XVIII

8607-1, Session 1

Formation of quantum dots from precursors in polymeric films by ps-laser

Gediminas Raciukaitis, Institute of Physics (Lithuania) and Ctr. for Physical Sciences and Technology (Lithuania); Paulius Ge?ys, Institute of Physics (Lithuania); Francesco Antolini, Lenuta Stroea, ENEA (Italy); Ashu K. Bansal, Ifor D. W. Samuel, Univ. of St. Andrews (United Kingdom); Sybille Allard, Ulrich Scherf, Bergische Univ. Wuppertal (Germany); Luca Ortolani, Istituto per la Microelettronica e Microsistemi (Italy)

Quantum dots (QDs) of semiconductors are promising materials for light emission applications due to their size-tunable optoelectronic properties. We present results of direct quantum dot (QD) formation from precursors inside a polymer matrix using laser irradiation. The method is important because it provides a simple means of patterning nanocomposite material within selected regions of a polymer, as required for device design.

Several combinations of polymer/precursors films were treated with a picosecond laser at wavelength of 266 nm in order to verify the formation of the QDs inside the polymeric matrix. Precursors for CdS and CdSe QDs were used in experiments. The structural studies of laser-irradiated samples carried out by means of transmission electron microscopy (TEM) showed the QD formation. The size of QDs and the clusters depended on the laser irradiation dose transferred to the film. The QDs were collected to clusters including 10-60 QDs of different size. The mean size of QDs was less than 10nm.

The optical analysis carried out by means of UV-VIS and optical microscopy confirmed the formation of the QDs after laser processing. The time-resolved photoluminescence revealed the energy transfer from the organic host to QDs. However, the charge separation was present due to a certain energy level alignment. Modification of the polymer/precursor blends is still required to prevent imbalance of carrier injection to QDs. Photo-luminescent spectroscopy and fluorescence microscopy have revealed that even if the QDs are not emissive, in certain polymer/QDs combinations the PL emission of the polymer is restored after laser treatment.

8607-2, Session 1

Growth of periodic ZnO nano-crystals on buffer layer patterned by interference laser irradiation

Daisuke Nakamura, Tetsuya Shimogaki, Kota Okazaki, Mitsuhiro Higashihata, Kyushu Univ. (Japan); Yoshiki Nakata, Osaka Univ. (Japan); Tatsuo Okada, Kyushu Univ. (Japan)

Zinc oxide (ZnO) nano-crystal is great interest for optoelectronic applications in particular ultraviolet (UV) region such as UV-LEDs, UV-lasers, etc. For the practical optoelectronic applications based on the ZnO nanocrystals, control of nanowire growth direction, shape, density, and position are essentially required. In our study, we introduced a ZnO buffer layer and interference laser irradiation to control the growth position of ZnO nanocrystals. In this presentation,

structural and morphological characteristics of periodic ZnO nano-crystals synthesized by the nanoparticle-assisted pulsed laser deposition will be discussed.

8607-3, Session 1

Sintering of solution-based aluminum nano-particles by laser ignition

Jie Zhang, Panasonic Boston Lab. (United States)

Low-temperature solution processing of metallic aluminum (Al) film using conventional thermal sintering of nano-particle (NP) ink is very difficult due to large particle size. Most Al-inks consist of high population of large sized particles (~a few ?m) due to the fact that making <100nm sized NP ink is almost impossible due to oxidation and safety issues. In addition, oxidation of Al during processing is another major issue because of high sintering temperature and long sintering time. People are looking for alternative methods.

Laser induced sintering, however, appears to be a perfect solution for achieving the low-temperature processing and minimizing the oxidation by utilizing the combustion property of smaller Al-NPs (~<100nm). In this process, laser mainly plays a role of trigging firing of those small Al-NPs at low temperature. This is an exothermal reaction and tremendous heat is generated. The heat simultaneously burns organic ligands and sinter and/or melt the large Al particles. Dislike normal direct laser sintering of metal-NPs (Ag and Au etc) based on low meting point of nano-particles, the laser ignited sintering (LIS) of Al-NP is based on heat self-propagating induced by laser ignition.

Motivated by this idea, sintering of Al-NP using a laser on ink-printed/coated films was investigated. Organic Al-ink (Applied Nanotech Inc. Al-is3000PV) was used as precursors. A CW 1064nm fiber laser (IPG, YLR-50) was used as the ignition source. The laser beam profile can be either Gaussian shape or flat top-hat depending on requirements. The Al film was processed by scanning laser beam at speed of 1-25mm/s. The sintering was carried both in air and a N2 purged chamber.

Electrically conductive Al thin film was successfully processed on glass and Si substrate, respectively. The sintered Al film shows the lower resistivity of ~30 cm on glass substrate and higher resistivity of ~150 cm on silicon substrate. N2 ambient helps to reduce resistivity by reducing oxidation. In addition to the sintering procedure and recipe, the sintered films were also characterized using scanning electric microscopy and laser canning microscopy. The mechanism of laser ignited sintering (LIS) was also discussed.

8607-4, Session 1

F2 laser induced surface and interface modifications of aluminum thin films for selective metallization

Masayuki Okoshi, Kazufumi Iwai, National Defense Academy (Japan); Hidetoshi Nojiri, Renias Co., Ltd. (Japan); Narumi Inoue, National Defense Academy (Japan)

Precise, fine pattering of metal thin films on substrate is currently required for device fabrications in electronics, photonics and life-science applications. In this paper, we applied the 157-nm F2 laser to Al thin films on silica glass substrate to induce the photochemical surface modification for selective metallization. The Al thin film surface was strongly oxidized to show high resistance to potassium hydroxide (KOH) aqueous solution to etch the nonirradiated Al thin films for selective metallization. Moreover, high adhesion between Al and silica glass was found by the F2 laser irradiation.

Experimentally, the Al thin films were deposited on a silica glass by the vacuum evaporation of Al wires. A three-slit metallic mask was set on the Al thin films before laser irradiation. The F2 laser irradiated the Al thin films through the metallic mask. The F2 laser fluence was 10 mJ/cm2. The pulse repetition and irradiation time were 10 Hz and 15 min, respectively.

After the F2 laser irradiation and the KOH chemical etching, three lines of 100-?m-wide Al thin films, according to the shape of metallic mask, were clearly formed. By the XPS analyses, it was found that the surface of Al thin films was oxidized and modified into Al2O3 after the F2 laser irradiation. High adhesion strength of 663 kgf/cm2 was also obtained for the F2 laser-irradiated sample. Mechanism of the high adhesion strength in the F2 laser-irradiated samples was discussed; the Al-O-Si chemical bonds might be formed between Al and silica glass substrate.

This work was partly aided by MEXT-supported Program for the Strategic Research Foundation at Private Universities.

8607-5, Session 2

Nanopatterning beyond the far-field diffraction limit *(Invited Paper)*

Rajesh Menon, The Univ. of Utah (United States)

Green Photonics: A technique for creating deterministic structural complexity is essential to achieve high functionality at the nanoscale, whether in electronics, photonics, or molecular biology. Scanning-electron-beam lithography (SEBL) is the most widely used method in research, but it has a number of drawbacks. SEBL tends to be slow, expensive, prone to placement errors, and not compatible with organics and biological material. Ideally one would prefer to employ benign photons in the visible or near IR range for patterning that is scalable to large areas. However, the so-called far-field diffraction barrier (first realized by Abbé) limits the smallest feature achievable by wavelength, ? to ~ ?/4. In this presentation, I will describe a technique that circumvents this barrier by means of wavelength-selective photochemistry. I call the technique Absorbance Modulation.[1] I will also describe the application of absorbance modulation to scanning-optical nanoscopy.[2] Recently, an alternative to absorbance modulation has also been developed that exploits unique combinations of spectrally-selective reversible and irreversible photochemical transitions to potentially achieve single-molecule resolution at low light levels.[3]

Finally, I will highlight several applications of these nanopatterning technologies; particularly a nanostructured diffractive concentrator that will concentrate sunlight as well as assign optimal spectral bands to laterally separated single-junction photovoltaic devices with the goal of achieving greater than 50% energy-conversion efficiency.

[1] T. L. Andrew, H-Y. Tsai and R. Menon, “Confining light to deep sub-wavelength dimensions to enable optical nanopatterning,” Science, 324, 217 (2009).

[2] H-Y. Tsai, S. W. Thomas, III and R. Menon, “Parallel scanning optical nanoscopy with optically confined probes,” Opt. Exp. 18(15), 16015 (2010).

[3] N. Brimhall, T. L. Andrew, R. V. Manthena and R. Menon, “Breaking the far-field diffraction limit in optical nanopatterning via repeated photochemical and electrochemical transitions in photochromic molecules,” Phys. Rev. Lett. 107, 205501 (2011).

8607-6, Session 2

Periodic surface structures generated by cross-polarized double femtosecond laser pulse irradiation sequences

Arkadi Rosenfeld, Sandra Höhm, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany); Jörn Bonse, Jörg Krüger, Bundesanstalt für Materialforschung und -prüfung (Germany)

The formation of laser-induced periodic surface structures (LIPSS) upon irradiation of dielectrics (SiO2), semiconductors (Si) and metals (Ti) with multiple irradiation sequences consisting of equal energy linearly polarized Ti:sapphire femtosecond laser pulse pairs (pulse duration 50 fs, central wavelength ~800 nm) is studied experimentally. The temporal pulse delay between the individual cross-polarized fs-laser pulses can be varied between -70 to +70 ps with a temporal resolution of ~50 fs. The surface morphology of the irradiated areas is characterized by means of scanning electron (SEM) and scanning force microscopy (SFM).

For all materials, a characteristic 90°-rotation of the LIPSS orientation is observed in a material dependent delay, indicating the importance of the laser-induced free-electron plasma in the conduction band of the laser-excited material [1]. For low fluences (where only the joint action of both laser pulses induces LIPSS) and temporally separated pulses, the polarization of the first laser pulse arriving on the surface determines the orientation of the LIPSS in all observed materials. For temporally overlapping pulses, the coherent superposition of both polarizations determines the LIPSS orientation. For example: If in fused silica the delay between the two pulses is about the laser pulse duration an intermediate 45°-rotation of the LIPSS direction is observed.

The associated LIPSS formation mechanisms are discussed on basis of recent theoretical models.

[1] S. Höhm, A. Rosenfeld, J. Krüger, J. Bonse, J. Appl. Phys. 112, 014901 (2012)

8607-7, Session 2

Periodic surface nanopatterning controlled with preformed scattering structures excited by femtosecond laser irradiation

Go Obara, Naoki Maeda, Hisashi Shimizu, Mitsuhiro Terakawa, Keio Univ. (Japan); Eric Mazur, Harvard Univ. (United States); Minoru Obara, Keio Univ. (Japan)

The plasmonic scattered field consists of far-field and near-field induced by coherent plasmon polaritons excited by a femtosecond laser. Although the near-field optical nanoablation has recently been investigated extensively, however, the long-range plasmon polaritons (far-field) processing has not been investigated yet. In this paper, we describe experimentally periodic ripples patterning using far-field scattered by near-resonant plasmonic and resonant Mie scattering structures, as preformed scatterers, excited by femtosecond laser. We used a 200-nm gold nanosphere, and also 2D silica nanoparticle arrays on Si substrate. Ti:sapphire femtosecond (fs) laser irradiates normally the substrate.

As for the gold particle, fs laser (800 nm, 400 nm with circular polarization) irradiates the Si surface with fluences lower than the single shot ablation threshold, and periodic circular ripples are observed. The ripple periodicity is dependent on the fs laser wavelength. In this case, the gold particle behaves as the near-resonant plasmonic scattering source for far-field. The decay range of the long-range plasmon polaritons, in other words, the number of formed ripples is discussed.

As for 2D silica nanoparticle arrays, a single intense fs laser pulse is illuminated, and 2D crater arrays are fabricated by resonant Mie scattered enhanced near-field. With subsequent low fluence, multiple pulses illumination to the preformed 2D crater surface, 1D periodic ripples are produced, which are well controlled with the preformed structures. In this case, the preformed crater structures behave as the Mie scattered far-field source.

We will present accurate periodic surface ripples fabrication on various substrates including transparent materials.

8607-8, Session 2

Far-field laser direct synthesis of 60 nm silicon nanowires for chemical sensing

James I. Mitchell, Woongsik Nam, Xianfan Xu, Purdue Univ. (United States)

Direct laser writing in combination with CVD growth is a mask-less, single step, catalyst free method for producing silicon nanowires with low global heating. Doping needed for device fabrication can also be achieved in-situ during laser writing. Boron doped nanowires with sizes comparable to those of traditional VLS (vapor-liquid-solid) catalyst grown nanowires are made with far field optics, using a 400 nm femtosecond laser to locally heat a substrate surface and decompose silane and diborane gases onto the heated area. To achieve nanowire sizes far below the far field optical diffraction limit, we utilize laser induced periodic surface structures (LIPSS) and a high numerical aperture phase zone plate with a diffraction limited spot size near the LIPSS period spacing. Only the center of the interference pattern exceeds the silane decomposition temperature for silicon deposition, resulting in individually written silicon nanowires. Using this technique, we grow nanowires with widths as small as 60 nm. The nanowires are then used as components in field effect transistor (FET) chemical sensors where they demonstrate high sensitivities.

8607-9, Session 3

Modelling electron excitation and relaxation in solids under ultrafast laser irradiation *(Invited Paper)*

Bärbel Rethfeld, Technische Univ. Kaiserslautern (Germany)

High-energy laser pulses of subpicosecond duration irradiating metals or dielectrics are primarily absorbed by electrons within the solid.

In metals, conduction band electrons directly gain energy from the laser while in dielectrics electrons have first to be excited from the lower bands.

In the latter type of materials the density of electrons in the conduction band is a crucial parameter in the description of laser-matter interaction.

Its temporal evolution due to nonlinear multiphoton ionization and collisional ionization can be described in terms of a rate equation, which is, however, questionable for laser pulse durations in the range of the photon absorption time.

In our work we model absorption, re-distribution of the absorbed energy and its transfer to the crystal lattice for ultrashort laser pulse durations in the femtosecond regime.

We apply a large variety of kinetic approaches as Boltzmann equation, Monte Carlo simulation and systems of energy resolved rate equations.

With that we are able to identify distinct effects of nonequilibrium energy distributions and to discuss differences of materials reaction due to the ultrashort timescales as compared to a near-equilibrium situation, which can usually be assumed on longer timescales.

In this talk, special attention is paid to the influence of the electronic energy distribution on the electron-phonon coupling parameter.

Here we study different materials like metals with realistic density of states or dielectrics with increasing density of excited electrons.

8607-10, Session 3

Time-resolved X-ray scattering studies of ultrafast phase transitions in laser-excited materials

Klaus Sokolowski-Tinten, Univ. Duisburg-Essen (Germany)

Irradiation of solid materials with intense femtosecond laser pulses can induce phase transitions on very short time scales, and often along non-equilibrium pathways. The advent of ultrafast diffraction techniques has made it possible to directly follow the associated structural changes with spatial and temporal atomic scale resolution. This contribution will report about experiments carried out at the Linear Coherent Light Source (LCLS), the worlds first hard X-ray free electron laser. Using time-resolved diffuse X-ray scattering we studied the structural response of materials undergoing rapid phase transitions after strong femtosecond excitation. Thin films of solid materials deposited onto free standing Si_3N_4-membranes have been irradiated by 50 fs, 800 nm optical laser pulses. Subsequently the scattering of a time-delayed 50 fs, 9.5 keV X-ray pulse from the LCLS has been observed in normal-incidence transmission geometry . The measurements covered a large range of scattering angles and the scattering data provide, therefore, information about the transient structural changes of the irradiated material on different length scales. Examples to be discussed include laser-induced melting and ablation, as well as the structural dynamics in phase change materials used for optical recording.

8607-11, Session 3

Time and space resolved fs-laser ablation of transparent tantalum pentoxide thin films

Stephan Rapp, Janosch Rosenberger, Matthias Domke, Gerhard Heise, Heinz P. Huber, Hochschule München für Angewandte Wissenschaften (Germany)

Rapid prototyping of biocompatible sensor chips, consisting of Ta_2O_5/Pt layer systems on glass substrates, can be realized by using ultra short laser pulses enabling fast and cost efficient changes of the chip pattern. The processing of different Ta_2O_5 layer thicknesses (100 nm and 300 nm) with laser pulses at low fluencies and at a wavelength of 1053 nm leads to a selective lift-off of the Ta_2O_5 layers resulting in an almost ideal blind-hole without detectable thermal damages like burrs or cracks. Moreover, the applied pulse energy is not sufficient for a complete evaporation of the Ta_2O_5 layer. At the used wavelength of 1053 nm the Ta_2O_5 is transparent and the laser pulse is absorbed in the underlying Pt. In consequence, the physical effect causing this clean ablation reaction is assumed to be a so called “indirectly-induced ablation”. The underlying physical effects are investigated by pump-probe microscopy allowing the observation of the whole ablation process ranging temporally from the femtosecond to the microsecond time domain. Results show the formation of a gas-liquid-mixture 10 ps after the reaction onset, initiating a shock-wave that drives the bulging of the Ta_2O_5 film after some nanoseconds. Finally, the Ta_2O_5 film disintegrates after 50 ns. With our method precise relative reflectivity changes and bulging velocities of 750 m/s (100 nm Ta_2O_5) and 140 m/s (300 nm Ta_2O_5) are determined. Due to the used low fluencies indirectly-induced ablation processes enable very efficient material removal leading to process speeds of several hundreds of m/s maintaining excellent structuring quality.

8607-12, Session 3

Factors controlling the incubation in the application of ps laser pulses on copper and iron surfaces

Beat Neuenschwander, Beat Jaeggi, Marc C. Schmid, Berner Fachhochschule Technik und Informatik (Switzerland); Alex Dommann, Antonia Neels, Ctr. Suisse d’Electronique et de Microtechnique SA (Switzerland); Guido Hennig, Daetwyler Graphics AG (Switzerland)

For laser micro processing with short and ultra short pulses the threshold fluence is affected by the well known incubation and often reported in the literature. In general the incubation effect is described with the incubation coefficient S and for metals and semiconductors it is normally smaller than 1, i.e. the threshold fluence drops when the number of pulses is raised. Recently, it has been reported that for ultra short pulses also the energy penetration depth shows an incubation effect of the same kind as well, i.e. it also decreases with increasing pulse number.

The behavior of the threshold fluence may be explained by increased absorption (due to changes in the surface reflectivity), chemical changes of the surface (e.g. due to oxidation) or changes in the microstructure of the material whereas the behavior of the energy penetration depth could be explained by the “latter two effects” but should not be affected by a change in the absorption.

The results of a systematic ablation study for copper and iron will be presented. The study has been done for single crystal and poly crystalline material as well. The influence of the ambient conditions is analyzed by measuring the incubation coefficients for different ambient gases (e.g. oxygen, nitrogen and argon) at several pressures whereas the change in the microstructure will be analyzed by X-Ray diffraction. The results of the study will help to distinguish between the different causes of the incubation effect.

8607-13, Session 4

High throughput laser micro machining on a rotating cylinder with ultra short pulses at highest precision

Beat Neuenschwander, Beat Jaeggi, Markus Zimmermann, Thomas Meier, Berner Fachhochschule Technik und Informatik (Switzerland); Guido Hennig, Daetwyler Graphics AG (Switzerland)

Recently, it has been shown by several groups that moderate fluences, just little above the threshold, should be used for real high throughput laser micromachining with ultra short pulses. Small spot sizes with low pulse energies at high repetition rates guarantees the precision of the ablated structures, but this requires marking speeds from 10 m/s up to the region of the speed of sound to keep the surface quality high and to prevent from heat accumulation effects.

A rotating cylinder offers one option to achieve these marking speeds. We have set up a device with a rotating electro-plated copper cylinder (0.3 m diameter, 20 rotations per second) and a ps laser system. Further synchronizing of all axes and the laser, acting as master, makes it possible to control the spot positions on the rotating cylinder with a precision of better than 1µm during full motion of the cylinder. For a wavelength of 532nm and a spot diameter of 8µm it is possible to work with a repetition rate of about 8 MHz, which currently is the limit of the laser system. However, to take benefit from the maximum average power of the system one has to change to a wavelength of 1064 nm and a spot radius of about 10µm. We will present the results of the strategy optimization process with respect to surface quality, minimum sizes and machining time of the structures generated on the cylinder.

8607-14, Session 4

Formation of mixed metal oxides by femtosecond laser irradiation for solar harvesting

Kasey C. Phillips, Jin Suntivich, Harvard Univ. (United States); Tian Ming, Shao-Horn Yang, Massachusetts Institute of Technology (United States); Eric Mazur, Harvard Univ. (United States)

We present a novel method for producing mixed metal oxides using femtosecond laser doping of metallic foil in the presence of oxygen and another metallic dopant. We discuss doping titanium dioxide (TiO2) for above bandgap absorptance by irradiating titanium metal with an evaporated thin film of metal. As a wide bandgap, TiO2 most strongly absorbs in the UV range (? < 387 nm). We explore the possibility of creating intermediate states in the band gap by doping with metals, such as chromium, manganese, and nickel. Using femtosecond laser doping, we produce laser-induced periodic surface structures on a variety of transition and mixed metal oxide surfaces. We present compositional data from X-ray photoelectron and Raman spectroscopy and structural data from scanning electron microscopy. Using a three-electrode setup, we present photoelectrochemical results and show enhanced water oxidation under illumination. Our research presents an innovative approach using laser scanning techniques to create new materials for visible-light watersplitting.

8607-15, Session 5

Double-pulse irradiation of ultrafast laser for high-efficiency glass microwelding *(Invited Paper)*

Koji Sugioka, Sizhu Wu, Katsumi Midorikawa, RIKEN (Japan)

Efficient microwelding of glass substrates by irradiation by a double-pulse train of ultrafast laser pulses is demonstrated. The bonding strength of two photosensitive glass substrates welded by double-pulse irradiation was evaluated to be 22:9 MPa, which is approximately 22% greater than that of a sample prepared by conventional irradiation by a single-pulse train. Futher, we investigate dependence of delay time between 1st and 2nd pulse irradiation on the bonding strength. The bonding strength rapidly increases as the delay time increases from 0 ps to 12.5 ps, but it drastically decreases after 12.5 ps up to 30 ps. From 30 ps to 1-2 ns, it's almost saturated with the larger bonding strength than that for 0 ps, and it gradually decreases after 1-2 ns again. Finally, the bonding strength for 60 ns becomes smaller as compared with that for 0 ps. The rapid increase between 0 and 12.5 ps is responsible for individual control of each electron excitation process, i.e., multiphoton ionization or tunneling ionization by the 1st pulse followed by electron heating or avalanche ionization by the 2nd pulse. The drastic decrease after 12.5 ps is ascribed to relaxation of free electrons generated by 1st pulse. The saturated but still higher bonding strength between 30 ps and 60 ns than that for 0 ps is due to the absorption of 2nd pulse by self-trapped exciton. The pump-probe measurement of transient absorption supports these consideration. The detailed mechanism will be discussed.

8607-16, Session 5

Selective localised modification of silicon crystal by ultrafast laser induced micro-explosion

Ludovic Rapp, Bianca Haberl, Jodie Bradby, Eugene G. Gamaly, The Australian National Univ. (Australia); Saulius Juodkazis, Swinburne Univ. of Technology (Australia); Andrei V. Rode, The Australian National Univ. (Australia)

Femtosecond laser pulses can deposit a volume energy density up to several MJ/cm3 in a sub-micron volume. This creates highly non-equilibrium, hot, dense and short-lived plasmas with conditions favorable for arrangement of atoms into unusual material phases. At least twelve crystalline phases of silicon are currently known to exist at pressures up to 250 GPa in a diamond anvil cell. Confined micro-explosion induced by tightly focused fs-laser pulse inside a solid opens new strategies for the synthesis of exotic materials into the unexplored area of terapascal pressures [1-3].

Single-crystal silicon was exposed to strong shock waves induced by fs-laser micro-explosion in confined geometry. The conditions of confinement were realized by focusing fs-pulses on a Si surface buried under a 10-µm thick SiO2-layer formed by oxidation of a Si-wafer. 170-fs laser pulses with the energy up to 2.5 µJ were tightly focused to the intensity 1015 W/cm2, well above the threshold for optical breakdown and plasma formation. The shock wave modified areas of the Si crystal were sectioned using a focused-ion beam and characterized with scanning and transmission electron microscopy. A void surrounded by a shock-wave-modified Si was observed at a Si-SiO2 boundary. Raman micro-spectroscopy of the structure surrounding the void revealed that the crystalline Si has undergone a transition to an amorphous state.

The results demonstrate that confined micro-explosion unfolds new routes for formation of exotic material phases expanding the technique possibilities into the domain of non-transparent materials exposed to terapascal-level pressure.

[1] S. Juodkazis et al., Phys. Rev. Lett. 96, 166101 (2006)

[2] A. Vailionis et al., Nature Comm. 2, 445 (2011)

[3] E. G. Gamaly et al., High Energy Density Physics 8, 13 (2012)

8607-17, Session 5

Contrast of femtosecond near infrared and nanosecond deep ultraviolet laser interaction with fused silica glass

Jianzhao Li, Samira Karimelahi, Peter R. Herman, Univ. of Toronto (Canada)

Fused silica glass is one of the most important optically transparent materials that serve in a large range of industrial and research applications including optical windows or substrates, lenses, optical fibers and UV lamp sleeves. On the other hand, glass processing and micro/nano-machining by ultrafast lasers and UV or deep UV lasers have been shown promising to fabricate various optical devices such as optical waveguides, surface or volume nanogratings, and 2D or 3D diffractive optical elements. Precise control of laser interactions to optimize laser modification while minimizing damage and retaining superior optical transmittance and long lasting laser radiation resistance is key to enabling high performance optical devices. This demands an improved understanding of laser-glass interaction mechanisms, particularly on the excitation and relaxation pathways induced by different modes of laser beam delivery. This paper reports a comprehensive time-resolved spectroscopic study of photoluminescence in fused silica glass induced by two extreme modes of laser light: near infrared ultrashort pulses and deep UV nanosecond pulses. Contrast of the photoluminescence spectra and their time evolution together with Raman and Argon ion laser fluorescence study indicates different reaction pathways for generating optical defects that are responsible for refractive index modification. The multi-photon interactions of the ultrashort pulse laser exposure stimulates cross-bandgap excitation of transient self-trapped excitons that lead to concurrent formation of defects dominated by oxygen deficiency centers with relaxation mechanisms lasting shorter than a few nanoseconds. As a comparison, the deep UV nanosecond laser exposure pumps ‘single-large’-photon intra-bandgap excitation through intrinsic defects and generates defects dominated by non-bridging oxygen hole centers in over ~60 nanoseconds since laser excitation via a cascading process. While a deep UV nanosecond laser is suitable for higher resolution or large area mask projection glass processing, the cascading defect formation is prone to inducing inhomogeneous glass modification that underlies optical scattering and propagation losses for laser fabricated optical devices such as waveguides.

8607-18, Session 6

Laser through hole formation for microelectronic substrate vertical interconnection

Chong Zhang, Nikhil Sharma, Amanda E. Schuckman, Islam A. Salama, Tao Wu, Sheng Li, Intel Corp. (United States)

Micro-electronic substrate vertical interconnection is presently enabled through mechanical drilling. Due to the increasing trend of I/O density in the substrate, dimension of vertical interconnection continuously shrinks. Laser drilling offers advantages of high throughput, low operating cost and technological scalability and is poised to replace mechanical drilling for future generations. In this paper we present the results of a systematic and comprehensive study on laser drilling of glass reinforced organic core materials to form vertical interconnection. Drilling results using UV laser (solid state and Excimer), ultrafast lasers (IR and UV) and CO2 laser are presented. Extensive damage to the polymer matrix was observed on the holes drilling with 355nm solid state laser and ultrafast laser (IR and UV). Excimer laser shows good drilling quality but low throughput. CO2 laser shows good balance between drilling quality and throughput. Glass fiber protrusion observed in through hole is a drilling quality concern for all laser types. The mechanism underlying the formation of glass protrusion during laser materials interaction is developed. The glass protrusion observed in glass fabric reinforced core materials occurs as a consequence of the opto-thermal mismatch between the resin and reinforcement phase. Methods to reduce glass fiber protrusion were studied. Temporal or spatial domain optimization of the laser energy was presented as suitable concepts to reduce glass fiber protrusion.

8607-19, Session 6

Micro-hole drilling with femtosecond fiber laser

Huan Huang, Lih-Mei Yang, Jian Liu, PolarOnyx, Inc. (United States)

Femtosecond (fs) laser becomes more popular in precise material processing due to the superiority over longer laser pulses. In this paper, micro-hole drilling with fs fiber laser of 1030 nm wavelength is presented. Micro holes were fabricated on glass and metal materials with fs laser pulses in single step. A systematic study of the laser parameters used for drilling with varying the drilling direction, speed, pulse energy and repetition rate is presented. A scanning electron microscopy is used to investigate the corresponding formation mechanisms. At first micro-hole drilling from the front surface of materials in ambient air is shown. High quality micro holes with limited heat affected zone (HAZ) were demonstrated. Then the aspect ratio of the drilled hole can be increased and the quality of the hole can be improved by using technique of drilling in contact with distilled water from the rear surface for glass materials. It is found that distilled water introduced into the drilled holes helps to reduce the blocking and redeposition effects of ablated material. Finally, it is demonstrated that three-dimensional channels can be micro-machined inside transparent materials by use of this method. This study can be extended to micro-optics, microelectronics, and microchemistry.

8607-20, Session 6

Understanding femtosecond laser hyperdoping mechanism via pump-probe methods

Yu-Ting Lin, Harvard Univ. (United States); Guoliang Deng, Sichuan Univ. (China); Weilu Shen, Rensselaer Polytechnic Institute (United States); Meng-Ju Sher, Eric Mazur, Harvard Univ. (United States)

Irradiating silicon substrates using femtosecond laser pulses in the presence of dopant precursors can result in the incorporation of high dopant concentrations beyond equilibrium values, i.e., hyperdoping. This process drastically alters the optical properties of the resulting material, hyperdoped silicon, by extending absorption throughout the visible spectrum into the mid-infrared. In addition, hyperdoped silicon exhibits metallic-like carrier transport. These properties make hyperdoped silicon a potential candidate for intermediate band solar cells. To better control the doping process and engineer the resulting material, it is essential to understand how hyperdoping occurs. In this work, we study the surface melting and resolidification using pump-probe methods. By probing reflectivity of the silicon surface after receiving single femtosecond pulses, we can extract position of the liquid/solid interface as a function of time, i.e., the melt dynamics. Furthermore, we make cross-sectional TEM samples to examine the actual melt depth by analyzing the crystallinity change. Combining the pump-probe measurement and the TEM analysis, we hope to better understand the melt dynamics. Knowing the melt dynamics under varying processing parameters completes a picture of laser doping mechanism. It also sheds light on how to control the dopant concentration depth profile and the resulting material properties.

8607-44, Session PTue

Reducing damage in femtosecond laser processed silicon for photovoltaics

Benjamin Franta, Harvard Univ. (United States); Clarissa Klein, Menlo School (United States); Eric Mazur, Harvard Univ. (United States)

Ultrafast laser processing is a promising tool for increasing the efficiency and decreasing the cost of photovoltaic (PV) energy. For example, fs laser irradiation can be used to produce nanometer- and micrometer-scale surface textures that have excellent light-trapping and anti-reflective properties, and such textures can be readily produced on a range of materials, including amorphous and polycrystalline systems. Furthermore, fs laser irradiation can be used to chemically dope materials beyond the solid solubility and Mott limits, which is a route toward fabricating an intermediate band PV device, predicted to have a maximal conversion efficiency above 60%. One of the major challenges facing both efforts, however, is the large amount of laser-induced structural damage that accompanies fs laser processing, including the formation of defects and phases that decrease the carrier lifetime and severely limit device performance. Understanding how to reduce or remove such laser-induced damage while maintaining the desired material optoelectronic properties is thus crucial for the development of advanced optoelectronic devices that make use of ultrafast laser processing. Here, we study the relationship between fs laser processing conditions and laser-induced damage in silicon, as well as approaches toward removing such damage. We show that fs laser-induced damage can be controlled during fabrication and that it can be removed almost entirely after fs laser processing by nanosecond pulsed laser melting (PLM), leading to a highly crystalline intermediate band material.

8607-49, Session PTue

Research on period microstructure induced by femtosecond laser in transparent dielectric

Shuwei Fan, Yan Zhang, Xi'an Jiaotong Univ. (China)

Femtosecond lasers have opened a new field for microfabricating due to their unique advantages of super strong power and super short pulse. Researchers have paid more attention to period microstructure induced by femtosecond laser in trasparent material.However,physical mechanisms of inducing period microstructure was not clear yet. This paper did some researches on the physical mechanism of period microstructure induced by femtosecond laser.Main work was as follow:

Physical process of femtosecond laser propagation in dielectric was described by Non Linear Schrodinger (NLS) equation. The math model of NLS was built and were solved by alternative direction implicit method.

The influence of nonlinear effects of femtosecond laser propagation in transparent dielectric such as self-focusing,GDV,MPA,plasma defocusing and interface aberration were analyzed. The electric field distribution along with the direction of laser propagation was simulated with different optical power intesity and different pulse time in different locations.

Also, by employing electromagnetic diffraction theory, the influence of interface aberration on laser field distribution was analysied. Research showed that interface aberration changed optical energy distribution and had obvious influence on location and length.of the period void array.

Considering both the nonlinear effects and interface aberration, the influence of several paramaters on period microvoid were researched. It was showed that laser power and focusing depth had obvious influence on the produced period mocrovoid array. Simutaneously,the simulation results with different focusing lens numerical aperture demonstrated that the period microvoids could be produced more easily with bigger numerical aperature and deeper focus Length.

8607-50, Session PTue

Fresnel attenuator of laser radiation power

Jan A. Owsik, Military Univ. of Technology (Poland); Yury Avdeev, A. N. Severtsov Institute of Ecology and Evolution (Russian Federation); Anatoly A. Liberman, Alexander A. Kovalev, Alexey S. Mikryukov, Sergey A. Moskalyuk, All-Russian Research Institute for Optical and Physical Measurement (Russian Federation); Janusz Noga, Military Univ. of Technology (Poland); Anna Z. Rembieli?ska, LOT Polish Airlines (Poland); Joanna Walczuk, Agency for Restructuring and Modernisation of Agriculture (Poland)

Fresnel attenuators of radiation are frequently used in optical systems and one could presume they are well and thoroughly known. Particularly known is the construction where two reflecting surfaces are situated in a way enabling the resultant reflection coefficient's independence of the type of falling radiation polarization. The reflection coefficient's polarization-independence constitutes the grounds for executing the calibrated attenuator of laser radiation power. Practical realization of such an attenuator is difficult as it requires not only fulfilling accuracy requirements for manufacturing optical elements (Dove's prisms), but also the attenuator's assemblage and the whole system's spatial alignment. There are two elements in the whole system's assemblage. The first is a laser, which generates a beam of such and such possible linear polarization having equal amplitudes of an electric field. The second are the Dove's prisms connected with the radiation receiver. During the systems' assembly the beam's optical axis should be parallel to the longest edge of the first Dove's prism and the radiation polarization surface should be perpendicular (or parallel) to the largest [bottom] face of the prism. In an ideal case the receiver's readings should not change when the radiation polarization surface is rotated by 90°. Yet every stage of the attenuator's execution and implementation might have errors that altogether can lead to a divergence of attenuation coefficients for different polarizations up to 10% and more. This work presents a method enabling to determine the attenuator's parameters deviation from the ideal ones and calculate the attenuator's alignment angles corresponding with the attenuation coefficient independence from the falling radiation polarization.

8607-51, Session PTue

Development of hybrid ArF laser system for lithography

Takashi Onose, Shinji Ito, Kouji Kakizaki, Takashi Matsunaga, Hakaru Mizoguchi, Gigaphoton Inc. (Japan); Shuntaro Watanabe, Chun Zhou, Tokyo Univ. of Science (Japan); C. T. Chen, X. T. Wang, Chinese Academy of Sciences (China); Teruto Kanai, Yohei Kobayashi, The Univ. of Tokyo (Japan)

We have developed a 90W hybrid ArF excimer laser system operating at 6kHz for 193nm microlithography. This system consists of a high efficiency solid-state laser oscillator with a KBBF nonlinear crystal for 193nm pulse generation and an ArF excimer laser power oscillator. It is well known the KBBF crystal has high conversion efficiency in deep-ultra violet (DUV) wavelength region around 193nm, but the practical use development is not yet carried out. When the line-narrowing ArF excimer laser oscillator is replaced with the solid-state laser oscillator, the power consumption of the oscillator can be reduced from 30kW to 6kW and the power consumption of the laser system can be reduced to 60%.

The solid-state laser master oscillator consists of a Ti:sapphire laser system operating at 6kHz and a wavelength conversion system with a LBO and a KBBF nonlinear crystals. We achieved the high efficiency up to 27% and the average output power of 18W in the Ti:sapphire laser system. We also achieve the high conversion efficiency above 12% and the power of 980mW in the KBBF crystal at 6kHz burst-mode operation.

When the 193nm pulses from the KBBF crystal was injected the ArF

excimer laser power oscillator, the average output power of 112W was obtained at 6kHz operation.

8607-52, Session PTue

Laser-induced front side etching using self-regenerating adsorbing layer (SAL-LIFE) of commercial glasses

Pierre Lorenz, Martin Ehrhardt, Klaus-Peter Zimmer, Leibniz-Institut für Oberflächenmodifizierung e.V. (Germany)

The structuring of commercial glasses by lasers, e.g. for optical components, requires high demands and specific methods. The laser-induced front side etching using the self-regenerating adsorbing layer (SAL-LIFE) method has an outstanding potential for nm-precision structuring of dielectrics with a etching depth up to a few 10 µm and a lateral etching range from sub-µm to cm. The sample was positioned in a vacuum chamber which was filled with toluene gas and the gas phase induced the self-regenerating adsorber layer on the sample surface. The laser beam was focused onto the sample surface through the gas.

Within this study the SAL-LIFE of BK7, LiF, CaF2, MgF2, and fused silica is presented. An excimer laser with a wavelength of 248 nm and a pulse duration of 25 ns was used. The influence of the laser fluence and the pulse overlap on the etching process was investigated. The surface morphology of the irradiated surfaces of the commercial glasses was analysed by white light interferometry (WLI), scanning electron microscopy (SEM) as well as the surface contamination was measured by X-ray photoelectron spectroscopy (XPS) and energy dispersive X-ray spectroscopy (EDX). Furthermore, the etching depth was measured by WLI.

8607-53, Session PTue

Measuring the complex refractive index of metals in the solid and liquid state and its influence on the laser machining

Marc C. Schmid, Sarah Zehnder, Patrick Schwaller, Beat Neuenschwander, Joseph Zürcher, Urs W. Hunziker, Bern Univ. of Applied Science (Switzerland)

Knowing the complex refractive index of metals in solid and liquid phase is important for understanding and optimizing material processing like cutting and drilling. When machining with laser in general a thin liquid metal film is formed. This liquid film mainly absorbs the laser energy under a certain angle of incidence. Our studies suggest that the behavior of the absorbed power in this liquid metal film as a function of the angle of incidence (defined by the Fresnel coefficient) has a strong influence on the performance and quality of the laser treatment.

But so far the complex refractive index of liquid metals is not that well known. Also there exists an extended Drude-model taking into account inter-band absorptions and anomalous skin effects for calculating the complex refractive index, this extended theory is not that accurate as it needs other, difficult to measure parameters like the specific conductivity of the liquid metal. Several papers suggest that this extended Drude-model might accurately predict the qualitatively behavior of the complex refractive index as a function of temperature and wavelength but it fails when calculating the effective values.

In this paper we will present our experiments of measuring the complex refractive index of several solid and liquid metals (up to 1500°C) at near-infrared and compare our results with the extended Drude-model. Further we will discuss the difference of the complex refractive index of different metals at 1.06µm and 10.6µm and its influence on the machining performance and quality.

8607-54, Session PTue

Laser processing system development of large area and high precision

Hyeongchan Park, Kwanghyun Ryu, Tae-sang Hwang, ASTJETEC Co., Ltd. (Korea, Republic of)

As industry of PCB(Printed Circuit Board) and display growing, this industry requires an increasingly high-precision quality so current cutting process in industry is preferred laser machining than mechanical machining. Now, laser machining is used almost “step&repeat” method, but this method has a problem such as cutting quality in the continuity of edge parts, cutting speed and low productivity. To solve these problems, on-the-fly(stage-scanner synchronized system) is gradually increasing. On-the-fly technology is able to large-area cutting and high speed because of stage-scanner synchronized moving.

We designed laser-based high precision system with on-the-fly. In this system, we used UV nano-second pulse laser having average power of 14 W, power controller and scanner with telecentric f-theta lens. The power controller is consisted of HWP(Half Wave Plate), thin film plate polarizer, photo diode, micro step motor and control board. Laser power is possible to monitor real-time and adjust precision power by using power controller. Also this machine can be processed in roll-to-roll and sheet type. Using this machine, we tested cutting of roll-to-roll coverlay and sheet type large-area PCB by applying on-the-fly. As a result, our developed machine is processed with high precision and speed than previous cutting methods and productivity has increased significantly. Also it is possible to cut large-area without the problem of the continuity of edge parts.

8607-55, Session PTue

Sub-ns and ps laser performance and results

Joyce P. Kilmer, Matthew Terraciano, Yusong Yin, Photonics Industries International, Inc. (United States)

In the field of ablative-based material processing there is a desire to use short pulse width (sub-ns) laser sources. If the pulse width is too long >10 ns the processing is fast, but crude. If the pulse width is too short <10 ps the processing is precise, but slow. In an effort to balance the process fidelity with material removal rate, a unique TEM00 mode quality sub-ns (~0.5 ns nominal pulse width) laser was developed.

These efficient lasers prove in for next generation applications such as:

- Tempered Glass, Sapphire, or Ceramics Cutting, Scribing and Drilling
- ITO & TiO2 patterning/FPD & OLED processing
- Thinner Low K wafers and LED substrates scribing and dicing
- large area embossing on polymer film processing
- Crystalline Si or thin film based solar cell processing
- Smaller via hole drilling/flex circuit cutting

and other novel micromachining applications.

In this paper, the performance and results of these sub-ns lasers are reviewed and compared with the more conventional ~10 ps laser performance.

8607-57, Session PTue

Femtosecond laser based in-fiber grating fabrication techniques for improved solution sensing

Farid Ahmed, Univ. of Victoria (Canada); Md. Shamim Ahsan, Man Seop Lee, KAIST (Korea, Republic of); Martin B. G. Jun, Univ. of Victoria (Canada)

This work reports femtosecond laser assisted diverse techniques to fabricate in-fiber long period Bragg gratings (LPGs). Point-by-point, line-by-line, and femtosecond laser induced periodic index modification followed by selective hydrofluoric acid (HF) etching method are employed to write gratings in single mode optical fiber (SMF). The femtosecond laser system (Spectra-Physics, U.S.A), operating at 800 nm with a pulse duration of 120 fs and repetition rate of 1 kHz, is used to induce refractive index changes in the core of single mode optical fiber. During fabrication, LPGs are optimized by simultaneously monitoring the growth of its transmission valley in output spectrum.

For the point-by-point, and line-by-line inscription methods, the impact of index change location relative to the fiber axis is investigated. In addition, it is turned out that for a specific period, a gradual increase of index change in the fiber core by consecutive laser scanning reduces the base noise in LPG's transmission side-lobes compared to high index change in the core for a single laser scan. The method of fabricating LPGs by periodic index change and subsequent HF etching is found to have inherited enhanced sensing capability without any further modification because the etched features (holes, grooves etc.) let the sensing solution closely interact with LPG cladding mode. For each method, the position of transmission dip can be tailored relatively easily simply by varying the period.

8607-58, Session PTue

Low cost of ownership solid state laser delivering 120 W at 355 nm for material processing applications

Aleksej M. Rodin, Nick Hay, Young Kwon, Yili Guo, Powerlase Photonics Ltd. (United Kingdom)

A 120 W average power frequency tripled diode-pumped Q-switched Nd:YAG laser has been developed for UV material processing applications. High conversion efficiency to the 355 nm wavelength is achieved using intracavity second harmonic generation and sum frequency mixing in a nested sub-cavity design. Output pulses of 50 ns duration emitted from two identical channels have been polarisation combined and synchronised to form a single output with smooth Gaussian transverse intensity distribution and pulse energy up to 12 mJ at repetition rate 10 kHz . Experimental data supported by numerical modelling shows significant enhancement of nonlinear conversion efficiency using optimised non-linear sub-cavities. Pump diodes with long operational life (>20,000 hours) together with field replaceable modules and elimination of the beam homogenisers needed in excimer laser systems ensure considerable cost of ownership reduction and uptime improvement for a range of industrial material processing applications.

8607-59, Session PTue

Micromachining of Ti-3Al-2.5V tubes by nanosecond Nd:YAG laser

Yaomin Lin, Alfred E. Mann Foundation for Scientific Research (United States); Mool C. Gupta, Univ. of Virginia (United States)

Laser micromachining is one of many laser material processing technologies employed in scientific research and engineering application. It involves the interaction of photon energy and the material. The laser beam can be focused onto an object material to a very small spot area. Through selecting the focusing lens and changing the laser pulse duration, small spot size and high laser beam intensity can be realized. The intense photochemical energy is transported into the target material causing melting and evaporation. The material is removed layer by layer by melting and blowing away or by direct vaporization / ablation. It is due to the focused small spot size that the laser micromachining can remove material in small quantity at a time, thus precise control of geometrical dimension is possible. In this work, a nanosecond pulsed Nd:Yttrium-Aluminum-Garnet (Nd:YAG) laser was employed to generate relatively long notch of different dimensions (25.4 mm-length ? 0.1 mm-width ? 0.051/0.102/0.152 mm-depth) on Ti-3Al-2.5V seamless tubes for fatigue life study. Notch dimensions (length and depth) were calibrated in the experiment. Cyclic hydraulic impulse pressure test was conducted to find out the fatigue limits of the titanium tube containing the laser micromachined notch. Fatigue lives, crack profile and pattern of crack propagation are presented and discussed in this paper. Scanning electron microscopy was employed to characterize the fatigue crack profile and the laser micronotch. The capability of generating sharper notch root and consistent pre-crack on the surface of materials makes nanosecond pulsed Nd:YAG laser a great choice in preparing for fatigue test samples for crack growth life study.

8607-60, Session PTue

Mechanism of micromachining of semiconductor silicon by nano short pulses of multi wavelength laser

Shiva P. Gadag, Southern Methodist Univ. (United States)

Theory of laser ablation of single crystal silicon by nanosecond Q-switched pulses of multi kilohertz frequency of an IR 1064 nm laser is numerically formulated and experimentally validated. The multi kilohertz repetitive pulses of the high intensity peak power oscillator propagate inside the material like a cylindrical piston of diameter equal to laser focused diameter. The impingement pressure of the so called laser pulse piston creates a first indentation crater of its equivalent diameter. The laser impingement crater is surrounded by shiny grey Si ablation crater formed by the ionization of its positive particles and negative electrons during solid to vapor phase transition with intermediate melting phase. The hydrodynamic pressure of laser piston forms the annular melt zone surrounding the ablation crater due to the expulsion of Si liquid. The crater is analytically described by depth and diameter of the ablation in terms of peak fluence to threshold fluence, radius of the laser, absorption coefficient and various optical parameters. The Laser Ablation depth, d of drilled micro via is derived in terms of optical penetration depth of laser wavelength times the square of a characteristic diameter, D. The characteristic diameter is a ratio of diameter of crater to the diameter of laser spot. The depth of the formed micro via is experimentally validated for ?=532 and 1064 nm wavelengths using HIPPO laser. The morphology of the crater is numerically simulated for the experimental conditions in a cylindrical coordinates using temperature dependent thermo-physical properties and optical absorption coefficients of the silicon. The mechanism of micromachining of nano short pulsed ablation is identical to that of ultrashort pulses except for the fact that heat transfer to the lattice phonon is inevitable in case of nanosecond short pulses, leading to some unwanted melting and associated shallow heat affected zone surrounding area of laser irradiation.

8607-21, Session 7

Laser-based spectroscopy and spectrometry *(Invited Paper)*

Yong Feng Lu, Xiang Nan He, Xi Huang, Lian Bo Guo, Univ. of Nebraska-Lincoln (United States)

Laser-based spectroscopy and spectrometry were extensively investigated in nanoscience, materials science, biomedical science, and others. Different lasers with wavelengths from ultraviolet to infrared, and with duration from continuous-wave (CW) to femtoseconds have been employed in various spectroscopic techniques to investigate the properties of materials and nanostructures. However, the sensitivity, spectral resolution, and spatial resolution of these techniques still need to be improved to better serve the purposes of detecting and analyzing various materials. The objective of our research was to improve the sensitivity, spectral resolution, and spatial resolution of different laser-based spectroscopy and spectrometry techniques, such as tip- and surface-enhanced Raman spectroscopy (TERS and SERS), coherent anti-Stokes Raman spectroscopy (CARS), optical emission spectroscopy (OES), laser-induced breakdown spectroscopy (LIBS), and laser-assisted mass spectrometry (LAMS).

8607-22, Session 7

Raman and fluorescence microscopy in polarized light to probe local femtosecond laser-induced partial amorphization of the monoclinic doped crystal LYB:Eu3+

Nicolas Marquestaut, Univ. Bordeaux 1 (France); Marc Dussauze, Yannick G. Petit, Institut de Chimie de la Matière Condensée de Bordeaux (France); Arnaud Royon, Gautier Papon, Univ. Bordeaux 1 (France); Véronique Jubera, Institut de Chimie de la Matière Condensée de Bordeaux (France); Michel Couzi, Vincent Rodriguez, Univ. Bordeaux 1 (France); Thierry Cardinal, Institut de Chimie de la Matière Condensée de Bordeaux (France); Lionel S. Canioni, Univ. Bordeaux 1 (France)

Glass modification by femtosecond direct laser writing has been extensively treated in the literature, but only few studies are related to laser modifications induced in crystals. Laser-induced modifications in crystal matrix are promising research topics for perennial optical devices and applications, thanks to the intrinsic stability of the crystalline matrix arrangement. Laser-induced modifications could lead to local melt, local amorphization or even local recrystallization, leading to differential optical properties with respect to the non-irradiated bulk matrix.

Local modifications induced by femtosecond NIR laser on a monoclinic LYB crystal matrix, highly doped with Eu3+ rare earth ions has been studied. Thanks to point-by-point optical mapping in both Raman and fluorescence micro-spectroscopy, we report on the local changes corresponding to partial amorphization of the LYB:Eu3+ crystal, resulting in significant reshaping of the spectral properties in polarized light. The optical features of this low-symmetry crystal were properly taken into account, to provide meaningful interpretation of the modified Raman and fluorescence spectra. Correlated Raman and fluorescence spectroscopies have demonstrated that structural alterations as well as changes in rare earth Eu3+ environment were accordingly occurring during the laser irradiation above the modification threshold.

Ability to control damage thresholds is the key to understand the different mechanisms occurring simultaneously/consecutively in the laser writing process. Such study shows that both Raman and fluorescence spectroscopies are relevant tools to probe soft laser-induced modifications, which opens interesting potentiality to further identify the fundamental modifications of LYB:Eu crystal that could behave as the elementary brick for photonics applications.

8607-23, Session 7

Quantum cascade laser-based sensing to investigate fast laser ablation process

Francesco P. Mezzapesa, Vincenzo Spagnolo, Antonio Ancona, Gaetano Scamarcio, CNR-IFN UOS Bari (Italy)

A continuous performance improvement of quantum cascade lasers (QCLs) coupled with their intrinsically high sensitivity to external optical feedback is attracting the worldwide interest of the research community working on the development of QCL-based sensing applications. We report on the experimental demonstration of a QCL-based interferometric sensor capable to investigate laser ablation dynamics via the instantaneous measurement of compliance voltage modulations at the QCL terminals, induced by self-mixing optical feedback effects into the laser cavity. In the voltage sensing configuration, a single QCL works as source and detector of radiation, therefore no output coupling is required. This optical diagnostic method results non-invasive and self-aligned, enabling the periodical sawtooth fringes of the interferometric waveform to be sampled during the material removal process in order to perform time-resolved analysis of the penetration depth per laser pulse. Experimental measurements of ablation rates as high as 160 nm/pulse at the maximum power available with our machining laser were demonstrated, and correlate well with the theoretical prediction. Real-time detection of the ablation front velocity as well as in-situ investigations of the surface temperature were also provided. Finally, we show that the detection range of our diagnostic system was only limited by the emission wavelength of the QCL probe source. In this interferometric approach, the sensing technique cannot return a sawtooth-like signal for ablation rate higher than a third of the fringe period, i.e. one sixth of the laser probe wavelength. Hence, a large variety of QCL systems emitting in the mid-IR to THz spectral region can be implemented to extend the application range to ultrafast laser ablation processes.

8607-24, Session 7

High resolution laser direct imaging technology for package substrate high density routing application

Sheng Li, Islam A. Salama, Danny R. Singh, Chong Zhang, Intel Corp. (United States)

Increasing microprocessor input/output density drives shrinking of package substrate features (e.g. copper filled vias, traces, pads, etc.) and tighter layer to layer alignment. This trend raises concerns on manufacturing yield and leakage failures due to electrochemical migration between the closely spaced features formed by the semi-additive process used for substrate fabrication. Commonly used lithography exposure technologies such as contact printing and projection exposure rely on masks to transfer patterns to panels. The associated limitations include pattern quality due to defects or foreign materials on masks and layer-to-layer misalignment related to the panel dimensional variation (i.e. panel to panel or lot to lot deviations) attributed to the thermal treatment steps used in the manufacturing process. Laser direct imaging (LDI) technology has gained a lot of momentum in printed circuit board manufacturing and is an emerging patterning technology for IC package substrate applications. The mask-less exposure technology offers advantages of minimized tooling cost and lead time as well as real time scaling and panel distortion compensation. In this paper, we present the results of an in-depth study on LDI patterning for package substrate high density routing application. Challenges associated with pattern quality and registration accuracy improvement are discussed. The interaction between LDI equipment and dry film resist materials is also examined.

8607-25, Session 7

Femtosecond single-beam dual-voxel local probing of two-photon excited fluorescence in the Eu3+-doped monoclinic Li6Y(BO3)3 crystal

Yannick G. Petit, Institut de Chimie de la Matière Condensée de Bordeaux (France); Arnaud Royon, Nicolas Marquestaut, Univ. Bordeaux 1 (France); Marc Dussauze, Philippe Veber, Véronique Jubera, Thierry Cardinal, Institut de Chimie de la Matière Condensée de Bordeaux (France); Lionel S. Canioni, Univ. Bordeaux 1 (France)

The Eu3+-doped monoclinic crystal Li6Y(BO3)3 is a potential laser crystal for laser emission in the visible red-orange wavelength range. As demonstrated in other laser crystals, direct laser writing (DLW) of waveguides could be of high interest in such promising LYB:Eu crystal. Here, we report on two-photon fluorescence excited under tightly focused near-infrared femtosecond laser irradiation below the material modification threshold.

The orientation of the biaxial LYB:Eu crystal was fixed out of the dielectric principal axes, so that the femtosecond NIR laser could propagate undergoing spatial walk-off refraction. Crystal irradiation under polarized light, below the material modification threshold, led to single-beam dual-voxel two-photon excitation of the Eu3+ fluorescence, demonstrating the simultaneous existence of two spatially-separated nonlinear focuses under microscope objective. The spatial location of the two nonlinear voxels was investigated. The polarization dependence of both two-photon absorption and fluorescence emission, as well as the quadratic dependence of fluorescence intensity, were measured, proving the third-order behavior of the nonlinear excitation of the fluorescence. For high incident irradiances, we even observed partial saturation of the two-photon absorption, showing the efficient depletion of the ground level of the Eu3+ ions. The associated spectral fluorescence distributions in polarized light are also reported.

Such work suggests the potential ability to perform single-beam dual-focus direct laser writing, possibly allowing the simultaneous writing of two waveguides. Two-photon absorption anisotropy indicates that writing thresholds may highly be polarization-dependent. We also believe that two-photon fluorescence can provide relevant tool for local 3D probing of further laser-induced modifications in such crystals.

8607-26, Session 8

3D printing, additive manufacturing, and solid freeform fabrication: a new direction in manufacturing *(Invited Paper)*

Joseph J. Beaman, The Univ. of Texas at Austin (United States)

Starting in the late 1980's, several new technologies have been created that have the potential to revolutionize manufacturing. As stated in a recent Economist article, Additive Manufacturing (AM) "makes it as cheap to create single items as it is to produce thousands … it may have as profound an impact on the world as the coming of the factory did." This presentation will describe these AM processes, give a brief history of AM, and give a critical assessment of the technology. Finally, a discussion a new applications and future directions of AM will be presented.

8607-27, Session 8

Laser additive manufacturing in China *(Invited Paper)*

Henry Peng, Rui Guo, Yanmin Li, Zoe Wu, GE China Technology Ctr. (China)

There has been an increasing interest given to laser additive manufacturing (LAM) in recent years from across the global. While the industrialized nations continue to remain strong in both developing the LAM equipment and the supply chain applications, China market sees the similar trend and moves very fast to this area of all-measures importance. This presentation will review the research and applications of LAM in China and share the authors' views on the market place future of the technology and the future challenges.

8607-29, Session 9

Laser processing of 2D and 3D metamaterial structures *(Invited Paper)*

Nicholas A. Charipar, Kristin M. Metkus, Heungsoo Kim, Matthew A. Kirleis, Raymond C. Y. Auyeung, Andrew T. Smith, Scott A. Mathews, Alberto Piqué, U.S. Naval Research Lab. (United States)

The field of metamaterials has expanded to include more than four orders of magnitude of the electromagnetic spectrum, ranging from the microwave to the optical. While early metamaterials operated in the microwave region of the spectrum, where standard printed circuit board techniques could be applied, modern designs operating at shorter wavelengths require alternative manufacturing methods, including advanced semiconductor processes. Semiconductor manufacturing methods have proven successful for planar 2D geometries of limited scale. However, these methods are limited by material choice and the range of possible feature sizes, thus impacting the deployment of metamaterials due to manufacturing challenges. Furthermore, it is difficult to achieve the wide range of scales encountered in modern metamaterial designs with these methods alone. Laser direct-write processes can overcome these challenges while enabling new and exciting fabrication techniques. Laser processes such as micromachining, laser transfer, laser interferometric lithography and multiphoton polymerization are ideally suited for the development and optimization of 2D and 3D metamaterial structures. These laser processes are advantageous in that they have the ability to both transfer and remove material as well as the capacity to pattern non-traditional surfaces. This talk will discuss recent advances in laser processing of various types of metamaterial designs.

This work was sponsored by the Office of Naval Research.

8607-30, Session 9

Optical tweezers in microassembly

Andreas Ostendorf, Reza Ghadiri, Sarah I. Ksouri, Ruhr-Univ. Bochum (Germany)

Integrated hybrid MEMS devices, i.e. microsystems which are based on different materials, are one of the drivers of microassembling. New micromanipulation devices have been developed mostly based on more or less conventional grippers. Although the absolute forces are restricted to lower values, optical tweezers provide some unique properties in micromanipulation. New approaches in tailored beam shaping, however, allow to precisely control the movement of different tiny particles from nanoparticle size to several 100 µm in diameter. Optical manipulation is not only applied for moving or sorting micro-scaled objects, but also for the assembly of tiny structures. Here, the specific microparts are fabricated by a generative assembling process. Particles of spherical shape, primarily coated with high-affinity biomolecules, can be applied as elementary building blocks to form a more complex structure. Moreover, almost arbitrary shaped particles, which can be generated by a two-photon polymerization (2PP) process are suitable for subsequent assembly. By moving the particle into the requested orientation by holographic optical tweezers (HOT) highly complex parts become possible. Finally, entire lab-systems have been integrated on a single chip (lab-on-a-chip, LOC) to provide stand-alone medical analysis systems. State-of-the-art manufacturing techniques allow the precise realization of micron-sized valves, gears and motors for microfluidic applications. These tools can be driven by applying optically induced forces to the typically dielectric micro-objects. Optical gradient fields can also be applied to sort particles and living cells by size or shape in a microfluidic system.

8607-31, Session 9

Hologram design for holographic laser machining inside transparent materials

Masaaki Sakakura, Naoaki Fukuda, Yasuhiko Shimotsuma, Kazuyuki Hirao, Kiyotaka Miura, Kyoto Univ. (Japan)

One of the important research targets in laser machining is to improve the processing efficiency. A holographic laser machining is one of the promising methods for improvement of the processing efficiency, because multiple positions are processed simultaneously by multiple light spots generated by a holographic method. In this method, multiple light spots are generated by focusing a spatially phase modulated laser beam with a spatial light modulator (SLM). We have applied this method to a femtosecond laser bulk machining inside a glass and found a problem which is not obvious in a surface laser processing. The problem is that the focusing of light could be distorted at some positions and it reduces the processing accuracy. We found that this problem is due to the conventional calculation method of a phase hologram, in which only light intensities are considered in the optimization of the light distribution. We present a calculation method of phase hologram for reducing light distortions. The calculation method is based on the Optimal Rotation Angle method, but special constraints are added in the conventional calculation. The constraints reduce the light intensities around the intensity peaks and generate symmetric light spots at the desired positions. In addition, we will show an application of this method to the fabrication of optical waveguides inside a glass by a holographic femtosecond laser machining.

8607-32, Session 9

LIFT printing of conductive materials for passive microelectronic components

Julie Ailuno, Ludovic Rapp, Anne Patricia B. Alloncle, Philippe Delaporte, Lasers, Plasmas et Procédés Photoniques (France)

In plastic microelectronics, the deposition of highly conductive materials, such nanoparticle metallic inks, on flexible substrates is of prime importance for both the 2D and 3D connection and the realization of passive components. Material with low curing temperature is expected to prevent any thermal damage of the substrate during the sintering post-process. The ideal technique to print such conductive structures should allow transferring lines of few microns wide and with thickness ranging from few hundred of nanometers and few micrometers for high current applications. Recent works demonstrated that the Laser Induced Forward Transfer (LIFT) process has a great potential for the deposition of these conductive structures.

In this work, the LIFT technique has been applied to transfer silver nanoparticles paste or ink with a viscosity varying from 100 to 100000 mPa.s. Ejection mechanisms have been investigated using time-resolved shadowgraphy experiments, in order to correlate the velocity, directivity, and cohesion of the ejected material with the viscosity of the inks. 2D and 3D lines with different thicknesses have been printed with good resolution and high precision on different kinds of flexible substrates (PET, polyimide, teslin, ABS…).

Passive components like diodes, capacitors, resistors and thermal sensors have been printed and their properties have been characterized. The morphological properties of these deposits have been analyzed by means of optical, atomic force, confocal and scanning electron microscopes.

8607-61, Session 9

Investigation of cw and ultrashort pulse laser irradiation of powder surfaces: a comparative study

Robby Ebert, Frank Ullmann, Joerg Schille, Udo Loeschner, Jan Drechsel, Horst Exner, Hochschule Mittweida (Germany)

The paper presents results obtained in laser irradiation of powder surfaces using a 20 W continuous wave fiber laser and a 13 W average power high repetition rate femtosecond laser. The powder layer is coated with special cylindrical dispenser blade in vacuum with a residual gas pressure of 5*10-4 mbar. In the investigations single lines at a distance of 50 µm from each other were processed applying a focal spot size of 40 µm, an average laser power ranging between 1.2 and 6.7 W, and a scanning speed from 0.1 to 0.5 m/s.

Depending on the energy input per unit length different melt structures have been produced. Whereas in case of the lower energy input per unit length skin-deep crossed-linked melt trenches have been observed, deep melt trenches were arising induced by the higher energy input per unit length. Generally, if the same average power level was applied the structures show similar appearance independent from the laser source. But, there was both a higher degree of initial fusing and cross-linking along the processed path when the powder surface was irradiated with ultra-short pulses. Further, with increasing laser intensity a change in structure formation as well as a broadening of the processed path has been occurred, although the en-ergy input per unit length remains constant.

However, accumulation of clods, which was previously observed in high-intense ultrashort pulse laser irradiation, has been become more pronounced in cw laser irradiation above a certain number of consecutive scans. As expected, characteristic effects, such as formation of nanostructures and nanofibers induced by ultrashort pulse laser irradiation have been absent using cw laser radiation.

8607-33, Session 10

Film-free laser microprinting of transparent solutions *(Invited Paper)*

Pere Serra, Adrian Patrascioiu, Juan Marcos Fernández-Pradas, José Luis Morenza, Univ. de Barcelona (Spain)

Liquids laser printing has been usually addressed through laser-induced forward transfer, a technique that allows the deposition of microdroplets with good resolution and control. However, it presents a significant drawback that can compromise its future industrial implementation: the need for the preparation of the liquid to be printed in thin film form. Such constraint results especially detrimental when very high degrees of resolution need to be achieved. In order to overcome the problem, we have recently shown that in the case of solutions transparent or weakly absorbing to the laser radiation, liquid printing is possible directly from the liquid contained in a reservoir, without the requirement of thin film preparation.

The principle of operation of the film-free laser printing technique is the tight focusing of ultrashort laser pulses underneath the free surface of a liquid. Subsurface absorption leads to the formation of a cavitation bubble through optical breakdown, and the subsequent bubble expansion displaces some liquid towards the substrate, where the pattern is formed. Though the feasibility of the technique for microdroplets printing has already been proved, there is not much insight yet in the mechanisms of liquid ejection and transport.

In this work we investigate the mechanisms of liquid ejection during film free laser forward printing. The study, essential for the optimization of the technique, reveals that the process is complex: the bubble expansion-collapse cycle results in the formation of two consecutive jets which display completely different dynamics, and which behavior is strongly dependent on the laser pulse energy density.

8607-34, Session 10

Applications of laser printing for organic electronics *(Invited Paper)*

Philippe Delaporte, Centre National de la Recherche Scientifique (France)

The realization of high performance and reliable organic electronic devices requires the development of both new materials and printing technologies. The Laser-Induced Forward Transfer (LIFT) technique has demonstrated its ability to print a wide range of materials in liquid or solid phase, and functional devices like Organic Thin Film Transistors (OTFT) and Organic Light Emitting Diodes (OLED). The European project e-LIFT studied the potential of LIFT for the manufacturing of organic and inorganic devices.

After the optimization of LIFT process for the transfer of organic materials, devices have been laser-printed. Chemical sensors have been realized for monitoring volatile organic compounds (VOCs) by combining the sensitivity of acoustic wave (SAW/BAW) devices with the selectivity of special polymers. Two kinds of biosensors have also been realized, for the detection of pesticides and odours. The detection limits and the sensitivities of these sensors are close to the state of art and sometimes better. Thermoelectric materials have been transferred for energy harvesting applications. Tri colour (RGB) PLED pixels have been LIFT-printed without degradation of their characteristics. They can be smaller than 20 x 20?m? and their luminance are always higher than 120 cd/m? (up to 210 cd/m?). At last, and a special emphasis will be done on this application, organic thin film transistors have been laser printed and exhibit mobilities of few 10-2 cm2.V-1.s-1.

8607-35, Session 10

Chemical and Z-scan analysis on the direct laser writing of 3D nanofabrication of metal structures

SeungYeon Kang, Kevin Vora, Christopher C. Evans, Kelly Miller, Eric Mazur, Harvard Univ. (United States)

Recent advances in the direct laser writing technique have allowed realization of various three dimensional (3D) nanostructures for photonic and metamaterial applications. Although femtosecond laser patterning has many advantages over conventional fabrication techniques, it has been mainly used to fabricate polymeric structures. Through various optimized chemistries and by using a femtosecond laser with computer-controlled 3D translation stage, we directly write both connected and/or disconnected metal nanostructures that are embedded in a polymer matrix. By varying the types of solvent, polymer and the concentration ratio between metal ion precursors and a polymer capping agent, we limit the nonlinear metal-ion photo-reduction process to a focused spot smaller than that of the diffraction-limit and gain control over the morphology of the resulting metal structures. We demonstrate that the morphology and the fabrication process can depend on the various chemical mixtures. With certain chemistries we show enhancement in various characteristics of our structure such as conductivity or flexibility. In addition to studying the chemistry that affects the photo induced metal growth, we explore the nonlinear interactions between chemical precursors and femtosecond pulses using Z-scan and other spectrophotometric techniques. We characterize the multiphoton absorptions. From analyzing the mechanism of our fabrication process, we hope to gain a better understanding to create more diverse metal nanostructures for a wider range of applications.

8607-36, Session 10

Maskless selective laser patterning of PEDOT:PSS on barrier/foil for organic electronics applications

Dimitris Karnakis, Tim Stephens, Oxford Lasers Ltd. (United Kingdom); Greg Chabrol, ECAM Strasbourg-Europe (France)

Rapid developments in organic electronics promise low cost devices for applications such as OLED, organic transistors and organic photovoltaics on large-area glass or flexible substrates in the near future [1]. The technology is very attractive as most device layers can be solution printed. But when directly patterned deposition is impossible, a post-patterning step is required and laser processing is gradually emerging as a key enabling tool [2]. DPSS lasers offer several advantages including maskless, non-contact, dry patterning but also scalable large area processing well-suited to roll-to-roll manufacturing at ?m resolutions. However, very few reports discuss in detail the merits of DPSS laser patterning technology, especially on flexible substrates [3].

This paper describes the potential of ultrafast DPSS laser technology for OLED fabrication on foil and specifically, picosecond laser ablation of PEDOT:PSS on multilayered barrier/foil or metal grids aimed as a synthetic alternative to inorganic transparent conductive electrodes [4]. Key requirements include: (a) the complete removal of PEDOT layers without residue, (b) the complete absence of surface contamination from redeposited laser debris to avoid short circuiting and (c) no loss in performance of from laser exposure. We will demonstrate that with careful optimisation and appropriate choice of ultrafast laser, the above criteria can be fulfilled. A suitable process window exists resulting in clean laser structuring without damage to the underlying heat sensitive barrier layers while also containing laser debris. A low temperature ablation most likely proceeds via a stress-assisted (film fracture and ejection) process as opposed to vaporisation or other phase change commonly encountered with longer pulse lasers.

[1] “Towards green Electronics in Europe” EU Strategic Research Agenda, Organic & Large Area Electronics (2009)

[2] D.Karnakis, A. Kearsley and M.Knowles, J. Laser Micro/Nanoengi neering 4, 218–223 (2009)

[3] D.Karnakis, G.Van Steenberge, A.Gielen, J.deBaets, J.van den Brand, Proc.LOPE-C 2010

[4] EU FP7 ICT-3 Program Fast2light, No 216641, www.fast2light.org

8607-37, Session 11

Laser patterning of thin indium tin oxide film on a plastics substrate for high-resolution touch applications

Tao Zhang, Di Liu, Hee K. Park, Stony Brook Univ. (United States); Dong X. Yu, YUCO Optics Corp. (United States); David J. Hwang, Stony Brook Univ. (United States)

Indium-tin oxide (ITO) has been widely used as a transparent electrode for display and touch panels due to its low electrical resistance and high optical transmittance in the visible range of the optical spectrum. Direct laser patterning technique has been actively tested to replace conventional etching process that typically suffers from process complexity and environmental concerns. In response to the continuing efforts for higher resolution, improved performance, lower cost, and extended life time display/touch devices, the development of improved and highly stable ITO electrode patterning technology is an urgent task. While the laser patterning for ITO on glass has been extensively studied, the laser technology for ITO on flexible, plastic substrate has not been fully developed, especially in the context of low-cost, high-reliability industrial implementation.

In this study, we focus on laser scribing techniques for high resolution ITO patterning on PET (polyethylene terephthalate) substrate. High repetition rate picosecond and nanosecond pulsed lasers of a wide range of wavelengths from near-infrared to ultraviolet are operated at practical processing speed of the order of m/s. With target line width of ~10µm, the spacing between adjacent and crossing scribing lines is varied, and morphological, optical, electrical, and mechanical characterization are performed to find optimal scribing conditions for high resolution display devices. In addition, the detailed effects of film delamination, re-deposited debris, molten droplets, damage/deformation of substrate, and the influence from the neighboring scribes as a function of spacing are analyzed.

8607-38, Session 11

Laser processing of GaN-based light-emitting diodes: the suitable laser source

Rüdiger Moser, Michael Kunzer, Christian Goßler, Klaus Köhler, Wilfried Pletschen, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany); Ulrich T. Schwarz, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany) and Albert-Ludwigs-Univ. Freiburg (Germany); Joachim Wagner, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany)

The fabrication of highly efficient, state of the art LEDs is quite elaborate since it requires individual photolithography steps for mesa definition, n- and p-contact deposition, passivation and device isolation. Hence prototyping of customer- or application-specific chip layouts is expensive and time consuming due to the required design and fabrication of specific lithography mask sets. During the last years ultra-short-pulse laser processing has been established in solar cell fabrication. In this presentation we report on the development of a device process flow for

group III-N LEDs solely based on laser-direct-writing techniques. The individual laser processing steps comprise the p- and n-metallization as well as trench and p-mesa definition. The epitaxially grown p-GaN contact layer has to be removed first for mesa definition down to a specific depth by laser ablation, whereas at the same time cracking or the formation of crystal defects or leakage paths at the created mesa sidewall has to be avoided. Two different laser sources for mesa definition are compared: (a) a tightly focused direct-writing 355 nm, 10 ps, ultra-short-pulse laser with Gaussian beam profile and (b) a 248 nm, 20 ns, "long pulse" excimer laser with a quadratic hat-top beam profile used in projection mode. The latter features a much shallower penetration depth into p-GaN. The mechanical and electro-optical properties of the resulting LED devices are investigated and compared, in order to identify suitable laser parameters. Finally the laser processed LEDs are compared with conventionally dry etched reference devices, demonstrating that there is no adverse effect due to laser processing.

8607-39, Session 11

Laser cutting of carbon fiber reinforced plastics (CFRP)

Hiroyuki Niino, Yoshizo Kawaguchi, Tadatake Sato, Aiko Narazaki, Ryozo Kurosaki, Yoshihisa Harada, National Institute of Advanced Industrial Science and Technology (Japan) and ALPROT (Japan); Takahiro Nagashima, Zyunpei Kase, Miyachi Corp. (Japan) and ALPROT (Japan); Masafumi Matsushita, Koichi Furukawa, Shin Nippon Koki Co. Ltd. (Japan) and ALPROT (Japan); Michiteru Nishino, Mitsubishi Chemical Corp. (Japan) and ALPROT (Japan)

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=40 W, 50 kHz, 30 ns, 355 nm). 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 (single-mode fiber laser, P=350 W, 1084 nm), a fast beam scanning with a galvanometer scanner was effective to reduce thermal-damages around the grooves.

8607-40, Session 11

Contrasting methods for high speed picosecond laser drilling of high aspect ratio holes in glass

Samira Karimelahi, Ladan E. Abolghasemi, Peter R. Herman, Univ. of Toronto (Canada)

Various means for laser drilling of high aspect ratio holes in brittle glasses have been explored by exploiting the strong nonlinear interactions of ultrashort pulses, the beneficial heat accumulation effects of burst-trains, the plasma driven assistance of liquid interfaces, and chemical etching guided through laser-formed nanogratings. These methods all seek to overcome the unique challenges of glasses with low absorption, frail brittle structure and poor thermal properties to meet a growing industrial interest in processing advanced glasses for display, laboratory, and photonics applications. In this paper, we examine the utility of ps-pulses (12 ps) and burst trains that can take advantage of higher power delivery (50 W), multiple wavelengths (1064, 532, 355 nm), and variable repetition rates (50 kHz-1 MHz) that are available today in commercial laser systems to rapidly form narrow diameter (10s of microns) holes through 1mm thick glass. In this regime, the heat accumulation, self focusing, multiphoton absorption, plasma formation, and filamentary propagation of laser pulses via channeling are effective in extending vias into the high aspect ratio holes. This paper explores a wide range of laser exposure conditions on multiple approaches in hole drilling in fused silica that includes synchronous scanning, static laser exposure, and HF etching assistance. Contrasts in exposure conditions that vary widely with power delivery, laser wavelength (UV to IR), repetition rate, and focusing condition were found to yield dramatically varying interaction domains with unpredictable benefits and disadvantages from self focusing through to burst-train heat accumulation effects. A substantial 700-fold improvement in drilling rates for static drilling was found in contrast with the best speed available in synchronous scanning or with HF etching assist; however, there was a trade off in total required energy, maximum hole depth, and control of hole quality and shape. The results reveal wider processing windows are available for hole drilling of fused silica in the picosecond domain in comparison with the best results found for the much more studied domain of femtosecond laser machining, but with a trade off in the hole quality.

8607-41, Session 11

Novel micro-dots design to resolve hotspot appeared on ultra-slim LED backlight

Wei Ping Chan, Modie Tsai, Yu Ren Chiou, Chih Sheng Jao, Forhouse Corp. (Taiwan)

Light guide plate (LGP) is a key component of the backlight module in LCD display. It determines the efficiency and uniformity of the whole backlight performance. The kernel mechanism of the LGP is the spatial distribution of micro-dots which were fabrication by micro-machining. Accompanied with the high efficiency of LED and promotion of green phonics, reduction of LED amount is very essential in LCD and illumination design. Nevertheless, the reduction of LED numbers introduces serious Hotspot phenomenon. Conventionally, the micro-dots were designed to reduce the Hotspot by conducting geometrical ray tracing with millions of rays. But ray tracing is difficult to explore the spreading of light wave coupled by discrete LED array inside the LGP. Therefore, the LED Hotspot cannot be eliminated overwhelmingly by traditional micro-dots due to lack of quantitative description of light waves from LED propagated inside the LGP. Hence, we first introduced an optical model considering the LED light wave to implement the novel micro-dots design numerically. And then fabricated the micro-dots on the reflected side of the LGP with solid-state laser (YVO4: Wavelength 1064 nm). The LGP with 0.4mm in thickness either with mirror or micro-structured (V-cut) in the LGP entrance plane was also fabricated by mechanically diamond-machining with ultra-precision. After the optical measurement of luminance and subjective JND (just noticeable difference) judgment, this analytical pattern design shows great correspondence between numerical and experimental results that are valid to eliminate the Hotspot phenomenon in LED back-lighted illumination.

8607-42, Session 12

Laser-assisted doping process for selective emitter formation in solar cells via combined pulsed and continuous wave laser illuminations

Di Liu, Hee K. Park, Stony Brook Univ. (United States); Dong X. Yu, YUCO Optics Corp. (United States); David J. Hwang, Stony Brook Univ. (United States)

Laser-assisted doping for selective emitter formation has been investigated in order to achieve better performance in solar cells. Current research focus is in realizing increased doping depth at desired dopant concentration for improved performance of crystalline solar cell design based on spin-on-dopant layers on silicon substrates with passivation layers.

Lasers of different wavelengths ranging from near-infrared to ultraviolet are tested in order to control depth of laser-induced heat source, and temporal modulation of laser Illumination is also performed to adjust temperature dependent dopant diffusion trend. Continuous wave lasers offer an extended dopant diffusion time but have limit in achievable peak temperature. On the other hand, pulsed nanosecond laser illumination is favorable in reaching higher peak temperature and even molten state of the substrates significantly enhancing dopant diffusion rate, but dopant diffusion time is very limited. In this context, combined illumination schemes of pulsed and continuous wave lasers are applied to obtain optimal doping performance by taking advantage of intermittently enhanced dopant diffusion by a pulsed laser over extended diffusion period by a continuous wave laser, using spin-on-dopant layers coated on silicon substrates with various passivation layers. Characterization results by cross-sectional scanning electron microscope (SEM), energy dispersive X-ray spectroscopy (EDS), and secondary ion mass spectroscopy (SIMS) will be presented in conjunction with electrical characterization and cell performance measurements under dark and solar irradiation conditions.

8607-43, Session 12

Fabrication of polymer-nanocomposite anti-reflective coatings by RIR-MAPLE

Richard F. Haglund Jr., Vanderbilt Univ. (United States) and Vanderbilt Univ. (United States); Daniel C. Mayo, Vanderbilt Univ. (United States); Senthilraja Singaravalu, Hee K. Park, Kenneth E. Schriver, AppliFlex LLC. (United States)

As plastic structural components become more common in optical and visual structures, there is a growing need to develop plastic or polymeric coatings for these components. This is primarily because conventional inorganic coatings have differing thermal properties — especially the coefficients of thermal expansion — that often match poorly to those of the underlying plastic substrate. However, in the case of anti-reflective (AR) coatings, this is particularly challenging because polymers exhibit a relatively narrow range of refractive indices, while high-performance AR coatings require alternating high- and low-index layers with the largest possible index contrast.

Here we describe a novel route to synthesizing multilayer anti-reflective coatings for plastic substrates, using hybrid polymer:nanoparticle materials deposited by resonant infrared matrix-assisted pulsed laser evaporation (RIR-MAPLE). As one example, we suspended TiO2 nanoparticles (diameter ~ 10 nm, bulk index of refraction 2.54) in a solution comprising 15% PMMA and 85% water; a second solution without the nanoparticles was also prepared. The two solutions were then pipetted into two different wells, frozen in liquid nitrogen and transferred to a vacuum chamber. An Er:YAG laser operating in free-running mode (pulse duration ~200 s) then was used to ablate the targets sequentially to produce alternating high- and low-index layers at thicknesses computed from commercial thin-film software.

The optimized AR multilayer stacks yielded a coating for a polycarbonate substrate with transmission greater than 97%, scattering less than 3% and a reflection coefficient below 0.5% across the visible wavelength range. Surprisingly, the performance exceeds that expected from a simple mean-field model.

8607-45, Session 12

Scribing of thin film solar cells by high repetition rate picosecond and nanosecond pulsed lasers and in-situ scribing thickness monitoring

David J. Hwang, Di Liu, Hee K. Park, Stony Brook Univ. (United States); Dong X. Yu, YUCO Optics Corp. (United States)

Photovoltaic (PV) cells remain one of the most attractive approaches to the utilization of renewable energy. Due to complex and energy intensive manufacturing process of conventional bulk silicon cells, thin-film PV technique has been actively developed. However, the actual efficiency of thin film PV is often significantly less than values obtained in the laboratory and it is still expensive due primarily to high cost and low accuracy manufacturing steps. Scribing for the required electrical interconnections is a critical step, and laser scribing of thin films has been tested, taking a number of advantages over mechanical scribing, such as precise and reliable operation. However, not all scribing steps are satisfactory by laser as frequently complemented by mechanical scribing modules, and further improvement in the processing budget and accuracy is in urgent need.

In this paper, recent efforts will be demonstrated to develop cost-effective laser solutions for challenging P2 and P3 scribing processes of CIGS (Copper Indium Gallium Diselenide) solar cells through comparison study based on high repetition rate nanosecond and picosecond pulsed lasers of wavelengths ranging from near infrared to ultraviolet at a practical scribing speed of ~m/s. A further reduction in laser power requirements and an improvement in the quality of laser scribing are also attempted by gas injection or suction method, considering fundamentally different ablation mechanisms at high repetition rate operation. In addition, we will present a recently developed in-situ process monitoring technique for the precise detection of thin film layers under laser irradiation for an accurate process feedback.

8607-46, Session 12

Luminescence down shifter effect in hydrogenated amorphous silicon modified by femtosecond laser radiation

Andrey Emelyanov, Andrey G. Kazanskii, Mark Khenkin, Pavel Forsh, Pavel Kashkarov, Lomonosov Moscow State Univ. (Russian Federation); Mindaugas Gecevicius, Martynas Beresna, Peter G. Kazansky, Univ. of Southampton (United Kingdom)

Thin film technology based on hydrogenated amorphous silicon (a-Si:H) has been playing a significant role in the world production of photoelectric modules for several decades. However metastable structure of a-Si:H requires improvement to increase charge carrier mobility and to reduce light-induced degradation. Nanocrystalline silicon (nc-Si:H) in comparison with a-Si:H attributes larger carrier mobility and higher stability. One of technologically attractive methods for a-Si:H crystallization is femtosecond laser processing, which allows achieving localized structural modifications. Recently various experiments have been reported on femtosecond laser irradiation of a-Si:H films. Most of the experiments were dedicated to the investigation of the effect of femtosecond laser processing on a-Si:H film crystallization, surface nano-structuring, optical absorption and photoelectric properties. In particular, ultrafast laser irradiation was demonstrated to produce simultaneous surface nano-structuring and crystallization of amorphous silicon film.

a-Si:H films with a thickness of ~0.5 μm were deposited on silica glass substrates by PECVD upon the decomposition of the mixture of silane (SiH4) and argon (Ar) at substrate temperature of 250 oC. Ultrafast laser treatment of a-Si:H films was carried out with Yb:KGW based femtosecond system that delivered pulses of 500 fs with repetition rate of 200 kHz and wavelength centered at 1030 nm. The Gaussian beam spot was circular with the beam diameter of about 15 μm on the film surface. The samples were irradiated by scanning with the translation speed of 5 mm/s. The scanning step was 2 μm. The average laser beam power was varied from 20 to 300 mW corresponding to the laser fluences from 30 to 480 mJ/cm2. The laser processing was carried out in air.

For the first time, as far as we know, we observed visible photoluminescence with the peak at 675 nm from the composite of Si nanocrystals and SiO2, created by femtosecond laser irradiation of a-Si:H films in air. The luminescence intensity increased with the laser fluence used for film treatment. The photoluminescence is most likely associated with defects at the interface between Si nanocrystals and SiO2 matrix. Demonstrated ultrafast processing offers the possibility

of precisely localized SiO2 formation in a-Si:H based solar cells. The observed red luminescence allows increasing the photosensitivity of solar cells to higher photon energies thanks to so called luminescence down shifter effect that will result in several percent relative enhancement of the energy conversion efficiency.

8607-47, Session 13

Investigation of a reliable all laser scribing process in thin film Cu(In,Ga)(S,Se)2 manufacturing

Reiner M. Witte, Bruno Frei, Stefan Schneeberger, Solneva SA (Switzerland); Andreas Burn, Valerio Romano, Martin Muralt, Bern Univ. of Applied Science (Switzerland); Stephan Buecheler, Shiro Nishiwaki, EMPA (Switzerland)

New developments in the thin film solar market continue the trend towards solar modules with higher energy conversion while at the same time, reducing significantly manufacturing costs. Especially thin film technologies based on Cadmiumtellurid (CdTe) or Cu(In,Ga)(S,Se)2 (CIGS) seem to be suited to improve the energy conversion and hence, take over larger market shares. With this work, we present our latest achievements towards a CIGS "all laser" scribing process with the emphasis on structuring the absorber layer and its implications to the production. While P1 laser scribing through the substrate is already implemented in production today a variety of different approaches, like "lift-off', ablation, or remelting are possible for the P2 process where commonly a mechanical process is state of the art. One challenge P2 and P3 processes face is the layer side processing. Therefore a thorough investigation has been conducted including different laser wavelengths (355 nm to 1550 nm), pulse durations (10 ps to 100 ns), and beam shaping to find the best possible solution for each scribing process. Optimization took place utilizing not only resistance measurement and optical microscopy but also LSM, REM, EDX, EL, and Lock-In Thermography. Combining the best results of each scribing process with a high speed, high accuracy motion system a functional lab size module has been produced with a reduced dead zone of below 200 µm. In an outlook, a way is presented on how to take the lab results into a productive system and place it in a manufacturing environment.

8607-48, Session 13

Scribing of CIGS thin films for solar module fabrication by external integrated interconnection

Pierre Lorenz, Martin Ehrhardt, Anja Wehrmann, Leibniz-Institut für Oberflächenmodifizierung e.V. (Germany); Christian Scheit, Steffen Ragnow, Alexander Braun, Solarion AG (Germany); Klaus-Peter Zimmer, Leibniz-Institut für Oberflächenmodifizierung e.V. (Germany)

High-quality scribing of the CIGS thin film (TF) stack for external integrated interconnections is needed for developing CIGS thin film solar modules and reducing the production costs to below $1/Wp. The scribing of CIGS and related material with pulsed laser may cause material modifications ranging from amorphization to new phase formation [1]. Ablation and scribing of CIGS with ultrashort laser pulses can cause still little material modifications [2]. Therefore, the optimization of ultrashort pulse laser scribing of TF material stacks is even more challenging due to the different material properties of the included layers and requires advanced analytical techniques [3, 4].

In this presentation scribing of CIGS TF material with ultrashort laser pulses for external integrated interconnection is discussed from various points of view. The main issue is the defect formation at laser scribing. Different experimental approaches for the optimization of the laser scribing procedure are discussed. One main approach is the quasi in situ measurement of the electrical cell properties during laser scribing. The experimental result will be presented and the results concerning the parameter influence on the TFSC properties will be discussed. An optimized interconnection process enables module fabrication with the same active area efficiency compared to TF solar cells.

[1] K. Zimmer, et al., Appl. Surf. Sci. 127-129(1998)800-804.

[2] D. Ruthe, et al., Appl. Surf. Sci. 247(2005)447-452.

[3] A. Wehrmann, et al., Proc. of SPIE 7921(2011)79210T-14.

[4] A. Wehrmann, et al., Optics & Laser Technology, 44(2012)1753-57.

Conference 8608: Laser-based Micro- and Nanopackaging and Assembly VII

LASE
SPIE Photonics West

Wednesday - Thursday 6 –7 February 2013

Part of Proceedings of SPIE Vol. 8608 Laser-based Micro- and Nanopackaging and Assembly VII

8608-1, Session 1

Enhanced light extraction from microstructured organic light-emitting devices *(Invited Paper)*

Hong-Bo Sun, Jing Feng, Jilin Univ. (China)

Microstructure with wavelength to subwavelength-scale periodicity has played an important role in optical and optoelectronic devices, particularly in optical fibers, distributed feedback lasers, LEDs and solar cells etc. through manipulating the generation and propagation of photons in materials. This talk will introduce our systematic investigations on the fabrication of microstructure in organic light-emitting devices and their effects on improving the device performance. The waveguide and surface plasmon-polariton (SPP) modes that were generally lost in conventional bottom-emitting organic light-emitting devices (BOLEDs) have been successfully recovered by employing a microstructure, and a much enhanced light extraction has been observed. We demonstrate that the introduction of a periodic corrugation into the top-emitting OLEDs (TOLEDs) is effective in relieving the tradeoff between device lifetime and efficiency, through the coupling of the SPPs associated with the Ag cathode and the microcavity modes. Moreover, the viewing characteristics of TOLEDs have been improved by employing microstructure to construct a microcavity with periodically changed cavity length.

8608-2, Session 1

Periodically structured optical materials by microsphere-assisted laser interactions

Deepak L. N. Kallepalli Lakshmi Narayana, David Grojo, L. Charmasson, Philippe Delaporte, Olivier P. Utéza, Lasers, Plasmas et Procédés Photoniques (France); Marc Dussauze, Institut des Sciences Moléculaires (France); Evelyne Fargin, Thierry Cardinal, Institut de Chimie de la Matière Condensée de Bordeaux (France); Yannick G. Petit, Lionel S. Canioni, Univ. Bordeaux 1 (France)

Laser near-field enhancements underneath transparent microspheres can be used to locally implement new functionalities in optical materials. Using this technique, we report micro- and nano-structuration on silicon (Si) and silver doped glasses. The Langmuir-Blodgett (LB) technique is primarily used to realize monolayers of C18 functionalized silica (SiO_2) on a large size area on the substrates. Afterwards, we investigate two ways to develop optical functions in materials. First is to produce micro-structured Si electrodes for electric-field poling experiments. By irradiating the deposited monolayer with an UV nanosecond laser pulses in the ablation regime, we thus demonstrate the formation of dense arrays of craters in silicon substrate. In particular, we describe our works to obtain mono dispersed craters of sub-micrometer size using LB technique and taking as variable irradiation parameters, the fluence and number of shots. Finite-difference time-domain (FDTD) simulations are presented to estimate the enhancement factor and near-field distribution in the experiments. Second is to write new functionalities by direct femtosecond laser writing of optical materials through the microspheres. We thus report on periodic nano-structurations of silver (Ag) doped photosensitive glasses. By irradiating these glasses with an IR high repetition rate femtosecond laser, silver aggregates are locally formed. Upon excitation with a CW blue diode laser, the activated aggregates emit broad visible fluorescence that can functionally serve as memory bit. The role of different laser parameters such as number of shots and energy (fluence) will be here discussed.

8608-3, Session 1

Picosecond and nanosecond pulsed laser ablation of aluminium, polypropylene, polyethylene, and their thin film combinations

Adrian H. Lutey, Univ. degli Studi di Bologna (Italy); Michele Sozzi, Stefano Selleri, Univ. degli Studi di Parma (Italy); Pier Gabriele Molari, Univ. degli Studi di Bologna (Italy); Annamaria Cucinotta, Univ. degli Studi di Parma (Italy)

The pico- and nano-second ablation thresholds and subsequent pulse-energy cut-depth and width relationships of aluminium, polypropylene (PP), polyethylene (PE) and their various thin-film combinations have been determined. Specimens were exposed to 500 ps, 800 ps, 10 ns and 12.5 ns laser pulses of 0.4 - 20 J/cm2 at 1064 nm and 10 ns and 12.5 ns pulses of 2.5 - 37 J/cm2 at 515 nm. High quality incisions were obtained for all structures within certain parameter ranges. The ablation threshold of aluminium in the picosecond range was found to be approximately 20% of that in the nanosecond range, with the latter in agreement with previously published data. The efficient incision of PP and PE was only possible in the picosecond range. Numerical simulations were used to show that the underlying ablation mechanism of aluminium is phase explosion, while attached materials, for multi-layers, are removed by thermal conduction. The behaviour of single-layer PP and PE was characterised by an effective absorption coefficient and a logarithmic function of laser fluence. The presented results provide necessary parameters for the efficient cut and scribe of such materials, allowing the laser to prevail in lieu of more costly and energy intensive methods.

8608-4, Session 1

Improvement of laser dicing system performance I: high speed and high quality processing of thick silicon wafer utilizing spatial light modulator

Naoya Matsumoto, Yu Takiguchi, Haruyasu Itoh, Masaharu Hoshikawa, Hiroyuki Iwaki, Tsukasa Hasegawa, Makoto Nakano, Masaki Oyaizu, Takeshi Sakamoto, Takafumi Ogiwara, Takashi Inoue, Hamamatsu Photonics K.K. (Japan)

A laser wafer-dicing technique called “Stealth Dicing (SD)” performs a multi-layer/depth scan of a laser beam that is tightly focused inside a silicon wafer. The focused beam creates multi-layered micro-cracks which allow dry and debris-free dicing. In order to reduce the dicing time, it is desirable to have a longer crack for each scan. However, when the laser beam is focused in a deep region of wafer, the beam is blurred and its power density becomes lower due to spherical aberration caused by a refractive index mismatching between air and the wafer. As a result, the generated cracks become shorter.

We will present an approach to make longer cracks at a deep region of wafer by correcting the spherical aberration. This correction was carried out by using a SD machine incorporating a phase-only spatial light modulator (SLM) to conduct aberration correction patterns. Such patterns were calculated with a method based on inverse ray tracing. Experimental results using 300-micrometers wafers show that, when the aberration correction was implemented, the lengths of cracks became longer even in the deep region of wafer with multi depths scan and that the dicing speed with correction is more than twice faster than that without correction

This is due to longer crack per scan and reduced number of multi depth scans with aberration correction. We also demonstrated that the quality of dicing was also improved.

8608-5, Session 1

Laser-induced self-organizing surface structures on cathode materials for lithium-ion batteries

Robert Kohler, Johannes Pröll, Michael Bruns, Torsten Scherer, Hans Jürgen Seifert, Wilhelm Pfleging, Karlsruher Institut für Technologie (Germany)

Rechargeable lithium-ion batteries have emerged as an attractive power source for a wide variety of applications, in particular for portable electronics. The development and modification of electrode materials is a major issue for the improvement of energy density and power density of lithium-ion batteries.

For this purpose, laser-induced self-organizing surface structures were generated using UV-excimer laser radiation with a wavelength of 248 nm and pulse widths of 4-6 ns. The self-organization process was applied for thin films made of lithium cobalt oxide with a thickness of about 3 µm. In order to identify the chemical changes due to laser processing, X-ray photoelectron spectroscopy and time-of-flight secondary ion mass spectroscopy were applied. It was found that this process can be linked to a decomposition of the electrode material forming a lithium oxide surface layer. Similar self-organized surface structures could also be obtained for thick film electrode materials, such as LiCoO2 and Li(NiMnCo)O2 mixed with binder and carbon black which were tape-casted onto aluminum foils. The film thicknesses were in the range of 50 - 100 µm.

Electrochemical cycling using a lithium anode and conventional electrolyte was applied to study the influence of the laser processing procedures on battery performance. It could be shown that the self-organized surface structures can improve the cycling stability for thin film electrodes as well as for tape-cast electrodes.

8608-6, Session 1

Thin film passivation of laser generated 3D micro patterns in lithium manganese oxide cathodes

Johannes Pröll, Robert Kohler, Michael Bruns, Vanessa Hermann, Peter G. Weidler, Stefan Heissler, Torsten Scherer, Hans Jürgen Seifert, Wilhelm Pfleging, Karlsruher Institut für Technologie (Germany)

The increasing need for long-life lithium-ion batteries requires the further development of electrode materials. Especially on the cathode side new materials or material composites are needed to increase the cycle lifetime.

On the one hand, spinel-type lithium manganese oxide is one promising candidate to be used as cathode material due to its non-toxicity, low cost and good thermal stability. On the other hand, the spinel structure suffers from change in oxidation state of manganese during cycling which is also accompanied by loss of active material into the liquid electrolyte. The general trend is to enhance the active surface area of the cathode in order to increase lithium-ion mobility through the electrode/electrolyte interface, while an enhanced surface area will also promote chemical degradation.

In this work, laser micro-structuring of lithium manganese oxide thin films was applied in a first step to increase the active surface area. This was done by using 248 nm excimer laser patterning using chromium/quartz mask imaging techniques. In a second step, high power diode laser-annealing operating at a wavelength of 940 nm was used for forming a cubic spinel-like battery phase. This was verified by means of Raman spectroscopy, X-ray diffraction analysis as well as cyclic voltammetric measurements. In a last step, the laser patterned thin films were passivated with indium tin oxide (ITO) layers with a thickness of 10 to 50 nm. The influence of the 3D surface topography as well as the ITO thickness on the electrochemical performance was studied by cyclic voltammetry. Post-mortem studies were carried out by using time-of-flight secondary ion-mass spectroscopy as well as scanning electron microscopy and focused ion beam analysis.

8608-7, Session 2

High speed micro scanner for 3D in-volume laser micro processing *(Invited Paper)*

Dagmar Schaefer, Jens Gottmann, Martin Hermans, Ingomar Kelbassa, RWTH Aachen (Germany)

The requirements of 3D laser micro processing of transparent materials are mainly based on high speed and high precision. Currently, high speeds in the order of several meters per second are realized using available high speed scanning systems with galvanometer mirrors. Normally these scanning systems are equipped with optical components with large focal lengths (f > 80 mm) and small numerical apertures (NA< 0.2). The relatively large focal volume is not sufficient for 3D in-volume micro processing. Otherwise, high precision is provided by air bearing translation stages. However, equipped with microscope objectives with large numerical apertures (NA > 0.2) the linear scan speed of translation stages is limited to about v = 1 m/s.

The solution to overcome these limitations in high speed and high precision is based on a galvanometer scanner which is integrated into a system with large numerical aperture (NA = 0.4-1.2), high precision (< 500 nm), small focal spot (2w0 = 0.6-2.2 µm) and high scan speed (v = 50-400 mm/s).

The developed high speed micro scanner enables precise and fast laser micro structuring simultaneously. With this technique new design opportunities are offered for the fabrication of 3D micro components in the volume of transparent materials. Optical components like waveguides, gratings and markings are realized with arbitrary shape. Mechanical components like mounted gears, cut holes and channels are produced with micrometer dimensions and nanometer precision using the developed high speed micro scanner for structuring and the following etching process (ISLE: In-volume Selective Laser Etching).

8608-8, Session 2

Improvement of laser dicing performance II: dicing rate enhancement by multi beams and simultaneous aberration correction with phase-only spatial light modulator

Yu Takiguchi, Naoya Matsumoto, Masaki Oyaidu, Jyunji Okuma, Makoto Nakano, Takeshi Sakamoto, Haruyasu Ito, Takashi Inoue, Hamamatsu Photonics K.K. (Japan)

“Stealth Dicing” laser processing is a dry and debris-free semiconductor wafer dicing method achieved by generating thermal micro-cracks inside a wafer with a tightly focused laser beam. This method has two practical issues; (1) the dicing speed is limited by the repetition rate of pulsed laser, and (2) potential damage of integrated circuits on the wafer from excessive dicing laser intensity due to insufficient beam divergence. The reason for the insufficient beam divergence is resulting from spherical aberration due to a refractive index mismatch between air and the wafer.

These problems are resolved by incorporating a phase-only spatial light modulator (SLM) into the laser dicing system. The SLM is used to control two types of wavefront configurations simultaneously for two different functions. One is for multi-beam generation with a phase grating pattern. This improves the speed of dicing by a factor of the number of diffracted beams. The other is for aberration corrections for the multi-beams with a pre-distorted wavefront pattern. By correcting aberrations, the focused multi-beams inside the wafer will become sufficiently divergent to avoid unnecessary potential laser damages.

We demonstrated these improvements by dicing sapphire wafers with a pulsed laser and a high-numerical-aperture objective lens.

8608-9, Session 2

High speed micromachining with high power UV lasers

Rajesh S. Patel, James M. Bovatsek, Ashwini Tamhankar, Spectra-Physics®, a Newport Corp. Brand (United States)

Increasing demand for creating fine features with high accuracy in microelectronics materials and devices has fueled growth for lasers in manufacturing. High power, high repetition rate ultraviolet (UV) lasers provide an opportunity to implement a cost effective high quality, high speed micromachining process in a 24/7 manufacturing environment. The energy available per pulse and the pulse repetition frequency (PRF) of diode pumped solid state (DPSS) nanosecond ultraviolet (UV) lasers have increased steadily over the years. Efficient use of the available energy from a laser is important to generate accurate fine features at a high speed with high quality. To achieve maximum material removal and minimal thermal damage for any laser micromachining application, use of the optimal process parameters including energy density or fluence (J/cm2), pulse width, repetition rate is important. It allows for a controlled and precise micromachining process with improved throughput and feature quality, while minimizing the negative effects of damage from overheating the part and micro-cracking. In this study we present results achieved using high power, high repetition rate nanosecond UV DPSS lasers in micromachining applications for printed circuit boards (PCBs), flat panel displays, semiconductors and other microelectronic applications. We demonstrate high quality, high throughput micromachining using these UV DPSS lasers.

8608-10, Session 2

UV laser writing system based on polar scanning strategy to produce subwavelength metal gratings for surface plasmon resonance

Jun Amako, Toyo Univ. (Japan); Eiichi Fujii, Seiko Epson Corp. (Japan)

We demonstrated the use of UV laser lithography in the production of subwavelength structures. A laser writing system with a 413-nm Kr laser was used to pattern a resist-coated fused silica substrate mounted on a rotating table and a linear slider. Because the system used polar coordinates, it was tested in terms of patterning accuracy, particularly in the azimuthal direction, for submicron patterns. We used the system to produce subwavelength metal gratings intended for biochemical sensing. The gratings can couple incident light with surface plasmons to enhance near fields. The gratings were written in a 3-mm-wide ring at distances of 49 - 74 mm from the center, depending on the grating period, using a ~500-nm-wide focused beam at a sampling frequency of 2.9 MHz. The rotation speed was fixed at 225 rpm. The patterned resist was then dry etched and coated with Au to obtain metal gratings with periods of 400, 500, and 600 nm. The reflectance spectra of the gratings showed surface plasmon resonance peaks at and around the theoretically predicted wavelengths, and the peak deviation was ~5 nm, which was smaller than the peak width. This indicated that the curved grid of the system hardly affected the optical characteristics of the gratings. The filling factor was varied by adjusting the writing beam intensity and thus holes and pillars were realized. In addition, molds were created to replicate the gratings. We concluded that UV laser lithography based on this polar scanning strategy is a candidate for surface structuring on submicron scales.

8608-12, Session 3

Ultrafast laser processing of thin and strengthened display glasses *(Invited Paper)*

Dirk Mueller, Andreas Blumenrath, Bernhard H. Klimt, LUMERA LASER GmbH (Germany); Abbas Hosseini, FiLaser Inc. (Canada)

Today's display glasses, as ubiquitously used in handheld electronic devices, are generally chemically strengthened in order to provide a more scratch resistant surface and enhance its break strength. Unfortunately, chemically strengthening the glass poses a very difficult challenge for subsequent glass cutting. Low yield and elaborate process steps make the cutting a significant cost in display glass manufacturing.

LUMERA LASER GmbH together with its partners has developed a cutting process able to cut chemically strengthened glass with a high yield and excellent bend strength. Chemically strengthened glass can be cut at speeds up to 500mm/s and even tight radii of curvature and inside cuts are possible using this unique ps-laser based cutting technology. The talk will present the latest progress on this cutting technology and elaborate on its impact for combining the functionality of cover glass and touch screen sensors in one glass.

8608-13, Session 3

Pico second laser ablation of transparent materials

Simone Russ, TRUMPF Laser GmbH & Co. KG (Germany); Christof Siebert, Birgit Faisst, TRUMPF Laser- und Systemtechnik GmbH (Germany); Wolfgang Schulz, Urs Eppelt, Claudia Hartmann, Fraunhofer-Institut für Lasertechnik (Germany)

The huge increasing market for smart phones and tablet computers requires new and faster processes in the production of flat panel displays. To decrease costs it is necessary to reduce process time by replacement of manual process steps with automated processes.

As display glass has to stand high demands like higher bending strength and improved light transmission the search for a suitable tool is difficult.

With ultra short, frequency doubled laser pulses in the regime of less than ten pico seconds it is possible to machine transparent materials with low thermal influence. Therefore it is possible to avoid strains and cracks. However a systematic and material specific optimization of the process is necessary to reduce the influence on materials properties like e.g. bending strength. Every kind of glass has different material parameters so that process parameters have to be adapted accordingly.

Basic research on processing glass with ultra short pulsed lasers has shown that the process can be controlled by the variation of parameters like laser power, scan speed and focus positioning. These parameters have a big influence on the morphology and geometry of the cutting edge which highly affects the flexural strain. Never-the-less many details of the process, like backside damage are not totally understood yet and have to be further investigated.

In research cooperation between the Fraunhofer Institute for Lasertechnology Aachen and the laser manufacturer TRUMPF Laser GmbH + Co. KG analytical as well as practical solutions are investigated to generate a deep process understanding.

8608-14, Session 3

Metal microdrilling combining high power femtosecond laser and trepanning head

Rainer Kling, Mathieu Dijoux, ALPhANOV (France); Luca Romoli, Univ. di Pisa (Italy); Jorge Sanabria, Amplitude Systèmes (France)

Trepanning heads are well known to be efficient in high aspect drilling and to provide a precise control of the hole geometry. Secondly,

femtosecond lasers enables to minimize the heat effects and the recast layer on sidewalls but are typically used on thin sheet. The combination of both present a high potential for industrial applications such as injector or cooling holes where the bore sidewall topology has a major influence on the dynamics of the gas flow. In this paper we present results using this combination. The effect of pulse energy, repetition rate and revolution speed of the head on both geometry and roughness are discussed. The quality of the sidewall is checked by roughness measurement and by metallographic analysis (SEM; chemical etching, micro hardness).

8608-15, Session 3

Direct curved micromachining with femtosecond accelerating beams

Amaury Mathis, Francois Courvoisier, Luc Froehly, Luca Furfaro, Maxime Jacquot, Pierre-Ambroise Lacourt, John M. Dudley, FEMTO-ST (France)

A particular challenge in material processing is machining structures that have controlled longitudinally-varying characteristics, because this requires the simultaneous control of beam steering, workpiece rotation and ablation rate. This is especially difficult when the desired features are of micron scale. Here, we report for the first time to our knowledge, a novel solution to this problem using accelerating beams. These beams consist of a strongly localized high-intensity lobe whose trajectory displays curvature in a dimension transverse to its propagation. We show that the curvature can be arbitrarily shaped since the properties of accelerating beams can be usefully interpreted in terms of optical caustics. These beams have recently attracted much attention in the fields of particle trapping and nonlinear optics. With this novel approach, we machine initially square sample edges to arbitrary curved profiles (circular, quartic) with radius of curvature as small as 70 µm. This approach is applicable to both opaque and transparent materials, and we report results on silicon, glass and diamond. We also show experimental results in silicon where accelerating beams have been applied to the direct writing of curved trenches within the bulk sample. Our results are interpreted in terms of an ablation threshold model. Interestingly, highly asymmetric debris deposition is observed and interpreted in terms of the optical properties of the incident accelerating beam. This approach is not restricted to femtosecond laser micromachining and we anticipate a broad range of applications in different technological fields such as the processing of flat panels and precision photonic components.

8608-16, Session 3

Ultrafast laser trimming for reduced device leakage in high performance OTFT semiconductors for flexible displays

Dimitris Karnakis, Oxford Lasers Ltd. (United Kingdom); Michael D. Cooke, Y. F. Chan, Simon Ogier, PETEC (United Kingdom)

Organic semiconductors (OSC) are solution processable synthetic materials with high carrier mobility that promise to revolutionise flexible electronics manufacturing due to their low cost, lightweight and high volume low temperature printing in reel-to-reel (R2R) [1] for applications such as flexible display backplanes (Fig.1), RFID tags, and logic/memory devices. Despite several recent technological advances, organic thin film transistor (OTFT) printing is still not production-ready due to limitations mainly with printing resolution on dimensionally unstable substrates and device leakage that reduces dramatically electrical performance. OTFTs have the source-drain in ohmic contact with the OSC material to lower contact resistance. If they are unpatterned, a leakage pathway from source to drain develops which results in non-optimum on/off currents and not controllable device uniformity (Fig.2). DPSS lasers offer several key advantages for OTFT patterning including maskless, non-contact, dry patterning, scalable large area operation with precision registration, well-suited to R2R manufacturing at overall ?m size resolutions. But the thermal management of laser processing is very important as the devices are very sensitive to heat and thermomechanical damage [2].

This paper discusses 343nm picosecond laser ablation trimming of 50nm thick PTAA, TIPS pentacene and other semiconductor compounds on thin 50nm thick metal gold electrodes in a top gate configuration. It is shown that with careful optimisation, a suitable process window exists resulting in clean laser structuring without damage to the underlying layers while also containing laser debris. Several order of magnitude improvements were recorded in on/off currents up to 106 with OSC mobilities of 1 cm2/Vsec, albeit at slightly higher than optimum threshold voltages which support demanding flexible display backplane applications.

[1] White Paper, “OE-A Roadmap for Organic and Printed Electronics” 4th edition (2011)

[2] D.Karnakis, M.D.Cooke, Y.F. Chan, S.D. Ogier, Proc.ISFOE 2012, Int. Symposium on Flexible Organic Electronics, Thessaloniki, Greece 2-5 July 2012

8608-18, Session 4

Laser sintering and crystallization for high performance electronics *(Invited Paper)*

Costas P. Grigoropoulos, Daeho Lee, Jungbin In, Hyck-Jun Kwon, Univ. of California, Berkeley (United States); Seung Hwan Ko, KAIST (Korea, Republic of)

Large area electronic systems, including flat panel displays as well as wearable electronics and health devices require the utilization of inexpensive, lightweight flexible substrates and integration of high performance devices. The typical approach in microfabrication involves complex deposition and lithographic processes that may not be compatible with hybrid organic-inorganic device layouts. These requirements pose significant challenges that need a new approach for the scalable, low-thermal budget heterogeneous integration of functional components on a flexible platform. In this talk, I will review recent progress on laser-assisted fabrication of high performance electronic materials via nanoscale engineering. The key approach entails the directed functionalization of nanoparticle and amorphous materials on sensitive substrates. In addition, I will present methods for achieving multi-scale,high-throughput fabrication.

8608-20, Session 4

Laser direct writing of graphene patterns on insulator substrates *(Invited Paper)*

L. S. Fan, Wei Xiong, J. B. Park, Yunshen Zhou, Yong Feng Lu, Univ. of Nebraska-Lincoln (United States)

Laser direct writing of graphene lines on silicon dioxide / silicon substrates was demonstrated using a single-step laser-induced chemical vapor deposition method. A laser beam irradiates a nickel-coated silicon dioxide / silicon substrate in a CH4 and H2 environment to induce a local temperature rise. The nickel layer evaporates during or immediately after the graphene growth, allowing the direct formation of graphene patterns on the SiO2/Si substrates. Energy dispersive x-ray diffraction spectroscopy was used to confirm the evaporation of the nickel layer. The development of this method which allows direct writing of graphene patterns provide a route for the rapid fabrication of graphene-based devices.

8608-25, Session 4

Laser transfer of reconfigurable patterns with a spatial light modulator

Alberto Piqué, Raymond C. Y. Auyeung, Andrew T. Smith, Heungsoo Kim, Nicholas A. Charipar, Scott A. Mathews, U.S. Naval Research Lab. (United States)

Laser forward transfer of arbitrary and complex reconfigurable structures has recently been demonstrated using a spatial light modulator (SLM) [1]. The SLM allows the spatial distribution of the laser pulse required by the laser transfer process to be varied from pulse to pulse, which is not possible with any other direct-write technique. The programmable image on the SLM spatially modulates the intensity profile of the laser beam, which is then used to transfer a thin layer of material reproducing the same spatial pattern onto a substrate. The ability to rapidly reconfigure the laser beam into any user-defined pattern, which then is transferred onto a receiving substrate, means that laser direct-write is no longer a serial-type process, but rather a parallel and dynamic digital fabrication technique. This talk will describe the use of Digital Micromirror Devices or DMDs as SLMs with UV (?=355 nm) or visible (?=532 nm) pulsed lasers depending on the application. The parallel laser printing of arrayed structures with a single laser shot will also be discussed together with the full capabilities of SLMs for laser printing of silver nano-inks. This talk will conclude with an overview of the unique advantages and capabilities of laser forward transfer with SLMs.

This work was sponsored by the Office of Naval Research.

[1] R.C.Y. Auyeung, H. Kim, N.A. Charipar, A.J. Birnbaum, S.A. Mathews and A. Piqué, "Laser forward transfer based on a spatial light modulator", Appl. Phys. A, 102, pp. 21-26, (2011).

8608-21, Session 5

Laser sintering of gold nanoparticles on a copper substrate toward an alternative to gold plating

Akira Watanabe, Tohoku Univ. (Japan)

Gold plating is widely used in electronics to provide a corrosion-resistant electrically conductive layer on copper, typically in electrical connectors and printed circuit boards. Recently, an alternative to the gold plating is desired to decrease the environmental impact. One of the candidates is the metallization by printing technique using a gold nanoparticle ink. The major problem in the gold coating on a copper substrate using a gold nanoparticle ink is that copper atoms have a tendency to diffuse to the surface through the gold layer and to form an oxide layer during the thermal sintering of gold nanoparticles, which is common problem in the direct gold on copper plating. The formation of a barrier metal like nickel on the copper substrate before gold coating is one of the solutions to avoid the diffusion of copper atoms through the gold layer, however, it increases the number of processing steps and the cost. In this paper, the laser sintering of gold nanoparticles on a copper substrate toward an alternative to the gold plating is reported. The effective reduction of the diffusion of copper atoms through the gold layer is expected because the laser sintering of metal nanoparticles is extremely fast process due to the nano-heater effect caused by the laser excitation of the plasmon band. The laser sintering of the gold nanoparticles was carried out using 532 nm CW DPSS laser. The duration and the total energy of laser irradiation were controlled by using an electromagnetic shutter. The depth profile of the elemental composition of laser-sintered gold layer on a copper substrate was compared with that of the gold layer prepared by heat treatment using a conventional electric furnace. The diffusion of the copper atom through the gold layer was remarkably reduced by the laser sintering of gold nanoparticles compared to the conventional heat treatment.

8608-22, Session 5

Laser-assisted ultrathin bare die packaging: a route to a new class of microelectronic devices *(Invited Paper)*

Val R. Marinov, Orven F. Swenson, Yuriy Atanasov, Nathan Schneck, North Dakota State Univ. (United States)

Ultrathin flip-chip semiconductor die packaging onto thin flexible substrates is an enabling technology for a variety of extremely low-cost electronic devices with huge market potential such as RFID banknotes, smart labels, security documents, etc. Highly flexible and imperceptible dice are possible only at a thickness of less than 50 µm, preferably down to 10-20 µm or less. Several cents per die cost is achievable only if the die size is ≤ 500 µm/side. Such ultrathin, ultra-small dice provide the flexibility and low cost required, but no conventional technology today can package such die onto a flexible substrate at low cost and high rate. The thermo-mechanical selective laser-assisted die transfer (tmSLADT) technology has been developed at the Center for Nanoscale Science and Engineering, North Dakota State University in Fargo, North Dakota, with this objective in mind. Presented are results using this new advanced packaging technology to assemble dice with various thicknesses, including dice as thin as 20 µm and less. To the best of our knowledge, this is the first report of using a laser to package conventional silicon dice with such small thicknesses. The experimental results clearly demonstrate that, when properly controlled, tmSLADT can transfer ultrathin bare dice with precision and accuracy comparable with those achievable by the conventional die placement methods for thicker dice.

8608-23, Session 5

Cellular scanning strategy for selective laser melting: evolution of optimal grid-based scanning path & parametric approach to thermal homogeneity

Sankhya Mohanty D.D.S., Cem C. Tutum, Jesper H. Hattel, Technical Univ. of Denmark (Denmark)

Selective laser melting, as a rapid manufacturing technology, is uniquely poised to enforce a paradigm shift in the manufacturing industry by eliminating the gap between job- and batch-production techniques. Products from this process, however, tend to show an increased amount of defects such as distortions, residual stresses and cracks; primarily attributed to the high temperatures and temperature gradients occurring during the process.

A unit cell approach towards the building of a standard sample, based on literature, has been investigated in the present work. An empirical model has been developed and calibrated using thermal distributions obtained using different existing scanning strategies. Two different techniques have been applied to develop new scanning strategies using genetic algorithms, with an objective of reducing thermal asymmetries. The resulting scan strategies are evaluated against several existing standard and non-standard scanning methods using the empirical model as well as a 3D-thermal finite element model.

The different scanning strategies including new paths developed using customized genetic algorithms, are used for selective laser melting of standard specimens. Simulations are carried out by varying parameters such as laser power, modulation frequency and scanning speed, in order to achieve homogeneous thermal distributions. Optimal parametric values are then used for selective laser melting of titanium (TiAl6V4) powder using the different scanning strategies. Finally, mechanical properties of specimens developed using different parametric combinations are compared against each other.

8608-24, Session 5

Embedding of ZnO nanoparticles in hybrid microgels by laser ablation in aqueous monomer solution

Nina Million, Univ. Duisburg-Essen (Germany); Philipp Nachev, Andrij Pich, RWTH Aachen (Germany); Stephan Barcikowski, Univ. Duisburg-Essen (Germany)

Last years have seen an increase of interest in bioactive nanoparticles-loaded microgels especially concerning the use in medical fields for agent transports and drug delivery. High purity standards can be reached using laser-ablation technique instead of chemical synthesis for nanoparticle generation. One of the advantages of pulsed laser fabrication of nanoparticles is the possibility of in-situ embedding into a polymer matrix without further working steps. [1] The development of production process in aqueous environment will prevent cleaning steps after the fabrication, minimizing hazards during the application on humans and animals. In particular, due to their cell-stimulation effect [2] and support of wound healing, zinc ions emitted from a loaded microgel by ion-release mechanisms could find application in the treatment of burns. For this purpose, ZnO-nanoparticles have been fabricated in-situ in a microgel network by laser ablation. After the nanocomposite preparation it is possible to process it using electrospinning to obtain polymer fibers and fabricate coverage for wounds. Microgels have been prepared from N-vinylcaprolactam (VCL) and acetoacetoxyethyl-methacrylate (AAEM) as monomers. Obtained microgels loaded with ZnO-nanoparticles show a thermal stability in nitrogen atmosphere up to 300°C which benefits further thermal sterilization processes. The successful integration of nanoparticles in a polymer matrix opens the way to integrate different metals, like iron, gold and silver (and metal mixtures or alloys) exploiting their peculiar properties for different areas of medicine.

[1] Nachev, P., et al., Journal of Laser Applications 24(4), 042012 (2012).

[2] Agren, M. S., et al., Journal of Surgical Research 50(2), 101-105 (1991).

8608-26, Session 5

Pulsed Nd:YAG laser fine spot welding for attachment of refractory mini-pins

Yaomin Lin, Guangqiang Jiang, Alfred E. Mann Foundation for Scientific Research (United States)

In some rechargeable batteries, the mini feedthrough pins (with a diameter of smaller than half of a millimeter) are made of molybdenum (Mo). Mo is a material with very high melting temperature and the pure Mo is not conducive to soldering. Plus the consideration of the small dimension, the attachment of electrical conducting wire/ribbon to the pin is very challenging if conventional attachment methods were possible. Solid state bonding by resistance welding can make it but with moderate bonding strength. In this work, the study of fine spot welding using a pulsed Nd:YAG laser for the attachment of a conductive ribbon to a Mo pin is reported. The effect of the materials of the conductive ribbon to the bonding strength was investigated first followed by a design of experiments (DOE) study aiming to find out the best sets of laser processing parameters including the angle of incident laser beam, the laser power, and the pulse width, etc. in the ribbon-to-pin assembling process. Tensile test by pulling the ribbon-pin weld structure was conducted. Failure modes of the ribbon-to-pin attachment were analyzed. The microstructure of the laser welds was investigated using scanning electron microscopy. To investigate the temperature field distribution, the numerical simulation by means of finite element method (FEM) was performed. Compared with resistance welding, the fusion welding achieved by laser fine spot welding can have three times higher bonding strength.

8608-27, Session 6

Diode laser processed crystalline silicon thin-film solar cells *(Invited Paper)*

Sergey Varlamov, The Univ. of New South Wales (Australia); Bonne Eggleston, Jonathan Dore, The Univ. of New South Wales (Australia) and Suntech Power Holdings Co., Ltd. (Australia); Rhett Evans, Daniel Ong, Oliver Kunz, Suntech R&D Australia Pty Ltd. (Australia); Jialiang Huang, The Univ. of New South Wales (Australia); Ute Schubert, Suntech R&D Australia Pty Ltd. (Australia); Kyung Hun Kim, The Univ. of New South Wales (Australia) and Suntech Power Holdings Co., Ltd. (Australia); Renate Egan, Suntech R&D Australia Pty Ltd. (Australia); Martin A. Green, The Univ. of New South Wales (Australia)

Line-focused diode lasers offer unique opportunities to advance thin-film solar cell technologies. In millisecond exposure range, the heat transfer is limited to a few tens of microns and thus mostly confined to a semiconductor film. As a result, higher temperatures can be applied to improve a semiconductor material while allowing low-cost and lower thermal stability substrates. In application to crystalline silicon thin-film solar cells on glass two new processes have been developed: defect annealing and dopant activation in solid-phase crystallized silicon films; and liquid-phase crystallization of silicon films. Defect annealing and dopant activation in 2-micron thick poly-Si films is achieved by scanning with a line-focus 808 nm diode laser beam at 3~5 ms exposure and 10-13 kW/cm2 laser power. The temperature profile shape in the film during the treatment is independent from laser power and exposure but determined by the beam shape. The solar cell open-circuit voltage of 496 mV after laser annealing is higher than the voltage after standard rapid-thermal annealing while the maximum temperature experienced by glass is 300C lower. Process conditions for laser crystallization of 10-micron thick silicon films are established for different intermediate layers between silicon and glass and a wide range of exposures and laser powers, 10-50 ms and 8-15 kW/cm2 respectively. The process produces large silicon grains with high crystal and electronic quality. After diffusing an emitter and applying point-contact metallization the open-circuit voltage of 557 mV is achieved and 8.4%-efficient cells are fabricated. Electronic quality of the cells is consistent with voltages exceeding 600 mV and cell efficiencies above 12%.

8608-28, Session 6

The photovoltaic potential of femtosecond laser textured amorphous silicon

Meng-Ju Sher, Benjamin Franta, Kenneth Hammond, Lysander Christakis, Eric Mazur, Harvard Univ. (United States)

Femtosecond laser texturing of silicon yields nanometer scale surface roughness that reduces reflection and enhances light absorption. In this work, we study the potential of using this technique to improve efficiencies of amorphous silicon-based solar cells by laser texturing thin amorphous silicon films. We use Ti:Sapphire femtosecond laser systems to texture amorphous silicon in either hydrogen or sulfur hexafluoride ambient gases and we also study the effect of laser texturing the substrate before depositing amorphous silicon. We adjust the thin-film thickness and laser fabrication condition. We report on the material properties including surface morphology, light absorption, crystallinity, as well as solar cell efficiencies before and after laser texturing.

8608-29, Session 6

Laser scribing integration of polycrystalline thin film solar cells

Michele Sozzi, Filomena Manilia, Roberto Antezza, Cristina Catellani, Alessandro Candiani, Enrico Coscelli, Annamaria Cucinotta, Stefano Selleri, Daniele Menossi, Alessio Bosio, Univ. degli Studi di Parma (Italy)

Thin films solar cells is a growing technology for the fabrication of low cost photovoltaic (PV) modules. They can also provide a good alternative to mono- and poly-silicon based modules, but it is necessary to develop devices with a comparable or even better efficiency/cost ratio.

The two most interesting materials to fabricate thin films solar cells are Cadmium Telluride (CdTe) and CuInGaSe2 (CIGS).

Thin films are continuous layers of material and if cut, they permit the creation of integrated connections. The interconnection between the different cells is performed through a laser scribing process, which is composed by three different steps: P1, P2, and P3. The use of laser radiation is a very efficient way to perform PV modules scribing, and it fits very well into the thin films modules production lines, where working speed and operation easiness are basic requirements for large scale production.

In this work P1 scribes have been performed on CdTe samples with a ns regime fiber laser, working at the wavelength of 1064 nm, developed at the Department of Information Engineering of the University of Parma. P2 and P3 scribes have been performed with a rod type photonic crystal fiber laser, working at the wavelength of 1030 nm and 515 nm. The possibility of performing laser scribing on CIGS samples has also been investigated. Moreover, scribes have been also performed by using a ps regime diode pumped solid state laser, working at the wavelength of 1064 nm.

Conference 8609:
Synthesis and Photonics of Nanoscale Materials X

Sunday - Tuesday 3 –5 February 2013

Part of Proceedings of SPIE Vol. 8609 Synthesis and Photonics of Nanoscale Materials X

8609-1, Session 1

Methods and materials for bio-nanophotonics: 10 years perspective *(Invited Paper)*

Andrei V. Kabashin, Institut de Neurosciences Cognitives de la Méditerranée (France)

No Abstract Available

8609-2, Session 1

SHG studies of self-assembled monolayers of phthalocyanines on gold

Nadezda Lilicenko, Ulrich Glebe, Ulrich Siemeling, Frank Hubenthal, Frank Träger, Univ. Kassel (Germany)

Self-assembly techniques provide a convenient, flexible, and simple way to tailor the interfacial properties of metals. In particular, self-assembled monolayers (SAMs) of functional molecules became an interesting topic of research in recent years. SAMs exhibit a wide range of applications in nanotechnology, for example as biosensors or for molecular and organic electronics. In this regard, phthalocyanines (Pcs) are of great interest. These macrocycles have attracted considerable attention during the last decade due to their outstanding chemical and thermal stability, intriguing electrical and magnetic behavior and superior optical properties. For incorporation of Pcs into devices, the SAM formation is a crucial task.

In our current research we have investigated the SAM formation of three types of Pc molecules, namely subphthalocyanine with boron as central atom [BClSubpc(Sn-C12H25)6] and the two bis(phthalocyaninato) terbium complexes [Tb{Pc(Sn- C8H17)8}2] and [Tb{Pc(Sn-C12H25)8}2]. The adsorption of the molecules was studied in situ by applying the powerful and sensitive technique of optical second harmonic generation (SHG). The kinetics of the monolayer formation were obtained by fitting the measured SHG data with three kinetic models: first-order, second-order, and diffusion limited Langmuir kinetic. The obtained results show that for all molecules the SHG data are in good agreement with first-order Langmuir kinetic. In addition, ellipsometrical measurements were performed, to confirm the monolayer formation.

8609-3, Session 1

Direct observation of early stages of surface ripples formation on LiNbO3 substrate

Hisashi Shimizu, Go Obara, Mitsuhiro Terakawa, Keio Univ. (Japan); Eric Mazur, Harvard Univ. (United States); Minoru Obara, Keio Univ. (Japan)

Many papers have been published on the surface ripples formation on various materials by multiple pulses irradiation of femtosecond laser with lower fluence than the single-shot ablation threshold fluence. The periodic ripple formation is a self-organization process with successive femtosecond laser pulses irradiation. At early stages, the plasmon polaritons are interfered with the incident wave to modulate the optical intensities for the periodic ripple formation. Hence, the periodicity of the ripples formed is observed as the same as the incident wavelength ?, and under some particular experimental conditions harmonic periodicity ripples ?/2, ?/3 are formed.

In this paper, we report the observation of the early stage of surface ripples formation on nonlinear optical material LiNbO3 (LN: bandgap is 4 eV approximately). LN is widely used as Q-switching devices using Pockels effect and ?(2) materials. The single-shot ablation fluence is experimentally 1.8 J/cm2 approximately (36 TW/cm2 at 50 fs pulse). With 5.9 TW/cm2, 11 pulses irradiation of 80 fs, 800 nm laser to the optical quality LN surface, dumbbell-like patterns were randomly observed. While with higher 7.6 TW/cm2, 11 pulses irradiation, dumbbell-like pattern with two satellite craters beside the dumbbell pattern were observed. With 22 pulses at 6.7 TW/cm2 (540 mJ/cm2), many areas inclusive of several periodic ripples were observed. The optical absorption mechanism in LN with multi TW/cm2 level intensities is still unknown. To explain the fundamental physics for the early stages of the ripple formation, we simulated the near-field and far-field patterns of Mie and plasmonic scattering.

8609-4, Session 1

Permanent dichroic coloring of surfaces by laser-induced formation of chain-like self-organized silver nanoparticles within crystalline titania films

Nathalie N. Destouches, Nicolas N. Crespo-Monteiro, Thierry Epicier, Yaya Lefkir, Francis Vocanson, Stéphanie Reynaud, Univ. Claude Bernard Lyon 1 (France)

Laser-induced periodic surface structures (LIPSS), also known as ripples, have been investigated for a long time on various materials. They are self-organized grating-like structures that form spontaneously upon irradiation with a single laser beam; their formation requiring a high temperature rise, it generally results from interactions with ultrashort laser pulses. Recently, similar phenomena leading to periodic changes in the morphology of metallic nanoparticles embedded in polymer films have been reported under femtosecond laser exposure.

Here, we demonstrate that chain-like self-organized silver nanoparticles can be grown, from an ionic silver precursor, within titania films under continuous wave visible laser beam. As for LIPSS, the nanoparticles chains are periodically spaced with a period that depends on the wavelength and an orientation parallel to the laser polarization. But no significant surface modulation occurs, all of the grown nanoparticles being located at the substrate-film interface, protected by a crystallized TiO2 film. Characterizations of the film nanostructuring by SEM, STEM-HAADF, HRTEM and EDX will be shown.

Due to a strong interparticle plasmon coupling along chains, such samples exhibit a strong dichroism whose characteristics depend on the laser exposure conditions. Color changes and spectral variations with polarization will be characterized and modeled under various geometrical configurations. An example of application using bright interferometric colors between polarizers will be also proposed. The high stability of such colored films under high temperature rises or high intensity UV or visible exposures will be shown; it makes them good candidates for colored data storage.

8609-5, Session 1

Combinatorial synthesis using pulsed laser deposition on patterned substrate

Rudresh Ghosh, Yukihiro Hara, Rene Lopez, The Univ. of North Carolina at Chapel Hill (United States)

High surface area porous nano-particle based thin films are widely used for photovoltaic applications. Using pulsed laser deposition we have shown that it is possible to obtain unique hierarchical structures especially suitable for photo-physical applications. Our earlier studies have shown the superiority of these structures over random nano-particle based networks. In this work we show that further directionality of the structures are possible by using an underlying patterned

substrate. Patterning of the substrate is done on a photoresist, SU-8 (MicroChem),by using a mold having a hexagonal array of holes with 1.5 µm periodicity. After several steps of treatment, holes with the same pattern were created. In the last, the holes were filled with ITO by pulsed laser deposition (PLD) and the pattern of cone-shape structure was fabricated. On deposition of a film a few microns thick on the patterned substrates, individual columns made of nano-particles and separated from each other is observed. Combinatorial film deposition using PLD on the patterned substrate further separates each of the columns elementally. Elemental mapping of the columns was done using EDX. This work opens up the possibility to use PLD as a method to fabricate lab-on-a-chip for photophysical applications.

8609-6, Session 2

Plasmonic-enhanced light-matter interactions *(Invited Paper)*

Steve Blair, The Univ. of Utah (United States)

This talk will overview plasmonic antennas and associated field-enhancement mechanisms. Applications of this highly-localized field enhancement for nanoscale light-matter interactions will be reviewed. Particular emphasis will be placed on biomolecule interactions for sensing and localized photochemical reactions.

8609-7, Session 2

Probing strong correlations in vanadium dioxide with plasmonic nano antennae

Davon W. Ferrara, Joyeeta Nag, Evan R. MacQuarrie, Richard F. Haglund Jr., Vanderbilt Univ. (United States)

Plasmonic structures in close proximity to strongly correlated materials can be used to probe phase changes — such as insulator-to-metal transitions (IMTs) — in those materials. Here we demonstrate this concept for nanocomposites comprising a gold nanodisk (ND) array covered by a thin vanadium dioxide (VO_2) film. For gold ND arrays with surface plasmon resonances (SPRs) in the near infrared, it is possible to design the NDs so that the SPR coincides with the VO_2 interband transition from occupied to filled d-bands. The gold NDs thus act as nanoantennae in which the near-field response of the localized surface-plasmon resonance (LSPR) reflects the correlated electron behavior in the vanadium dioxide as the thermochromic insulator-to-metal transition occurs.

Arrays of Au nanodisks (NDs) 20 nm thick and 180 nm in diameter, with a pitch of 450 nm, were fabricated on ITO-covered glass substrates by electron-beam lithography. Subsequently, 60 nm of VO_2 was deposited over the array by ablating a vanadium-metal target in an oxygen ambient, yielding amorphous VO_x on the glass substrate. Annealing the composite material at 450°C for 45 minutes produced a stoichiometric VO_2 film covering the Au ND array.

Extinction spectra for the nanodisk arrays were measured as the sample was heated and cooled using a broadband tungsten lamp, and used to determine the peak position and linewidth of the LSPR as a function of temperature. These spectra show the evolution of the peak position of the Au plasmon resonance as the VO_2 makes the transition from insulating to metallic and back to insulating; the width of the plasmon resonance also changes. The extinction spectra also show a weaker feature at higher energy which is identified with the quadrupole resonance of the Au nanodisks. Because the Au nanodisks are approximately the same size as the grain sizes in the polycrystalline VO_2 film, the changing width of the resonance mirrors the homogeneous linewidth of the electrons participating in the plasmon-electron interaction.

By modeling the LSPR as the response of oblate spheroids in the electrostatic limit, it can be shown that this response is dominated by homogeneous broadening, and is related to the plasmon dephasing time. This plasmon damping is controlled by electromagnetic energy losses to both near-field and far-field scattering. The interband resonance mirrors the strong electron correlation that leads to delocalization as well as the blue-shift in the LSPR that signals the collapse of the band-gap and the evolution of the metallic electron gas.

8609-8, Session 2

Light at the nanometer scale *(Invited Paper)*

Reuven Gordon, Univ. of Victoria (Canada)

This talk will review our recent progress on nanoplasmonics, including the development of Directivity Enhanced Raman Spectroscopy (DERS), optical trapping of single proteins and plasmonic hybridization for enhanced second harmonic generation.

8609-9, Session 3

Efficient nanoparticle production using wire ablation

René Streubel, Univ. Duisburg-Essen (Germany); Gabriele Messina, Univ. degli Studi di Catania (Italy); Philipp Wagener, Univ. Duisburg-Essen (Germany); Giuseppe Compagnini, Univ. degli Studi di Catania (Italy); Stephan Barcikowski, Univ. Duisburg-Essen (Germany)

Fabrication of nanoparticles using laser ablation in liquid is gaining more and more interest [1], especially in applications where high purity is mandatory, e.g. in the field of medicine or catalysis. This high level of purity is hard to achieve using conventional chemical synthesis, even in case of excessive purification [2]. In contrast to this, laser ablation in liquid provides a facile synthesis method for highly pure nanoparticles [3], but its implementation for large scale application is not common up until now due to its low productivity. A major issue is to increase ablation rate and subsequent nanoparticle productivity. For this purpose, we present a new ablation method by feeding a wire instead of a bulk target. In this case, a continuous flow of colloidal nanoparticles can be achieved utilizing the whole target material in a continuous process. Furthermore, first experiments show a strongly influence concerning the ablation efficiency for different wire diameter. For a 500 µm thick wire compared with a bulk target we reach an around 4.5 times higher ablation rate, normalized on fluence on target. In conclusion, wire ablation is a promising approach to enhance ablation efficiency and process control of laser ablation in liquid.

[1] Zeng, H., et al., Adv. Funct. Mater. 22, 1333-1353 (2012)

[2] Lopez-Sanchez, J. A., et al., Nature Chemistry, Vol. 3, 551-556 (2011).

[3] Petersen, S., Barcikowski, S., J. Phys. Chem. C 113, 19830-19835 (2009)

8609-10, Session 3

Synthesis of ultrasmall TiO_2 nanoparticles by pulsed laser vaporization

David B. Geohegan, Murari Regmi, Christopher M. Rouleau, David L. Swanson, Joshua W. Halstead, Mina Yoon, Alex A. Puretzky, Gyula Eres, Oak Ridge National Lab. (United States); Mengkun Tian, Gerd Duscher, The Univ. of Tennessee (United States); Karren L. More, Oak Ridge National Lab. (United States)

Laser vaporization of solid targets into background gases produces clusters and nanoparticles as primarily atoms and ions thermalize due to collisions. The dynamics of gas-phase nanoparticle formation and the role of ultrasmall nanoparticles as "building blocks" in the growth of thin films and larger nanostructures are key outstanding questions in pulsed laser vaporization and deposition. Here we study the synthesis of

TiO2 ultrasmall nanoparticles (UNPs) by laser vaporization into both inert and reactive background gases using time-resolved, in situ gated-ICCD imaging, spectroscopy, and ion probe diagnostics in conjunction with temporally- and spatially-resolved collection, particle sizing analysis and ex situ characterization. TiO2 is a workhorse wide-bandgap semiconductor for applications including photocatalytic water splitting and photoanodes for dye-sensitized solar cells. By controlling the plume expansion conditions, 2-3 nm ultrasmall TiO2 nanoparticles can be synthesized. Their phase and structure are investigated by atomic-resolution Z-contrast scanning transmission electron microscopy and electron energy loss spectroscopy. Preliminary measurements indicate that the TiO2 UNPs are crystalline yet do not conform to a known bulk phase. Conjugate gradient optimized Monte Carlo simulations of ultrasmall TiO2 nanoparticle structures at different temperatures are described to understand nanoparticle phase stability. Optical measurements of undoped and doped (N, Cr, and Cr-N) TiO2 UNP ensembles will be compared with EELS measurements of individual nanoparticles.

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.

8609-11, Session 3

In situ sensor for trace analysis of pollutant chemicals in water based on a SERS/SERDS set-up and supported optimized noble metal nanoparticles

Robert Ossig, Univ. Kassel (Germany); Yong-Hyok Kwon, Technische Univ. Berlin (Germany); Frank Hubenthal, Univ. Kassel (Germany); Heinz-Detlef Kronfeldt, Technische Univ. Berlin (Germany)

In this contribution we present a reliable chemical in situ sensor that is suitable to detect very low concentrations of pollutant chemicals, e.g. polycyclic aromatic hydrocarbons (PAHs). To meet the European Quality Standard (EQS) criteria for PAHs, which require limits of detection (LOD) in the sub nMol/l regime, we combined surface enhanced Raman spectroscopy (SERS) with shifted excitation Raman difference spectroscopy (SERDS) and used supported tailored noble metal nanoparticles (NPs) as substrates.

The NPs were prepared by Volmer-Weber growth under ultra high vacuum conditions. To gain optimal SERS enhancement the NPs plasmon resonance position and, thus, the optical properties were tuned to coincide with the excitation wavelengths for SERDS. We demonstrate that bare NPs yield LODs in the lower nMol/l regime, sufficient to detect the maximum allowable concentration of PAHs in water, as determined by the EQS. However, the annual average concentration requires LODs in the sub nMol/l regime. To reliably detect such low concentrations, experiments with functionalized NPs are currently underway. The functionalization enhances the adsorption of probe molecules to the NPs, which in turn leads to an improvement of the LOD. Thus, the combination of SERS with tailored NPs and SERDS yield a chemical sensor for in situ trace analysis of pollutant chemicals.

8609-12, Session 3

Development of visible-light activated titanium dioxide films with femtosecond laser

Naoto Horiguchi, Masahiro Tsukamoto, Osaka Univ. (Japan); Minoru Yoshida, Kinki Univ. (Japan); Togo Shinonaga, Osaka Univ. (Japan); Masanari Takahashi, Osaka Municipal Technical Research Institute (Japan); Masayuki Fujita, Nobuyuki Abe, Osaka Univ. (Japan)

Titanium dioxide (TiO2) has a variety of functions, but cannot be activated by visible-light illumination. It is important to extend the activity of TiO2 into the visible-light since no UV light is in the room. Therefore, the visible-light activated TiO2 is required. Visible-light activated TiO2 has been obtained by generation of oxygen defects in the TiO2. In our previous study, we fabricated TiO2 films with an aerosol beam and the films were irradiated with femtosecond laser. Although the TiO2 films were darkened after the laser irradiation. It is reported that oxygen deficiencies in TiO2 could be the cause for the darkening. The visible-light activity might be shown by the femtosecond laser irradiation.

In this study, we investigated variation of the photocatalytic activity of TiO2 films after the femtosecond laser irradiation. The wavelength, the pulse width and the repetition rate of the femtosecond laser were 775 nm, 150 fs and 1kHz, respectively. In the experiment, the laser spot was scanned on the TiO2 film surface and the laser fluence was changed within the laser fluence range in which the laser ablation was not caused and morphology of the TiO2 film surface was not varied.? The photocatalytic activity of the TiO2 films was evaluated with acetaldehyde reaction under visible-light illumination. The TiO2 films darkened by the femtosecond laser irradiation had photocatalytic activity under visible light.

8609-13, Session 3

Optical amplification at 1.06 µm from laser ablated neodymium nanoparticles embedded in a polymer host

Gabriel Pelegrina-Bonilla, Andreas Schwenke, Laser Zentrum Hannover e.V. (Germany); Hakan Sayinc, Laser Zentrum Hannover e.V. (Germany) and Ctr. for Quantum Engineering and Space-Time Research (Germany); Uwe Morgner, Laser Zentrum Hannover e.V. (Germany) and Ctr. for Quantum Engineering and Space-Time Research (Germany) and Leibniz Univ. Hannover (Germany); Jörg Neumann, Laser Zentrum Hannover e.V. (Germany) and Ctr. for Quantum Engineering and Space-Time Research (Germany); Boris N. Chichkov, Laser Zentrum Hannover e.V. (Germany) and Leibniz Univ. Hannover (Germany); Laszlo C. Sajti, Laser Zentrum Hannover e.V. (Germany); Dietmar Kracht, Laser Zentrum Hannover e.V. (Germany) and Ctr. for Quantum Engineering and Space-Time Research (Germany)

To the best of our knowledge, we demonstrate for the first time optical amplification at a wavelength of 1.06 µm from neodymium nanoparticles (NPs) generated by laser ablation. The NPs were generated from a Nd:YVO4 crystal in liquid environment producing high purity NPs. Due to the small size (sub-50-nm) the NPs have an increased surface-area-to-volume ratio and decreased Rayleigh scattering making them highly interesting as gain medium in laser amplifiers or oscillators. Acetone was chosen as solvent due to its stabilizing effect and the possibility to act as solvent carrier to embed NPs in polymeric matrices. In these investigations Poly(methyl methacrylate) (PMMA) was used as polymer host for the neodymium NPs, achieving a static particle distribution compared to colloidal systems. Slabs with thickness of 1 mm were fabricated by injection molding. This technique enables to prepare arbitrarily shaped NP-doped polymers. The optical amplification of these samples was studied by a classical pump probe method. Two laser diodes, emitting at 808 nm and 1.06 µm, were employed for pumping and seeding the samples. For demonstrating the optical amplification, the dependence of the gain from the pump power at fixed seed power and vice versa was measured. We observed for different particle concentrations saturation behavior of the gain at high pump powers and decrease of the gain with increasing seed power. This corresponds to the typical behavior of common laser amplifier systems. The achievable gain was 0.2 dBmm-1 at 0.7 mW seed power and 50 mW pump power.

8609-14, Session 4

Integration of graphene with fiber optics and integrated optical devices for ultrafast photonic applications *(Invited Paper)*

Kevin P. Chen, Mingshan Li, Qing Wang, Univ. of Pittsburgh (United States); Yong Feng Lu, Univ. of Nebraska-Lincoln (United States)

This paper reports the studies of nonlinear optical responses of graphene films and its application for mid-IR ultrafast laser development at 2-um and above. The integration of graphene films with waveguide laser devices in YAG and Ti:Sapphire crystals fabricated by the femtosecond ultrafast lasers are aslo studied for chip-scale compact pulse laser developments. Using a laser-assisted chemical vapor deposition process, high quality graphene films were directly deposited onto the fiber tip and laser crystal surfaces without transfer processes. Saturable absorption optical properties of directly-fabricated graphene film are studied at 2-um and beyond for mid-IR photonic applications. Ultrafast fiber lasers based on silica fiber and ZBLAN fibers are demonstrated using graphene as saturable absorbers. The nonlinear optical application of graphene films were also explored for chip-scale waveguides laser fabricated by the ultrafast laser direct writing technique.

8609-15, Session 4

Real-time optical diagnostics of isothermal graphene growth induced by chemical vapor and pulsed laser deposition

Alex A. Puretzky, David B. Geohegan, Sreekanth Pannala, Christopher M. Rouleau, Gyula Eres, Murari Regmi, Oak Ridge National Lab. (United States); Gerd Duscher, The Univ. of Tennessee (United States)

The unique thermal, electrical, and optical properties of graphene may enable many potential applications of this material. However, this will require reliable and controlled synthesis of graphene and understanding its growth mechanisms, which can be achieved through development of real-time diagnostics of the growth process. Here we report real-time optical imaging, reflectivity, and Raman spectroscopy combined with sub-second pulses of acetylene to measure the nucleation and growth kinetics of graphene on Ni films by pulsed chemical vapor deposition (CVD) and pulsed laser deposition (PLD). These pulsed approaches are compared with conventional growth of graphene using CVD with continuous gas introduction. We demonstrated that graphene grows rapidly and isothermally at high temperatures. Between 800-850 °C graphene is found to grow within one second on Ni after exposure to a sub-second C2H2 pulse. Time-resolved reflectivity and direct video-imaging through a microscope revealed a 0.5 s delay in the onset of growth after the gas pulse, followed by rapid (0.5 s) growth and termination. Raman spectroscopy confirmed the rapid appearance of characteristic graphene G and 2D bands. The described approach combining CVD (PLD) and real-time optical diagnostics opens new opportunities to understand and control the fast, sub-second growth of graphene on various substrates at high temperatures.

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.

8609-16, Session 4

Transport dynamics resulting from through thin film femtosecond laser ablation

Christopher M. Rouleau, Alex A. Puretzky, David B. Geohegan, Mina Yoon, Karren L. More, Linda Zhang, Kevin Chen, Oak Ridge National Lab. (United States); Gerd Duscher, The Univ. of Tennessee (United States); Cheng-Yu Shih, Chengping Wu, Leonid V. Zhigilei, Univ. of Virginia (United States)

Femtosecond laser ablation of nanometer-scale films on transparent substrates represents a viable nonequilibrium method for understanding the synthesis of alloyed nanoparticles for catalytic and plasmonic applications. However, nanoscale alloying is not well understood, and synthesis of metastable alloys, for example, requires knowledge of the process by which multilayer films intermix, and what factors determine particle size. Conversely, deposition of the alloy nanoparticles on a substrate requires understanding the factors that govern their temperature and sticking.

Gated-ICCD imaging, ion probe, scanning mobility particle sizing (SMPS), and modeling/simulation are combined with single laser pulses to understand the mechanism of nanoparticle formation, size, and velocities encountered during ablation. Hot, narrowly confined plumes that propagate at ~104 cm/s in vacuum, and slow significantly at higher pressures (>10 Torr) were observed. Deposits collected on witness plates consisted of large (~200 nm) particles with many more smaller (~30 nm) nanoparticles. Imaging showed a significant fraction of material rebound, suggesting that particle distributions observed on witness plates is different than those 'in flight'. Preliminary measurements of 'in flight' particle sizes by SMPS supports this idea as there is a marked reduction in particle count beyond 20 nm. The implications of the observed plume dynamics on nanoparticle synthesis will be discussed.

Research sponsored by the Materials Science and Engineering Division, U.S. DOE. Portions of this research were conducted at the Center for Nanophase Materials Sciences and Shared Research Equipment User Facility, which are sponsored at Oak Ridge National Laboratory by the Scientific User Facilities Division, U.S. DOE

8609-17, Session 4

Low-power plasmonic switching of an insulator-to-metal transition in vanadium dioxide *(Invited Paper)*

Richard F. Haglund Jr., Davon W. Ferrara, Victor Diez-Blanco, Vanderbilt Univ. (United States); Carl Merrigan, William Jewell College (United States); Joyeeta Nag, Evan R. MacQuarrie, Vanderbilt Univ. (United States); Anthony Kaye, ITT Advanced Engineering & Sciences (United States)

There is rapidly growing interest in the use of phase-changing materials (PCM) as control elements in electronic and opto-electronic devices. In this paper, we demonstrate that (1) the insulator-to-metal transition (IMT) in vanadium dioxide can be initiated at surprisingly low laser powers; and (2) that plasmonic elements coupled to PCMs can be used to control the IMT by sizing the plasmonic nanostructure to couple to an electronic transition in the PCM. Applications for plasmonic control of PCMs range from proximal probes of phase-changing materials to enhancing the efficiency of opto-electronic and opto-thermal devices based on phase transitions, such as metal-insulator-switched field-effect transistors (MISFETs).

We first confirmed the efficiency of low-power photothermal switching in bare vanadium dioxide films deposited on a glass substrate by pulsed laser deposition (PLD). A metallic vanadium target was ablated at room temperature in a 100 mTorr oxygen atmosphere by a KrF excimer laser emitting 25 ns pulses centered at 248 nm with a repetition rate of 25 Hz and a fluence of ~2 J/cm2. After the deposition, the samples were annealed at 450 °C in a background of 250 mTorr of oxygen for

45 minutes, yielding stoichiometric, polycrystalline VO2 films with a thickness of 150 nm.

To monitor the progress of the IMT, we employed a pump-and-probe geometry; the pump was a mechanically chopped green CW laser (532 nm) and the probe was a continuous-wave 1550 nm laser. Pump powers ranged from 10 to 100 mW; the power of the probe beam was 250 µW, low enough to ensure no sample modification. Both beams were spatially overlapped at the sample using focusing lenses of 50 mm focal length, with focal spot radii are of order 100 ?m as measured by knife-edge method. A retroreflection imaging setup with a NIR-CCD camera was used for alignment. Downstream from the sample, a second photodetector registered the transmitted probe signal as a function of time.

Next, arrays of Au nanodisks (NDs) 20 nm thick and 180 nm in diameter, with a pitch of 450 nm, were fabricated on ITO-covered glass substrates by electron-beam lithography. Subsequently, 60 nm of VO2 was deposited on the Au ND array using the same protocol; annealing the composite material at 450˚C for 45 minutes produced a stoichiometric VO2 film covering the Au ND array. The quality of the film on a witness sample was checked by static optical measurements of hysteresis and electron microscopy.

In this case, the IMT was induced by mechanically chopped, low-power laser radiation at 785 nm, while the evolution of the IMT as a function of laser power was probed at 1550 nm. For gold nanodisks of this size, the surface-plasmon resonance of the Au NDs occurs near 785 nm; the NDs can be considered as nanoantennas that scatter the absorbed laser light with increasing efficiency as the IMT progresses, exciting the interband transition in the VO2 and driving the insulator-to-metal transition at a substantially faster rate. Even though the Au NDs constitute less than 5% of the nanocomposite volume, their presence reduced the threshold for the IMT by 37% compared to that of the bare VO2 film, as the plasmon absorption peak of the gold NDs shifts from 1100 nm to 785 nm as the VO2 turns metallic.

8609-18, Session 5

10-year perspective on laser generation of sub-100 nm structures *(Invited Paper)*

Andreas Ostendorf, Ruhr-Univ. Bochum (Germany)

For many decades conventional diffraction theory was regarded as the natural limitation in optical structuring. Since 10-15 years researchers have made significant progress in the generation of structures with dimensions far beyond the diffraction limit. Numerous physical principles have been explored from nearfield processing via threshold dominated multiphoton processes to field enhancement of plasmonic components. Every month new results with further decreasing feature sizes are published. However, many questions still have to be addressed and lots of parameters have not yet been investigated or optimized. This presentation tries to identify the main technologies and extrapolates them for the next 10 years.

8609-19,

Hydrogenated amorphous silicon laser micromachining for photonic devices

Michael G. Moebius, Eric Mazur, Harvard Univ. (United States)

Development of integrated photonic devices is becoming increasingly important in technological applications. Hydrogenated amorphous silicon (a-Si:H) provides a promising platform. Variations in hydrogen content produce large changes in refractive index and band gap, on the order of 0.1-1. Previous research has demonstrated waveguide fabrication using photolithography and ion implantation techniques, which requires many steps and is limited to 2D patterns.

We have developed a laser micromachining technique to locally reduce the hydrogen content of a-Si:H in the laser focus to directly write waveguides and optical devices. Using pulsed lasers operating in the near infrared with photon energies below the band gap will enable direct writing of 3D photonic structures and will greatly simplify the fabrication process to two steps; film deposition and laser exposure. Developing a-Si:H laser micromachining has significant advantages over glass micromachining. Greater compatibility with the silicon material platform can provide applications in silicon photonics and direct integration with existing device platforms. Refractive index changes can be significantly higher than those produced by glass micromachining, where typical changes are fractions of a percent.

We have demonstrated reductions in hydrogen content within a-Si:H films using a 1050 nm femtosecond pulsed laser. Raman spectroscopy was used to study the silicon structure and hydrogen content of unaltered and laser treated material. We are now studying the index changes and are optimizing the process for 2D waveguide writing before expanding the study to 3D fabrication.

8609-20,

Wettability control of silicon surface by excimer laser irradiation in various aqueous environments

Neng Liu, Jan J. Dubowski, Univ. de Sherbrooke (Canada)

The wettability of silicon wafer is one of the key parameters in silicon based photoelectronic devices and biosensor fabrication. Therefore, to selective area control the wettability through surface roughing by photololithgraphy, electron beam lithography and laser techniques have generated worldwide research interest. In this paper, we present a novel method of using excimer laser irradiation in various aqueous environments to remarkably control the wettability of HF acid treated (100) silicon samples. The method is based on photon induced modification of chemical composition instead of surface morphology modification.

8609-21,

On the role of laser heating and adatom diffusion in femtosecond laser induced tungsten nanograting

Tsinghua Her, Mark E. Green, The Univ. of North Carolina at Charlotte (United States)

We have previously reported the observation of self-organized tungsten nanogratings during chemical vapor deposition of tungsten induced by a 400-nm 80-MHz laser oscillator on a wide range of substrates. We show that the growth of nanostructures begins with a thin tungsten film, followed by a rapid formation of periodic texture, when the laser power exceeds a threshold value. The threshold power is found strongly substrate dependent. The ubiquitous presence of thin films prior to nanograting growth suggests adatom diffusion induced by laser heating is vital, as the strong electron-phonon coupling in tungsten is expected to turn absorbed photon energy rapidly into heat. Using a simplified 1D heat diffusion model, we estimate the critical surface temperature on various substrates at the onset of nanograting formation, based on substrate-specific threshold power and material properties. We found interesting correlation of critical temperatures: all the covalent substrates (AlN, Al2O3, quartz, silica, and glass) exhibit a common critical temperature while the ionic substrates (MgO, MgF2, and CaF2) share another yet different critical temperature. The critical temperature of covalent substrates is found higher than that of ionic substrates, indicating the former possesses larger activation energy for adatom diffusion. Based on this model, we can also extract a substrate-independent enthalpy for nanograting formation. Although the present 1D model overestimates the surface temperature, the correlation of critical temperatures among substrates and the presence of a unique enthalpy independent of substrates strongly support the role of laser heating and adatom diffusion in the formation of tungsten nanogratings.

8609-22,

Femtosecond laser induced periodic nanostructures on titanium dioxide film for improving biocompatibility

Togo Shinonaga, Masahiro Tsukamoto, Naoto Horigutchi, Osaka Univ. (Japan); Akiko Nagai, Kimihiro Yamashita, Takao Hanawa, Tokyo Medical and Dental Univ. (Japan) and Institute of Biomaterials and Bioengineering (Japan); Nobuhiro Matsushita, Tokyo Institute of Technology (Japan); Guoqiang Xie, Tohoku Univ. (Japan); Nobuyuki Abe, Osaka Univ. (Japan)

Periodic nanostructures formation on Titanium dioxide (TiO2) film by scanning of femtosecond laser beam spot is reported. Titanium (Ti) is one of the most widely used for biomaterials, because of its excellent anti-corrosion and high mechanical properties. However, Ti is typically artificial materials and has no biofunction. Hence, it is necessary for improving the bioactivity of Ti. It is well known that periodic nanostructures formation and coating of TiO2 film on Ti plate surface are useful methods to improve biocompatibility of Ti plate. We propose periodic nanostructures formation on TiO2 film by femtosecond laser irradiation. Cell attachment could be controlled by periodic nanostructures formation on the film. Then, biocompatibility of the film could be also improved. In the experiments, the film was formed on Ti plate with an aerosol beam. A commercial femtosecond Ti : sapphire laser system was employed in our experiments. The wavelength, pulse duration and repetition rate of the femtosecond laser were 775 nm, 150 fs and 1 kHz, respectively. Periodic nanostructures, lying perpendicular to the laser electric field polarization vector, were formed on large areas of the film by scanning of femtosecond laser spot. The period of periodic nanostructures on the film was much shorter than that on Ti plate. By cell test, cells were attached to periodic nanostructures of the film. Then, cells were formed periodically on the film. These results suggested that cells attachment could be controlled by periodic nanostructures formation on the film with a femtosecond laser.

8609-23,

A study simulation on transmission characteristics of focused laser inside KDP crystal

Leimin Deng, Jun Duan, Xiaoyan Zeng, Shan Huang, Wuhan National Lab. for Optoelectronics (China)

Recently years, with the shortage of energy resource in the earth and the wide application prospects of laser inertial confinement fusion (ICF) system, many countries have set up powerful laser driver facilities. In these laser facilities, the Pockels cells and frequency multiplication devices made by large-aperture KDP crystals are widely used. With the increasing of laser power, various nonlinear optical effects in the KDP crystal will significantly present, among which, Transverse Stimulated Ramam Scattering (TSRS) is one limiting the 3? laser pulse intensity significantly. Laser processing 3D microstructures inside KDP crystals is an effective way to suppress the TSRS in high power lasers. In this paper, a simulation study on the transmission characteristics of focused laser inside KDP crystal was carried out to investigate the feasibility of laser processing 3-D microstructures and the effects of laser parameters on the micromachining accuracy, efficiency and quality. The simulated results are in good agreement with experiments and show that the effects of the peak power density, spot distortion and deviation of laser focus are the main factors on the micromachining accuracy and quality. The size and shape of the extraordinary ray focus will distort and its peak power density decreases rapidly with the increasing of the angle between incident laser and crystal optical axis. The stimulated results also indicate that the effect of the extraordinary ray will make the processing efficiency increase more than double while the angle is less than 15°, and can be neglected if the laser was in the low-energy or easily causes crystal cracked if the laser was in high-energy while the angle is greater than 30°, in this case, the extraordinary ray must be isolated.

8609-25,

Laser patterning of graphene using pulsed UV laser irradiation

Takeshi Sasaki, National Institute of Advanced Industrial Science and Technology (Japan)

Graphene is the most promising materials for the alternative transparent conductive electrode material of indium tin oxide (ITO) because of the high conductivity and optical transmittance. ITO transparent conductive films have been widely used as the electrode material for touchscreens. The constituent indium is the one of the rare metals and the production has been limited only in several areas in the world such as China, Canada, Japan etc., which could give a serious problem resulted from imbalance between the increasing demand and supply in the near future. The manufacturing of the touchscreens using graphene is the good resolution for this problem. The ITO transparent conductive film have to be etched to form the proper electrode patterns on it for the touchscreens using wet chemical or dry laser etching techniques. It could be very difficult to etch the stable carbon material, graphene by chemical pathway. In this study, the etching of the transferred graphene on polyethylene terephthalate (PET) films by the irradiation of nanosecond pulsed lasers with different wave length is reported. The clear edges of the transferred graphene were observed by the scanning of pulsed laser with wavelength of 355nm, which is used for the laser patterning of ITO transparent conductive films. The effect of the laser power would also be reported.

8609-26,

Photoconductivity of metal nanoparticle ensembles supported by localized surface plasmon polariton resonances

Elena Vashchenko, Tigran A. Vartanyan, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); Frank Träger, Frank Hubenthal, Univ. Kassel (Germany)

Alkali and noble metal nanoparticles exhibit extraordinary size dependent properties that have been exploited in numerous applications. In particular their superior optical properties have been intensively studied in the past decades. However, the electric properties of metal nanoparticle ensembles (MNEs) have found increasing attention recently. Since the nanoparticle separation in an ensemble is only several nanometers, electrons can tunnel between the nanoparticles with a certain probability. Thus, MNEs represent interlinked systems, which can be used as light driven electric devices.

In this contribution we demonstrate localized plasmon induced photoconductivity in silver and sodium nanoparticle ensembles prepared by Volmer-Weber growth. The extinction spectra of the MNEs exhibit pronounced plasmon resonances at wavelengths below the threshold of the external photo effect in the corresponding bulk metal. To demonstrate the effect of the plasmon resonances on the photoconductivity of the MNEs, a voltage has been applied and the current through the MNEs has been measured as a function of wavelength. The results show a significant increase of the current if the plasmon resonance in the metal nanoparticles is excited. A detailed analysis of the temperature dependence of the conductivity and measurements of the conductivity and photoconductivity as a function of the energetic position of the plasmon reso-nance yield the charge transfer mechanism in these structures. We find that the primary transfer mechanism is due to defects in the quartz glass structure which act as electron traps, energetically located near the Fermi level of the metal.

8610-2, Session 1

LLCD overview talk *(Invited Paper)*

Bryan S. Robinson, Don M. Boroson, MIT Lincoln Lab. (United States)

No Abstract Available

8610-3, Session 1

Simultaneous laser ranging and communication from an Earth-based satellite laser ranging station to the Lunar Reconnaissance Orbiter in lunar orbit *(Invited Paper)*

Xiaoli Sun, David R. Skillman, NASA Goddard Space Flight Ctr. (United States); Evan D. Hoffman, Honeywell Technology Solutions, Inc. (United States); Dandan Mao, Sigma Space Corp. (United States); Jan F. McGarry, NASA Goddard Space Flight Ctr. (United States); Leva E. McIntire, The Catholic Univ. of America (United States); Ronald S. Zellar, NASA Goddard Space Flight Ctr. (United States); Frederic M. Davidson, Johns Hopkins Univ. (United States); Wai H. Fong, Michael A. Krainak, NASA Goddard Space Flight Ctr. (United States); Maria T. Zuber, Massachusetts Institute of Technology (United States); David E. Smith, NASA Goddard Space Flight Ctr. (United States)

We report a free space laser communication experiment from the satellite laser ranging (SLR) station at NASA Goddard Space Flight Center (GSFC) to the Lunar Reconnaissance Orbiter (LRO) LRO in lunar orbit through the on board one-way Laser Ranging (LR) receiver. Pseudo random data and sample image files were transmitted to LRO using a 4096-ary pulse position modulation (PPM) signal format. Reed-Solomon forward error correction codes were used to achieve error free data transmission at a moderate coding overhead. The signal fading due to the atmosphere effect was measured for each laser pulse and the coding gain could be estimated.

The LRO LR receiver has a small telescope mounted on and co-bore-sighted with the spacecraft high gain antenna, which can detect laser pulses from Earth when LRO is in direct line of sight. The received laser pulses are sent via an optical fiber bundle to the Lunar Orbiter Laser Altimeter (LOLA) and time-tagged at <0.5 ns precision with respect to the spacecraft Mission Elapse Time (MET). The LRO clock oscillator is sufficiently stable to keep the time drift to <<1 ?s during a one-hour LR session. The LRO LR system has been in operation since June 2009 and the range window time could be predicted well enough to allow simultaneous laser communication and ranging from an SLR station.

We have built a PPM system to program the delay of the LR laser trigger pulses according to the PPM symbols to be transmitted. The LRO LR receiver detected the pulses and reconstructed the PPM symbols according to their arrival time within the range gate. The one-way LR measurements were unaffected as long as the laser pulses were time tagged in pairs at both the SLR station and LRO. The PPM symbol transmission rate was limited by the existing LRO LR receiver, which has a fixed 8-ms range window at 28 Hz to detect and time-tag the laser pulses from Earth. The PPM symbol alphabet size was limited by the time jitter of ground station laser pulse emissions and range window width. We chose a 4096-ary PPM format with a 1-?s slot time for each laser pulse. The data were sent in 4095-symbol blocks as required by the Reed-Solomon code. Periodic time synchronization patterns were inserted in between the encoded data blocks. As a result, the raw transmission data rate was 336 bits/s with <1% overhead for the time synchronization patterns. A series of experiments were conducted over a 4-month period. The raw PPM symbol transmission errors were >10%, mostly in the form of missed detections, or erasures, even under very clear sky conditions. Reed-Solomon codes were shown to be very effective in correcting these errors and recovering the data from brief laser outages due to the airplane avoidance maneuvers at the SLR station. Although the transmission data rate was relatively low, the technology demonstrated by the experiment is useful for tracking

and maintaining a low data rate contact with a spacecraft in deep space without the use of a conventional microwave system.

8610-4, Session 2

Multiplexing vortex beams for Tbit/s free-space optical communications *(Invited Paper)*

Alan E. Willner, The Univ. of Southern California (United States)

No Abstract Available

8610-5, Session 2

13 bits per incident photon optical communications demonstration *(Invited Paper)*

William H. Farr, Jet Propulsion Lab. (United States); John M. Choi, California Institute of Technology (United States); Bruce Moision, Jet Propulsion Lab. (United States)

To meet future NASA needs for increased data returns from planetary distances optical communications using near-infrared wavelengths has been proposed to either replace or supplement present microwave radio-frequency (RF) link technology. Minimizing the mass and power burden of the laser transceiver on the spacecraft drives the communications link to operate in a “photon starved” regime.

The relevant performance metric in the photon starved regime is Photon Information Efficiency (PIE) with units of bits per photon. Measuring this performance at the optical detector entrance facet, prior art has achieved performance levels around one bit per incident photon using pulse position modulation (PPM). By combining a PPM modulator with greater than 75 dB extinction ratio and using a tungsten silicide superconducting nanowire detector with greater than 83% detection efficiency we have demonstrated an optical communications link at 13 bits per incident photon PIE.

8610-6, Session 2

Mountain-top-to-valley optical link demonstration as part of a miniature terminal development

Thomas Dreischer, Martin Mosberger, Michael Bacher, Björn Thieme, Klaus Buchheim, RUAG Space AG (Switzerland)

A mountain-top-to-valley optical link demonstration was established in Switzerland between Säntis mountain, 2'502m altitude, and Dübendorf airfield, 448m altitude. The link was nearly horizontal over 55km distance. Main goal was to achieve an assessment of an optical communication system for LEO-to-Ground links in realistic atmospheric conditions, comprising the impact on data throughput and on pointing acquisition and tracking performance.

Three wavelengths were tested simultaneously, a downlink at both, 1550nm and 808nm together with a 1064nm uplink, thus allowing for comparison of atmospheric transmission impact over a wide wavelength range. Alongside, all transmitters were designed to be eye-safe. The mountain top transmitter was installed inside a service building and the 60cm receiver telescope on the airfield was placed in an open stand.

The link demonstration forms part of an on-going development activity started at RUAG Space with support from ESA in 2010. This activity is currently in the Engineering Model phase and aims at the Flight Model to be ready in 2016. Goal is to develop an optical downlink terminal that primarily addresses the needs of the emerging market of small satellites, the optical ground terminal and the ground network topology. The overall test approach is presented and explained together with a summary of all activities performed. Test results are presented and the issues discovered and lessons learned are addressed. Furthermore, a general overview is provided on the development activity and its current status.

8610-7, Session 2

Wide field-of-view single-mode-fiber coupled laser communication terminal

Yoshinori Arimoto, National Institute of Information and Communications Technology (Japan); Hiroyuki Yoshida, Katsuto Kisara, Japan Aerospace Exploration Agency (Japan)

Because of the recent progress of high power fiber amplifiers, it becomes easy to design a few watt optical transmitters to achieve broadband optical intersatellite links. In this case, we will need high-power laser beam acquisition/pointing/tracking system which can handle laser beams of at least a few watts or more.

NICT has been focusing on the R&D for compact high performance beacon tracking system to demonstrate the broadband access capability of single-mode-fiber (SMF) coupled laser communication terminals under terrestrial atmospheric turbulence conditions. They use 2-mm diameter internal optics and the same sized fast steering mirror actuator. However, such a compact design is not appropriate for a few watt laser beam control.

In order to study on the feasibility of existing high power beam tracking/pointing components, we at first made a survey of off-the-shelf fast steering mirrors and have evaluated the performance for SMF-coupled FSO terminal which has 5-times larger internal beam diameter and requires a few tens of micro-radian beam pointing accuracy.

This paper will describe the design of beacon tracking servo system using a commercially available fast steering mirror (Thorlabs Inc., FSM20XY-SP) and will also report the results of terrestrial low power laser beam transmission experiment over 500-m distance.

FSM20XY has another special feature of wide steering angles in two axes whose mechanical steering range is 6-12 degrees. This wide steering angle provides wide field-of-view beacon tracking system which makes opto-mechanical system requirements for coarse pointing system simple by not using any gimbals mechanism.

8610-10, Session 3

RIN-suppressed ultra-low noise interferometric fiber optic gyroscopes (IFOGs) for improving inertial stabilization of space telescopes

Farhad Hakimi, John D. Moores, MIT Lincoln Lab. (United States)

Pointing, acquisition, and tracking (PAT) systems in spaceborne optical communications terminals can exploit inertial sensors and actuators to counter platform vibrations, facilitating acquisition and reducing the optical beacon power required for tracking. Interferometric fiber optic gyroscopes (IFOGs) can provide sensitive angle rate measurements down to very low (sub-milliHertz) mechanical frequencies, potentially reducing the required beacon power and facilitating acquisition for a spaceborne optical communications terminal. Incoherent broadband light sources are used in IFOGs to alleviate detrimental effects of optical nonlinearities, backscattering, and polarization non-reciprocity. But incoherent broadband sources have excess noise or relative intensity noise (RIN), caused by the beating of different spectral components on the photodetector. Unless RIN noise is suppressed, IFOG performance cannot be improved once the light on the photodetector exceeds one photon per coherence time (~microWatts). We propose a simple method to dramatically suppress the RIN of an incoherent light source and thereby reduce the angle random walk (ARW) of an IFOG using such a source. We demonstrate 20 dB RIN suppression of a broadband EDFA source, which we predict could improve the angle random walk (ARW) of an IFOG using this source by 12 dB.

This work is sponsored by the National Aeronautics and Space Administration under Air Force Contract #FA8721-05-C-0002. Opinions, interpretations, conclusions and recommendations are those of the authors and are not necessarily endorsed by the United States Government.

8610-11, Session 3

Using a low-noise interferometric fiberoptic gyro in a pointing, acquisition, and tracking system

John E. Kaufmann, MIT Lincoln Lab. (United States)

Heritage pointing, acquisition, and tracking (PAT) systems have relied on optical tracking with a cooperative remote terminal to stabilize the line-of-sight of optical communications links. A hybrid approach, using new interferometric fiberoptic gyro (IFOG) technology to sense and correct local angular disturbances, blended with optical tracking, is shown to yield two significant advantages over traditional all-optical tracking: (1) line-of-sight stabilization over a very wide disturbance frequency range, down to extremely low frequencies (<<1 Hz), without the need for any optical signal power or cooperation from the remote terminal, and (2) a significant reduction in signal power required for the optical tracker. This paper will present fundamental performance analyses of a hybrid IFOG/optical tracking system and will derive simple design rules that the system designer can use to architect an optimal hybrid IFOG/optical PAT system. In addition, flow-down benefits that can simplify PAT system hardware will be discussed.

8610-12, Session 3

Centroiding performance of photon-counting array for optical communications

John M. Choi, California Institute of Technology (United States) and Jet Propulsion Lab. (United States); Kevin M. Birnbaum, William H. Farr, Jet Propulsion Lab. (United States) and California Institute of Technology (United States)

Deep-space optical communications promises orders of magnitude higher science data return compared to radio-frequency but one of the challenges is the accuracy of pointing. For a system utilizing a beacon, photon-counting detectors can be used to image the beam when operating the link at photon-starved power levels. We report experimental results of the effect of photon-counting array parameters on centroiding performance, as relevant to interplanetary optical communications.

8610-13, Session 3

Modeling and pointing performance of a CCD based deep space optical transceiver

Joel F. Shields, Meera Srinivasan, Martin W. Regehr, Abhijit Biswas, Jet Propulsion Lab. (United States)

In this paper we consider spatial acquisition and tracking for deep space optical communications using high TRL CCD detector technology. Though at a high TRL this technology suffers from relatively low readout rates, high noise, and low quantum efficiencies at the relevant optical communication wavelengths when compared with lower TRL photon counting detector (PCD) technology.

Models of the various components (mechanical, optical, scintillation, image and basebody motion) of the optical transceiver were developed in order to simulate the end to end pointing performance of the system. This included the development of a model for the four quadrant e2v CCD39 detector that incorporated the effects of readout noise, image smearing, and dark counts. A high fidelity model of the Earth image was also developed. The transceiver algorithms use the Earth light as part of the detection processing and to reduce the variance of the centroid estimates.

These simulations predict that both uplink and downlink jitter pointing performance can be met in the presence of allocated spacecraft basebody motion provided the quantum efficiency of the detector is sufficiently high and that both the uplink beacon and Earth light photons are used in the image processing and control.

8610-14, Session 3

Determination of the direction of arrival of a light beam using an angle-diversity array of photodiodes

Anjan K. Ghosh, Dhirubhai Ambani Institute of Information and Communication Technology (India); Adeola Fasiku, Pramode K. Verma, The Univ. of Oklahoma - Tulsa (United States)

A free-space optical communication based sensor network system consisting of mobile robots each equipped with super luminescent LED based optical transmitters and an angle-diversity photodiode array based receivers was discussed in Ref [1]. In this paper we show how direction of arrival of optical beams can be determined in such a system by using the MUSIC algorithm [2]. The effects of various system parameters such as the number of elements in the array, the detector noise, the number of samples taken to construct the correlation matrix, the field of view of the photodiodes, etc. on the performance of the algorithm are discussed in the paper. Finding the direction of arrival of light beams is useful in the surveillance, tactical or disaster management application of free-space optical systems.

References:

[1] A. Ghosh, S. Kunta, P. Verma, R.C. Huck, and A. Venugopalan, "Free-space optics based sensor network design using angle-diversity photodiode arrays", Prof. SPIE, Vol. 7814, Aug. 2010.

[2] D. Kundu, " Modified MUSIC algorithm for estimation of DOA of signals", Signal Processing, Vol. 48, Sept. 1994.

8610-15, Session 3

Base motion rejection performance of the low frequency vibration isolation system for interplanetary optical communications

Gerardo G. Ortiz, Didier Keymeulen, Santos F. Fregoso, Jet Propulsion Lab. (United States); Virginio Sannibale, California Institute of Technology (United States)

The residual jitter PSD of the Vibration Isolation System has been measured with an injected base motion disturbance in the active rejection control mode. The VIS provides acquisition, tracking, pointing and isolation functionality to the interplanetary flight optical communications terminal. The total residual jitter PSD and its disturbance components have also been modeled. The model includes environmental perturbations from the gravity free levitation system and the disturbance generator. The model has been experimentally validated with other disturbance test cases and other control modes of the VIS. The base motion rejection has been estimated by integrating the measured PSD over the 0.1 to 100 Hz band. The injected base motion is computed to be 475.9 urad and the residual base motion results in 1.1 urad. The base motion rejection has been measured to over 52 dB with a BLWM disturbance.

8610-16, Session 4

Nonlinearity mitigation of a 40 watt 1.55 micron uplink transmitter for Lunar laser communications

Robert T. Schulein, MIT Lincoln Lab. (United States); Robert E. Lafon, NASA Goddard Space Flight Ctr. (United States); Michael B. Taylor, John J. Carney, MIT Lincoln Lab. (United States); David W. Peckham, OFS Fitel LLC (United States); Benyuan Zhu, OFS Labs. (United States); John M. Fini, OFS Labs. (United States); David O. Caplan, MIT Lincoln Lab. (United States)

Improvements to a ground-based 40W 1.55 micron uplink transmitter for the Lunar Laser Communications Demonstration (LLCD) are described. The transmitter utilizes four 10W spatial-diversity channels to broadcast 19.4 - 38.9 Mbit/s rates using variable-duty cycle 4-ary pulse position modulation. At the lowest rate, with a 32-to-1 duty cycle, this leads to 320W peak power per transmitter channel. This paper discusses a simplified design using large core single mode fiber and polarization control to mitigate high peak power nonlinearities.

8610-17, Session 4

Highly efficient and athermal 1550um-fiber-MOPA based, high power down link laser transmitter for deep space communication

Doruk Engin, Frank Kimpel, John Burton, He Cao, Bruce McIntosh, Mark E. Storm, Shantanu Gupta, Fibertek, Inc. (United States)

We demonstrate highly efficient, high power, 1.5um-fiber-amplifier, optimized for athermal, reliable operation with low SWaP. System achieves 6W average and >1kW peak power with 8nsec pulses and 3Ghz linewidth. Stimulated Brillion scattering is managed by use of LMA fiber in final stage and precise linewidth control while maintaining the required diffraction limited, and highly polarized (PER>20dB) output. Total gain of 48dB is achieved with two stages minimizing size and component count of the system. System achieves wall plug efficiency of 13.5%, corresponding to a 2nd stage fiber optical to optical (o-o) conversion efficiency near 40%. A path to achieving >15% wall plug efficiency with slight improvements in available components while maintaining Er/Yb based final stages' efficiency will be discussed. High efficient operation is sustained for a wide range of pulse-position-modulation (16 to 128-ary PPM) formats with pulse widths varying from 8nsec to 0.5nsec. Fiber amplifier maintains required high extinction ratio (>33dB) operation for all the pulse formats. At low PRF operation significant pattern dependent pulse energy variation (>30%) is measured. Gain fiber, un-cooled pumps and key high power components for both stages are temperature cycled (10-50C) during full power operation and the system is shown to maintain an athermal performance. Also results showing temperature cycling of key fiber optic components under vacuum will be presented, showing significant maturity of the optical components and significant potential for the system to achieve TRL-6 level operation in near future.

8610-18, Session 4

Generation of exotic laser beams with fiber-array systems for active imaging and wavefront sensing applications

Svetlana L. Lachinova, Optonicus (United States); Mikhail A. Vorontsov, Optonicus (United States) and Univ. of Dayton (United States)

Coherent (phased) fiber-array laser transmitter systems allow unique opportunities for engineering of a variety of laser beams with complex spatiotemporal characteristics. This includes synthesis of laser beams with periodic, as well as stochastic, dynamically changing phase and/or polarization patterns. These unconventional beams, referred to here as exotic laser beams, are generated by means of dynamic control of GHz-rate fiber-integrated phase shifters and/or polarization modulators. Due to extremely short response time of these fiber-integrated controlling elements, coherent fiber-array systems with exotic beams provide capabilities for mitigation of speckles for various applications, including directed energy, laser communications, active imaging, and wavefront sensing. From the nonlinear dynamics viewpoint, these systems offer opportunities for analysis and practical demonstration of a great variety of nonlinear spatiotemporal dynamical processes with sub-microsecond response times and mW optical power levels – possibilities that cannot be realized with existing nonlinear dynamics "hardware" such as liquid-crystal-based spatial light modulators and optical nonlinear materials. In this talk, results of analysis and computer simulations are presented. Atmospheric turbulence impact on characteristics of fiber-array-generated exotic beams with various spatiotemporal characteristics is analyzed through numerical simulations.

8610-19, Session 4

Orthogonal on-off keying (O3K) for free space laser communication

Saleh Faruque, Shams Faruque, The Univ. of North Dakota (United States); Tasbirun Nahian Upal, Univ. of North Dakota (United States); William H. Semke, The Univ. of North Dakota (United States)

Laser communications provides wide bandwidth and high security capabilities to Unmanned Aircraft Systems. In this paper we present a method of Orthogonal On-Off Keying (O3K) for free space laser communications. O3K is a coded modulation technique, where the input digital signal is mapped into a block of orthogonal codes. The encoded data, which is in orthogonal space, modulates the carrier frequency by means of On-Off Keying. At the receive side, the data is recovered by means of code correlation. This modulation technique offers channel coding and modulation, and synchronization without any additional circuits. These techniques are especially beneficial in high bandwidth and secure laser communication applications, such as for use in Unmanned Aerial Vehicles.

8610-20, Session 4

The measurement and generation of orbital angular momentum using an optical geometric transformation

Martin P. J. Lavery, Univ. of Glasgow (United Kingdom); Andrew Fraine, Boston Univ. (United States); David J. Roberston, Durham Univ. (United Kingdom); Alexander V. Sergienko, Boston Univ. (United States); Johannes Courtial, Univ. of Glasgow (United Kingdom); Alan Wilner, The Univ. of Southern California (United States); Miles J. Padgett, Univ. of Glasgow (United Kingdom)

The desire to increase the amount of information that can be encoded onto a single photon has driven research in many areas of optics. One such area is optical orbital angular momentum (OAM). These beams have helical phasefronts and carry an orbital angular momentum of m h bar per photon, where the integer m is unbounded, giving a large state space in which to encode information.

We recently developed a telescope system comprising of two bespoke refractive optical elements to transform OAM states into transverse momentum states (Lavery et al, Opt. Express, 20, 3, 2110-2115, 2012). This is achieved by mapping the azimuthal position of the input plane to the lateral position of the output (Berkhout et al 2010 Phys. Rev. Lett. 105 153601). A mapping of this type transforms a set of concentric rings at the input plane into a set of parallel lines in the output plane. A spherical lens can then separate the resulting transverse momentum states into specified lateral positions, allowing for the efficient measurement of multiple OAM states simultaneously.

Our latest design increases the bandwidth of measurable states to over 50 OAM modes and shows simultaneous measurement of the radial co-ordinate. The transformation can be also reversed, transforming transverse momentum into OAM. This can be achieved rapidly through the use of a piezo controlled mirror or AOM. We will present our latest design and outline its use as a method for encoding and decoding the radial and azimuthal co-ordinates of OAM states.

8610-21, Session 4

A dual format communication modem development for the Laser Communications Relay Demonstration (LCRD) Program

Michael A. Krainak, Edward Y. Luzhansky, Steven X. Li, Scott A. Merritt, Anthony W. Yu, R. Butler, J. Badgley, L. Thomas, H. Stello, Y. Chen, Q. Nguyen, S. MacPherson, Pete Sparacino, P. Brown, C. Goodloe, W. Kem, W. Allison, NASA Goddard Space Flight Ctr. (United States)

The Laser Communications Relay Demonstration (LCRD) will demonstrate optical communications relay services between a geosynchronous satellite and Earth over an extended period, and thereby gain the knowledge and experience base that will enable NASA to design, procure, and operate cost-effective future optical communications systems and relay networks. LCRD is the next step in NASA eventually providing an optical communications service on the Next Generation Tracking and Data Relay Satellites (TDRS). LCRD will demonstrate some optical communications technologies, concepts of operations, and advanced networking technologies applicable to Deep Space missions. To fulfill these goals, LCRD will deploy two optical terminals on a commercial communications satellite with each optical terminal capable of transmitting and receiving data in either of two modulation formats: 1) Pulse Position Modulation (PPM), and 2) Differential Phase Shift Keying (DPSK). The PPM format is beneficial for both photon-starved Deep-Space Communication and severely Size, Weight and Power (SWaP) limited Near-Earth user-terminals (e.g. CubeSats). The DPSK format is beneficial for maximizing the data rate for Near-Earth Communication. To increase efficiency and reduce resources (SWaP and cost), the current LCRD payload concept is to combine common elements of the PPM and DPSK modems into a single optical modem. In this paper we describe the integrated dual format (PPM/DPSK) modem testbed development and performance.

8610-22, Session 5

The architecture of the laser communications relay demonstration ground stations: an overview

Keith E. Wilson, Jet Propulsion Lab. (United States); John D. Moores, MIT Lincoln Lab. (United States)

The Laser Communications Relay Demonstration (LCRD) mission will launch an optical payload on a Loral Space Systems GEO satellite in December 2017. The mission will demonstrate optical relay services between two ground stations as an early simulation of optical relay services of the next generation TDRSS. The planned two-year long demonstration will support high bandwidth optical modulation formats of the near-Earth and deep space links, 1.25 Gb/s DPSK and 311 Mb/s PPM, respectively. Measurements of atmospheric attenuation, turbulence, and sky background during the link will characterize the performance of the channel under a variety of operating conditions. This paper describes the architecture of the LCRD ground stations; namely the JPL Optical Communications Telescope Laboratory in Wrightwood California and the MIT LL Lunar Lasercom Ground Terminal in White Sands New Mexico that will be modified to support the demonstration.

8610-23, Session 5

Comparing adaptive optics approaches for NASA LCRD Ground Station #2

Jason B. Stewart, Daniel V. Murphy, John D. Moores, Andrew Fletcher, Keith Bonneau, MIT Lincoln Lab. (United States)

NASA's Laser Communication Relay Demonstration (LCRD) aims to demonstrate a geosynchronous satellite laser communications (lasercom) relay between two independent ground terminals. We report on the design and experimental evaluation of two adaptive optics (AO) techniques for LCRD Ground Station #2 (GS-2). GS-2 leverages the ground terminal developed for NASA's Lunar Laser Communications Demonstration (LLCD). Equipping GS-2's 40cm diameter receive telescope with AO to mitigate atmospheric turbulence effects will enable the use of single mode optically preamplified receivers for high data-rate near-Earth relay applications. In this work a direct wavefront sensing AO approach using a Shack-Hartmann sensor and a continuous facesheet micro-electro-mechanical system (MEMS) deformable mirror (DM) was compared with an indirect sensing, hill-climbing or multidither approach using a segmented MEMS DM. Design concepts and recent experimental progress for the two approaches will be presented.

8610-24, Session 5

Conceptual design of the adaptive optics system for the laser communication relay demonstration ground station at Table Mountain

Lewis C. Roberts Jr., Norman A. Page, Rick Burruss, Tuan N. Truong, Mitchell Troy, Jet Propulsion Lab. (United States)

The Laser Communication Relay Demonstration will feature a geostationary satellite communicating via optical links to multiple ground stations. The first ground station (GS-1) is the 1m OCTL telescope at Table Mountain in California. The optical link will utilize pulse position modulation (PPM) and differential phase shifting keying (DPSK) protocols. The DPSK link necessitates that adaptive optics (AO) be used to relay the incoming beam into the single mode fiber that is the input of the modem. The GS-1 AO system will have two MEMS Deformable mirrors to achieve the needed actuator density and stroke limit. The AO system will sense the aberrations with a Shack-Hartmann wavefront sensor using the light from the communication link's 1.55 micron laser to close the loop. The system will operate day and night. The system's software will be based on heritage software from the Palm 3000 AO system, reducing risk and cost. The AO system is being designed to work at r0 greater than 3.3 cm (measured at 500nm and zenith) and at elevations greater than 20 degrees above the horizon. In our worst case operating conditions we expect to achieve Strehl rations of over 70% (at 1.55 microns), which should couple ~57% of the light into the single mode DPSK fiber. This paper describes the conceptual design of the AO system, predicted performance and discusses some of the trades that were conducted during the design process.

8610-25, Session 5

The Lunar Lasercom OCTL Terminal (LLOT)

Abhijit Biswas, Kevin M. Birnbaum, Joseph M. Kovalik, Martin W. Regehr, W. Thomas Roberts, Jet Propulsion Lab. (United States) and California Institute of Technology (United States); Malcolm W. Wright, Jet Propulsion Lab. (United States)

The Optical Communication Telescope Laboratory (OCTL) telescope located at Table Mountain, CA is being readied as a backup ground station for NASA's upcoming Lunar Laser Communications Demonstration (LLCD). The 1-m diameter telescope will be configured as a mono-static transceiver for transmitting a laser beacon and receiving downlink at discrete data-rates between 39 Mb/s and 311 Mb/s. Interfaces to an operations center with near-real time exchange of telemetry will also be developed. A system level overview of this backup ground station for LLCD will be presented.

8610-26, Session 6

Lunar laser OCTL terminal (LLOT) optical systems

W. Thomas Roberts, Malcolm W. Wright, Jet Propulsion Lab. (United States)

The Lunar Laser OCTL Terminal is an auxiliary ground station terminal for the Lunar Laser Communication Demonstration (LLCD) The LLOT optical systems exercise modulation and beam divergence control over six 10-W fiber-based laser transmitters at 1568 nm which act as beacons for pointing of the space-based terminal. The LLOT design transmits these beams from distinct sub-apertures of the F/76 OCTL telescope at divergences ranging from 110 urad to 40 urad. LLOT also uses the same telescope aperture to receive the downlink signal at 1550 nm from the spacecraft terminal. Characteristics and control of the beacon lasers, methods of establishing and maintaining beam alignment, beam zoom system design, co-registration of the transmitted beams and the receive field of view, transmit/receive isolation, and downlink signal manipulation and control are discussed.

8610-27, Session 6

A post-processing receiver for the Lunar Laser Communications Demonstration project

Meera Srinivasan, Kevin M. Birnbaum, Abhijit Biswas, Michael K. Cheng, Kevin J. Quirk, Jet Propulsion Lab. (United States)

The Lunar Laser Communications Demonstration Project undertaken by MIT Lincoln Laboratory and NASA Goddard Space Flight Center will demonstrate high-rate laser communications from lunar orbit to the Earth. NASA Jet Propulsion Laboratory is developing a backup ground station supporting up to 311 Mbps that is based on a non-real-time software post-processing receiver architecture. This approach entails overcoming many system challenges, including optimization of the photodetector assembly within time and cost constraints, sample rate limited data capture without feedback, and high uncertainty in downlink clock characteristics. In this paper we present a receiver concept to meet these challenges, with descriptions of the InGaAs photodetector assembly, sample acquisition and recording platform, and signal processing approach. End-to-end coded simulation and laboratory data analysis results are presented that validate the receiver conceptual design.

8610-28, Session 6

Optical filter assembly for interplanetary optical communications

Yijiang Chen, Hamid Hemmati, Jet Propulsion Lab. (United States)

Development of optical spectral filter assembly for interplanetary optical communications using ground-based nanowire photon counting detectors, with wide spectral response region, will be reported. The filter has transmission efficiency of >90%, bandwidth of 0.14nm at 1550nm, and the wavelength range of 1000nm to 3000nm. It is tunable to track the received signal center wavelength variation due to Doppler effect.

8610-30, Session 7

Effects of atmospheric transmission of high power diode pumped alkali lasers

Glen P. Perram, Christopher Rice, Air Force Institute of Technology (United States)

As diode pumped alkali lasers (DPAL) are scaled to powers exceeding 1 kW, the effects of atmospheric transmission, including thermal blooming, is explored. The cesium and rubidium lasers operate near 894 and 795 nm, respectively, in the vicinity of atmospheric water vapor absorption lines. The potassium laser line lies in the high rotational limit of the O_2 X-b (0,0) band near 770 nm. We assess the effects of atmospheric transmission on high power propagation using the High Energy Laser End-to End Operational Simulation. HELEEOS uses the scaling laws of the Scaling the High energy laser And Relay Engagements (SHaRE) toolbox which is anchored to the wave optics code WaveTrain and all significant degradation effects, including thermal blooming due to molecular and aerosol absorption, scattering extinction, and optical turbulence, are represented in the model. The spectral transmission model is anchored to field data from 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. The ruggedized system has been field deployed and tested for propagation distances of greater than 1 km. The TDLAS approach achieves a minimum observable absorbance of 0.2%, whereas an FTIR instrument is almost 20 times less sensitive.

8610-31, Session 7

Measurements of partially coherent laser beam intensity fluctuations propagating through a hot-air turbulence emulator and comparison with the maritime environment

Charles Nelson, Svetlana Avramov-Zamurovic, U.S. Naval Academy (United States); Olga Korotkova, Univ. of Miami (United States); Reza Malek-Madani, U.S. Naval Academy (United States); Raymond Sova, Johns Hopkins Univ. Applied Physics Lab. (United States); Frederic M. Davidson, Johns Hopkins Univ. (United States)

A hot-air turbulence emulator is used in the laboratory to generate controlled optical clear air turbulence ranging from weak to strong scintillation and a spatial light modulator is used to control the degree of coherence of a propagating infra-red laser beam. A first and second order statistical analysis of partially coherent laser beam propagation through the hot-air turbulence emulator is explored and compared with over-the-water propagation at the United States Naval Academy. Specific analysis will focus on the probability density and temporal autocovariance functions of the fluctuating intensity and comparison across varying degrees of spatial coherence of the laser beam.

8610-32, Session 7

Lidar sensing of the turbulence based on the backscattering enhancement effect

Victor A. Kulikov, Alexander S. Gurvich, A.M. Obukhov Institute of Atmospheric Physics (Russian Federation)

Backscattering enhancement (BSE) effect is due to the fact that both the initial and back-scattered waves propagate through the same inhomogeneities of the refractive index. Mean value of the back-scattered intensity is higher than it would be with the same obstacle but no inhomogeneities. This effect is named backscattering enhancement (BSE) effect.

Numerical modeling of lidar that based on BSE effect was carried out in Rutov-Obukhov approximation in our work. The integral equation was considered which bundles up the distribution of turbulence intensity throughout the space between the source and a scatterer. Coefficient BSE was determined as ratio of relation dispersions of radiation intensity fluctuation that scattered straight back and at an angle.

BSE coefficient does not depend on the nature of scatterings in cases of aerosol or molecular scatterers. As example variants of turbulence intensity distribution Cn2 between sources in form select layer or boundaries of half-space with enhanced turbulence intensity scatterers were considered. Possibility of detection the sort out the regions with enhanced turbulence intensity was showed in the case isotropic turbulence for molecular or aerosol scatterings. Inhomogeneous distribution of turbulence intensity is reliably picked out on dependence of BSE coefficient on distance between source and probing laser beam.

The lidar scheme for BSE measurements with space modulation of probing beam is suggested. It allows suppressing systematic errors. Lidar allows measure BSE coefficient along with the routine lidar sensing. The dependence of BSE coefficient on the line along propagation path has considered for finite receiving aperture and finite diameter of probing laser beam. The results of modeling demonstrate that BSE measurements make it possible to remotely sort out the regions with enhanced turbulence intensity at distances determined by the maximum sensing range.

The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement n_ 233801.

8610-33, Session 7

Beaconless characterization of turbulent atmosphere

Anatoliy Khizhnyak, Vladimir B. Markov, Advanced Systems & Technologies, Inc. (United States); Joseph R. Chavez, Air Force Research Lab. (United States); Shiang Liu, Advanced Systems & Technologies, Inc. (United States)

Atmospheric turbulence is the key factor responsible for distortions in a propagating wave structure. Therefore, characterization of atmospheric perturbations along the propagation path is critical for effective compensation of turbulence-induced effects. Information related to the parameters of the turbulence can be derived by detecting the characteristics of a reference wave passing through an inhomogeneous medium. In practice, however, this requires a reference wave generated by a localized beacon placed at the opposite end of the light path where the parameters of the turbulence will be measured. Therefore, placing the beacon is critical for existing measurement systems, including adaptive optics. As a result, formation of the beacon in a turbulent environment remains one of the most pressing and difficult-to-solve problems, especially in the case of an extended target with a diffuse, scattering surface.

To date, several approaches targeting the formation of a localized beacon have been attempted with little success. These proposed methods have been simulated and studied experimentally in laboratories but haven't produced reliable results in practical environments, mostly because of the complexity of the problem. The most effective solution to the problem would be to develop a system for atmosphere characterization that does not require a localized beacon. This presentation discusses a beaconless technique that allows characterization of turbulence in an image-resolved scenario.

8610-34, Session 7

Determining seeing conditions of a horizontal turbulent optical path with video image analysis

Christopher C. Wilcox, Sergio R. Restaino, K. Peter Judd, Ty Martinez, Jonathan R. Andrews, U.S. Naval Research Lab. (United States)

The turbulent effects from the Earth's atmosphere degrade the performance of any optical system within it. There have been numerous studies in the effects of atmospheric turbulence on an imaging system that is pointed vertically to the sky looking at distant objects and the seeing conditions associated with it. We investigate the calculation of the seeing conditions with an imaging system pointed horizontally in terrestrial and maritime environments. We have acquired video data of different horizontal paths in the infrared wavelengths and performed data analysis that will be the basis of new characterizations and modeling of horizontal path atmospheric turbulence.

8610-35, Session 7

Efficiency comparison of spatial and spectral diversity techniques for fading mitigation in free-space optical communications over tactical-range distances

Jean Minet, Univ. of Dayton (United States) and Thales Research & Technology (France); Mikhail A. Vorontsov, Univ. of Dayton (United States) and Optonicus (United States); Daniel Dolfi, Thales Research & Technology (France)

In long-range situations, the performance of free-space optical (FSO) communication links is strongly impacted by atmospheric turbulence. In this paper we compare efficiency of turbulence effects mitigation in FSO communication links using spectral (wavelength) and spatial diversity techniques. Numerical analysis of both techniques is performed considering FSO communication settings with single-mode fiber-collimator transceivers. In the case of spectral diversity setting, the fiber-collimators are based on the use of photonic crystal fibers that provide single-mode operation for three distinct wavelengths (532, 1064 and 1550nm). In the spatial diversity communication setting, analysis is performed using multiple-transceiver configurations. Analysis includes both received signal's statistical and temporal spectral characteristics.

8610-36, Session 7

Digital adaptive optics and imaging through deep turbulence

Mathieu Aubailly, Univ. of Maryland, College Park (United States); Mikhail A. Vorontsov, Univ. of Dayton (United States) and Univ. of Maryland, College Park (United States) and Optonicus (United States); Jony Jiang Liu, U.S. Army Research Lab. (United States)

We present an alternative approach to conventional adaptive optics for mitigating the effect of atmospheric turbulence in imaging application. The technique, referred to as digital adaptive optics (DAO), consists of two sequential steps: (1) the complex-field (intensity and phase

distributions) of the incident optical wave is measured with high-resolution and (2) a post-processing algorithm is used to reconstruct an image and optimize its quality from the complex-field measurement. The presented technique has the advantage of relieving the imaging system of wavefront control devices such as deformable mirrors and their control hardware, but is limited to application for which real-time operation is not required. Numerical analysis results show substantial image quality improvements even in conditions of deep turbulence and strong anisoplanatism which are typical characteristics of near-horizontal and slant propagation paths.

8610-37, Session 7

Losses on a free-space optical link due to a channel turbulence

Bruce Moision, Sabino Piazzolla, Jon Hamkins, Jet Propulsion Lab. (United States)

The Laser Communications Relay Demonstration (LCRD) will implement an optical communications link from an Earth terminal to an Earth-orbiting satellite. Clear air turbulence over the path will cause random fluctuations, or fading, in the received signal irradiance over the (free space) channel. In this paper we characterize losses due to fading caused by the clear air turbulence. We determine the fading capacity loss for both weak and strong turbulence, and illustrate the performance for receivers with and without channel state information. We also illustrate the performance of the system planned for LCRD that mitigates the fading loss with a channel interleaver and error-corrrection-coding.

8611-1, Session 1

Biodegradable microsphere mediated perforation of cells using femtosecond laser for theranostics *(Invited Paper)*

Mitsuhiro Terakawa, Keio Univ. (Japan)

There is a growing interest in laser interaction with micro- and nanoparticles for biomedical applications. Laser irradiation to antibody-conjugated particles which are selectively bound to targeted cells realizes tumor detection, photothermal therapy, and drug delivery in an united system, so called theranostics. We demonstrate the perforation of cell membrane by focused optical field generated by polylactic acid (PLA) microspheres, a biodegradable polymer, excited by fs laser pulse. Unlike other particles, biodegradable particles have advantages of degradation and elimination by innate metabolic processes in human body, which resulted in safer phototherapy. Fluorescein isothiocyanate (FITC)-dextran and short interfering RNA were delivered into many A431 cells in vitro by applying a single 800 nm, 80 fs laser pulse in the presence of antibody-conjugated PLA microspheres. The focused intensity was simulated by the three-dimensional finite-difference time-domain (FDTD) method. The transparent sphere works as a microlens and the cell membrane under the sphere can be perforated by a focused optical field. We also show that cell lysis can be obtainable by using the same scheme but different pulse duration, demonstrating a flexibility of this method for both drug delivery and cell killing. Our investigation on the controlled drug release will also be presented.

8611-2, Session 1

High-throughput optical injection of mammalian cells using a non-diffracting beam in a microfluidic platform

Helen A. Rendall, Robert F. Marchington, Bavishna B. Praveen, Univ. of St. Andrews (United Kingdom); Gerald Bergmann, Friedrich-Schiller-Univ. Jena (Germany); Yoshihiko Arita, Univ. of St. Andrews (United Kingdom); Alexander Heisterkamp, Friedrich-Schiller-Univ. Jena (Germany); Frank J. Gunn-Moore, Kishan Dholakia, Univ. of St. Andrews (United Kingdom)

Femtosecond photoporation is an optical, non-invasive method of injecting membrane impermeable substances contained within the surrounding medium into cells. The technique typically addresses individual cells in a static monolayer. While this gives excellent selectivity, it can be time consuming or impractical to treat larger samples. We build on previous work using a microfluidic platform, which allows for a suspension of cells to be dosed with femtosecond light as they flow through a microfluidic channel. A reusable quartz chip is designed with an ‘s’-bend with facilitates the delivery of a ‘non-diffracting’ femtosecond Bessel beam along the centre of the channel. By implementing off-chip hydrodynamic focusing, cells are confined to the central region of the channel and pass along the Bessel beam core where they are photoporated.

This new parallel approach allows for higher flow rates to be used compared to the previous, orthogonal, design whilst maintaining the necessary dwell time in the Bessel beam core. Optical injection of the cell membrane impermeable stain propidium iodide has been successful with two cell lines. These have yielded viable injection efficiencies of 20.4±4.2% (Chinese hamster ovary cells, CHO-K1) and 31.0±9.5% (human promyelocytic cells, HL60) with a cell throughput of up to 10 cells/second. This marks an order of magnitude increase compared to the previous microfluidic design.

8611-3, Session 1

Femtosecond optical transfection as a tool for genetic manipulation of human embryonic stem cells

Maria Leilani Y. Torres-Mapa, Univ. of St. Andrews (United Kingdom); John Gardner, Helen Bradburn, Jason King, Roslin Cellab (United Kingdom); Kishan Dholakia, Frank J. Gunn-Moore, Univ. of St. Andrews (United Kingdom)

Human embryonic stem cell (hESC) research has increased over the past decade from its first successful in vitro culture. These cells, derived from the inner cell mass of an embryo at the blastocyst stage, readily proliferate in culture in a controlled environment. Considered as therapeutic cells, embryonic stem cells have the capacity to differentiate into each of the more than 200 cell types found in the body. Such qualities make human embryonic stem cells (hESCs) attractive tools for human therapeutic studies, such as toxicology for drug screening and cell replacement therapies. Important in realising the potential of hESC for in vitro therapeutic studies is an effective method of targeted gene expression or knockdown in order to fundamentally understand genetically related human diseases. Transfection experiments of hESCs commonly used viral methods but also chemical and electroporation techniques were previously employed. However, non-viral techniques for hESC transfection are still ideal to avoid both the time-consuming vector construction and the potential insertional mutagenesis due to random integration of foreign DNA into the host genome. Hence, we wish to test the applicability of femtosecond optical transfection in genetic manipulation of hESCs. In this work, we demonstrate successful transfection of fluorescently-labelled DNA in hESCs with efficiency of up to ~40% using three doses of focused femtosecond laser. A significant number of transfected cells retained their undifferentiated morphological feature of large nucleus with high nucleus to cytoplasmic ratio, 48h after photoporation. Furthermore, DNA constructs driven by different types of promoters were also successfully transfected into hESCs using this technique.

8611-4, Session 1

Off-resonance plasmonic enhanced ultrafast laser induced nanocavitation and transfection of cancer cells: effect of pulse duration

Michel Meunier, Rémi Lachaine, Hichem Guerboukha, Étienne Boulais, Ecole Polytechnique de Montréal (Canada)

The use of off-resonance plasmonic nanoparticles to enhance laser cells transfection is a novel approach using the plasma created in the near-field around the particle to generate nanobubbles in the cells vicinity [1-2]. Those bubbles may create transient holes in the cell membrane through which foreign genetic material can enter. Laser parameters are of great importance in the perforation process as irradiation may generate too small bubbles that would not perforate the cell membrane, or too large bubbles that could kill the cells. This “fluence operating window” depends on both the nanostructure optical properties and the laser parameters, in particular the pulse duration. Pulse duration modification changes the peak intensity and thus changes the plasma generation efficiency. A theoretical model including near-field enhancement and plasma generation have been developed to study the effect of pulse duration on plasma generation efficiency. Results are in good agreement with experimental observations and show that the plasma generation and diffusion are critical in the cavitation process.

Using an in situ optical probing method, effect of pulse duration on bubble diameter has been experimentally studied. Results show that, over 100mJ/cm2, femtosecond pulses generate larger bubbles than

picoseconds pulses. Also, cancer cells have been transfected using different pulse durations. Both experimental studies point toward a shift in the fluence operating window when pulse duration is changed from tenths of femtoseconds to few picoseconds. Pulse duration optimization could thus allow a better control on bubbles generation and cell transfection.

[1] Baumgart J, Humbert L, Boulais E, Lachaine R, Lebrun JJ, Meunier M, Off-resonance plasmonic enhanced femtosecond laser optoporation and transfection of cancer cells, Biomaterials, 2012.

[2] Boulais E, Lachaine R, Meunier M, Plasma mediated off-resonance plasmonic enhanced ultrafast laser induced nanocavitation, Nano Letters, 2012.

8611-5, Session 1

Material multiphoton nanoprocessing with a 12 fs NIR laser scanning microscope

Karsten König, Univ. des Saarlandes (Germany) and JenLab GmbH (Germany); Aisada Uchugonova, Hans G. Breunig, Martin H. Straub, Helmut Seidel, Maziar Afshar, Univ. des Saarlandes (Germany)

12 fs pulse width at the focal plane of an NA1.3 objective has been realized with chirped mirror technology and the use of a compact NIR 85 MHz laser resonator. Mean µW powers were found to be sufficient to induce two-photon NADH/flavin autofluorescence for 3D cell imaging as well as for 3D nanolithography. When increasing the mean power up to the sub-10 mW range, plasma-mediated material nanoprocessing was realized due to transient TW/cm2 intensities. Sub-wavelength and even sub-100 nm cuts that are far beyond the Abbe diffraction limit have been realized in photoresists, silicon wafers, glass, polymers, metals, and biological targets. ITO nanowires have been produced after laser-enhanced etching. Current laser developments include low-cost ultracompact sub-20 femtosecond laser sources for material processing and nonlinear imaging.

8611-6, Session 2

Two-photon guided surgery using fs lasers in vivo (embryonic hearts) *(Invited Paper)*

Jonathan Butcher, Cornell Univ. (United States)

No Abstract Available

8611-7, Session 2

Temporal focusing for photodynamic therapy

Christopher J. Rowlands, Sebastien G. M. Uzel, Massachusetts Institute of Technology (United States); Oliver J. Klein, Conor L. Evans, Wellman Ctr. for Photomedicine (United States); Peter T. C. So, Massachusetts Institute of Technology (United States)

Highly-localized two-photon excitation of chromophores within a treatment volume can be achieved using temporal focusing, whereby an ultrafast pulse is dispersed using a grating, and then recombined using a lens. The result is that the pulse has a high peak power only within a thin plane, located a short distance from a microscope objective. This approach permits photodynamic therapy to be performed with almost cellular level resolution, minimizing damage to surrounding tissue. The authors have designed an optical system that is capable of patterning this temporal focusing plane, and have demonstrated that cells within a culture medium can be selectively illuminated and destroyed. The design of this system will be discussed, and the design decisions elaborated upon. In addition, the system is intended to be extended, and some of the flexibility of the system in terms of wavelength, field of view and resolution will be explained.

Initially the system is intended for wound treatment during surgical excision; the system selects the sample volumes that must be illuminated and the resulting patterns are projected using a micromirror array. This application does not require large penetration depths; values of several hundred microns are deemed acceptable. Employment of the system in more complex environments is being investigated, and approaches will be proposed to increase the penetration depth to several millimeters or more, permitting more widespread application of the temporal focusing system, perhaps even including treatment modes where cells are targeted directly, without the need for surgical excision.

8611-8, Session 2

Simultaneous spatio-temporal focusing of femtosecond pulses: a new paradigm for material processing and tissue ablation

Erica K. Block, Michael Greco, Charles G. Durfee III, Jeff A. Squier, Colorado School of Mines (United States); Omid Masihzadeh, David A. Ammar, Malik Y. Kahook M.D., Naresh Mandava, Univ. of Colorado Denver School of Medicine (United States)

Recently, we have demonstrated, both experimentally and theoretically that simultaneous space-time focused (SSTF) femtosecond beams can be used to process optically transparent materials at depths with low numerical aperture (0.03 NA) without loss of precision. In this work, we show the tremendous utility of SSTF (compared to conventional femtosecond micromachining) through four metrics: theoretical modeling, direct measurements of the improved axial confinement using third harmonic generated at an interface, observation of suppression of self-focusing and ionization defocusing with SSTF pulses, and finally, ablation of ocular tissue at fluences well above threshold for both SSTF and non-SSTF. In all cases, axial confinement is significantly improved with application of SSTF. Nonlinear effects that can shift the focal plane in non-SSTF in material processing or ablation are entirely mitigated. This is illustrated rather dramatically through surface ablation of ocular tissues when cutting well above threshold with a focal spot of approximately 30µm. For the non-SSTF ablation, histology reveals damage that extends up to ~1mm, while with the SSTF cuts, ablation is confined to ~ 200µm in depth. Acknowledgements: E. Block and J. Squier acknowledge support from the NIBIB through EB-003832, M. Greco and C. Durfee acknowledge support from the AFOSR under grant FA9550-10-1-0394.

8611-9, Session 2

Pump-probe investigation of fs-LIOB in water by simultaneous spatial and temporal focusing

Robert Kammel, Roland Ackermann, Friedrich-Schiller-Univ. Jena (Germany); Andreas Tünnermann, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany) and Friedrich-Schiller-Univ. Jena (Germany); Stefan Nolte, Friedrich-Schiller-Univ. Jena (Germany) and Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

I would like to participate in the student competition.

Femtosecond (fs)-lasers are a versatile tool for processing transparent materials like glass, polymers or ocular tissue. However, focusing fs-laser pulses is often accompanied by perturbing side-effects such as self-focusing and filamentation. Especially focusing deep into tissue with low NA may result in high plasma lengths and fragmentation of the breakdown volume. To overcome this limitation, we studied the influence of simultaneous spatial and temporal focusing (SSTF) on the LIOB in water. In SSTF, the spectrum of the incoming laser pulse is spatially separated by a grating stretcher to increase the pulse duration. After

passing the focusing optic, the spectral components overlap at the focus and recompose the ultrashort pulse. Therefore, the laser-material interaction is confined closely to the focal volume.

We investigated the temporal evolution of the plasma and resulting disruption in water by pump-probe shadowgraphy. With conventional focusing (t = 80 fs, NA = 0.1) self-focusing and breakup of the disruption volume was observed at pulse energies > 2 µJ, leading to a breakdown length of ~ 800 µm at a pulse energy of 8 µJ. With SSTF the axial length of the breakdown is significantly reduced by a factor of 2 at the same pulse energy. Plasma formation and the resulting disruption stay within the focal region. No self-focusing could be observed for pulse energies up to 8 µJ. Therefore, SSTF appears to be a promising tool to precisely induce photo disruptions in transparent materials even with low numerical aperture, e.g. for fs-laser surgery within the anterior segment of the eye.

8611-10, Session 2

Femtosecond laser two-photon polymerization fabrication of three-dimensional microscaffolds functionalized for stem cell culture

Renato Bertozzi, Istituto di Fotonica e Nanotecnologie (Italy); Michele M. Nava, Politecnico di Milano (Italy); Mara Galli, Shane M. Eaton, Giulio Cerullo, Istituto di Fotonica e Nanotecnologie (Italy); Manuela T. Raimondi, Politecnico di Milano (Italy); Roberto Osellame, Istituto di Fotonica e Nanotecnologie (Italy)

3D scaffolds formed in biocompatible polymers can be exploited for tissue engineering and regenerative medicine. Here, we apply two-photon polymerization to form microscaffolds having pore sizes of 10, 15 and 20 microns, for the bottom, middle and top layers, respectively. The target of this configuration is to guide stem cell homing and differentiation through the scaffold microgeometry. The material used is a hybrid organic-inorganic zirconium/silicon sol-gel photoresist SZ2080 that has demonstrated good biocompatibility. We used two different photoinitiators: Irg (Irgacure 369, 2-Benzyl-2-dimethylamino-1-(4-morpholinophenyl)-butanone-1), and Bis (Michler's ketone, 4,4'-bis(dimethylamino)benzophenone) having absorption wavelengths of 320 nm and 370 nm, respectively. To drive efficient two photon absorption to maximize writing speed in Bis and Irg photonitiators, we applied femtosecond lasers having 800-nm and 515-nm wavelengths, respectively. In both cases, an oil immersion lens with NA = 1.4 was used to achieve sub-micrometer polymerized line widths.

In confocal fluorescence microscopy of microscaffolds seeded with rat mesenchymal stem cells, the progenitors of muskulo-skeletal cells, we observed strong background autofluorescence from the Bis-based SZ2080, hindering the detection of fluorescence markers of stem cell proliferation and differentiation. However, in the Irg-based polymer, we found significantly less background signal, enabling us to accurately resolve fluorescence markers within the microscaffolds. Our preliminary results show that, at 6 culture days, stem cells proliferate preferentially in the microscaffold areas with the highest surface density available for adhesion. Future work will seek to demonstrate the effect of mechanical and geometrical properties of the laser-formed microscaffolds on stem cell differentiation.

8611-11, Session 2

Functional scaffolds for bone tissue engineering fabricated by direct fs laser writing technique

Paulius Danilevicius, Foundation for Research and Technology-Hellas (Greece); Frederik Claeyssens, The Univ. of Sheffield (United Kingdom); Mohamed Oubaha, Dublin City Univ. (Ireland); Leoni Georgiadi, Foundation for Research and Technology-Hellas (Greece); Maria Vamvakaki, Foundation for Research and Technology-Hellas (Greece) and Univ. of Crete (Greece); Maria Chatzinikolaidou, Univ. of Crete (Greece); Maria Farsari, Costas Fotakis, Foundation for Research and Technology-Hellas (Greece)

Direct fs laser writing (DLW) by multiphoton polymerization is a rapid fabrication technique of three-dimensional (3D) polymeric micro/nano-structures with sub-100 nanometer resolution. Due to its unique properties, DLW has found applications in photonics, microoptics, microfluidics, as well as in biomedicine. A challenging biomedical application of DLW is engineering of artificial tailor-made tissues, which could be transplanted into patients to treat disease or trauma. DLW has been employed for the fabrication of artificial scaffolds, which could serve as an extra-cellular matrix and sustain stem cell growth in vitro. The topography of the scaffolds can affect cell viability, adhesion and direct their differentiation. This can be used for constructing artificial tissues of desirable form and functionality.

In this work we used Ti:Sapphire oscillator for fabrication of bone scaffolds from two different materials. The first material we used is custom-synthesized photocurable polylactide-based resin (PLA). We demonstrated the possibility to fabricate PLA scaffolds with well-controlled geometry and pore size, and we tested its biodegradability and biocompatibility. Our results indicate good cell adhesion and increase in proliferation. The second material we used is an electrically conductive photopolymer. We fabricated conductive scaffolds in order to stimulate bone cells with electrical pulses in order to investigate cell proliferation and differentiation. Critical parameters governing materials conductivity, structuring quality and biocompatibility were also found. Our results show that DLW is suitable for rapid and flexible fabrication of biomedical components with required shape and bio-physical functionalities.

8611-12, Session 3

Harmonic nanoparticles for nonlinear bio-imaging and detection *(Invited Paper)*

Luigi Bonacina, Univ. of Geneva (Switzerland)

Harmonic nanoparticles (HNPs) represent a new, inherently nonlinear, approach to bio-labeling. As they feature unprecedented long-term photo-stability and excitation wavelength flexibility, they can complement fluorescence-based labels (dyes, quantum dots,..) in several high-demanding applications. We present the benefits of HNPs for long-term cell tracking, by monitoring over long time-spans and at high imaging speed the evolution of stem-cells derived cardiac structures.[1] We show also how HNPs nonresonant excitation mechanism gives the possibility to work in the infrared spectral region, increasing imaging penetration depth.[2] Finally, we show how the interplay of infrared excitation and multi-harmonic detection can be exploited for high sensitivity individual HNP detection in blood plasma.[3]

References:

[1] SMALL, 8(17), 2614 (2012)

[2] ACS Nano, 6 (3), 2542–2549 (2012)

[3] Nano Lett., 12 (3), 1668–1672 (2012)

8611-13, Session 3

Conjugated gold nanoparticles as selective imaging tools in cell biology

Stephan Barcikowski, Christoph Rehbock, Lisa Gamrad, Univ. Duisburg-Essen (Germany); Ulrike Taylor, Friedrich-Loeffler-Institut (Germany); Daniel Werner, Univ. Duisburg-Essen (Germany); Wilfried Kues, Detlef Rath, Friedrich-Loeffler-Institut (Germany)

Gold nanoparticles (AuNPs) are suitable tools for bioimaging as they show a good biocompatibility and in contrast to organic dyes they do not suffer from photobleaching. However, in order to penetrate cell membranes and to selectively bind to target sites they need to be functionalized with biomolecules like aptamers for targeting tumors selectively [1]. Additionally, particle size influences AuNP imaging because cell penetration in some cells is favored by small particle sizes (5 nm) while optical imaging with confocal microscopy requires larger particles > 60 nm [2]. This means imaging strategies may include NP aggregation, which results in an optically detectable plasmon shift [3].

In this work bioconjugated AuNPs were examined for their applicability as bioimaging tools in sperm sexing experiments. Particularly their translocation across the complex sperm membrane is challenging. Therefore the bioconjugation with different cell penetrating peptides (CPPs), which are known to favor membrane penetration, was studied. The peptide´s sequence, length, charge, and concentration were systematically varied and conjugate stability and cell-penetrating properties were examined. In order to obtain particles with a high ligand load an advanced laser based synthesis combined with in-situ and ex-situ conjugation was applied. This method is known to increase the maximum ligand load by a factor of 5 compared to chemically synthesized particles.[4].

[1] Walter et al., J. Nanotech. 8, 21 (2010)

[2] Klein et al., J. Biomed. Opt. 15, 3 (2010)

[3] McKenzie et al., 2367-2369 (2008)

[4] S. Petersen, S. Barcikowski. J. Phys. Chem. C. 113, 19830-19835 (2009)

8611-14, Session 3

Label free optimal dynamic discrimination of biological macromolecules

Svetlana Afonina, Denis Kiselev, Jérôme Extermann, Luigi Bonacina, Jean-Pierre Wolf, Univ. of Geneva (Switzerland)

The fast development of laser techniques, in particular, the generation of ultrashort femtosecond and even attosecond pulses opens new frontiers and various experimental tools for biomedical applications.

The combination of pulse shaping and optimal control is a very promising tool based on coherent manipulation of wavepackets on an ultrafast time scale. It already has successfully been applied for optimal dynamic discrimination (ODD) experiments of biomolecules like free amino acids and flavins which are indistinguishable by spectroscopic means. This approach can be extended toward to label free cellular imaging and detection of chemical or biological substances.

Absorption bands of most of the biomolecules (including DNA) are in the deep UV region and consequently require phase modulation capabilities in this spectral range. For this reason a new dedicated reflective pulse shaper using Micro-Electro-Mechanical Systems (MEMS) mirror arrays was developed and used in this work.

Here we report the application of ODD for pump-probe fluorescence-based detection using optimally tailored UV laser pulses that selectively enhance or decrease fluorescence between the molecules. Target molecules were di-peptides based on tryptophan (alanine-, glycine-, and leucine-tryptophan). For several molecule pairs (trp vs dipeptides, gly-trp vs ala-trp) the discrimination capability of the approach achieved 20%. An extension was done to the proteins, commonly used as health indicators. Among others, we demonstrate the identification of the essential antibody of immune system, immunoglobulin G, directly in the human serum.

8611-15, Session 3

Femtosecond pumped lasing from the fluorescent protein DsRed in a one dimensional random cavity

Thomas M. Drane, Valery Milner, The Univ. of British Columbia (Canada)

Bio-materials present an exciting new source of components for coherent light generation and amplification. Here we present, to our knowledge, the first demonstration of lasing from the fluorescent protein DsRed. We chose to use a random 1D cavity for its technical simplicity and as a model of the simplest possible multiple scattering geometry.

A one dimensional scattering medium was constructed from a stack of 60 microscope coverslips with nominal thickness of 80 to 100 micron. The inherent variability of the coverslip thickness and glass-air-glass gap formed an optical potential sufficiently random to produce localized optical modes. A 3 mm pathlength cuvette containing a 12 mg/mL solution of DsRed protein was placed between layers 30 and 31 and the entire assembly was pumped at 1 kHz along the stacking axis either by the second harmonic from a Nd:YLF DPSS laser (529 nm, ~100 ns pulse width) or by the output of a femtosecond OPA (560 nm central wavelength, 35 fs pulse width). High intensity, narrow emission peaks appeared at wavelengths between 605 and 625 nm for per-pulse pump energies greater than 1.8 mJ for nanosecond pumping but this threshold lowers to 2 µJ with femtosecond pumping, an improvement of 3 orders of magnitude. Typically, lasing occurred in several spectral modes simultaneously while the number and position of the modes were dependent on pumping different positions in the transverse plane of the stack as each new position corresponded to a different random cavity configuration.

Application to spectroscopy and imaging will be discussed.

8611-16, Session 4

Single-beam fiber laser sources for CARS microscopy

Martin Baumgartl, Thomas Gottschall, Mario Chemnitz, Friedrich-Schiller-Univ. Jena (Germany); Tobias Meyer, Friedrich-Schiller-Univ. Jena (Germany) and Institut für Photonische Technologien e.V. (Germany); Javier Abreu-Afonso, Univ. de València (Spain); Cesar Jauregui-Misas, Friedrich-Schiller-Univ. Jena (Germany); Benjamin Dietzek, Friedrich-Schiller-Univ. Jena (Germany) and Institut für Photonische Technologien e.V. (Germany); Manfred Rothhardt, Institut für Photonische Technologien e.V. (Germany); Jürgen Popp, Friedrich-Schiller-Univ. Jena (Germany) and Institut für Photonische Technologien e.V. (Germany); Antonio Díez, Univ. de València (Spain); Jens Limpert, Friedrich-Schiller-Univ. Jena (Germany); Andreas Tünnermann, Friedrich-Schiller-Univ. Jena (Germany) and Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

In this contribution we present the development of compact fiber laser sources for multi-photon and, especially, coherent anti-Stokes Raman scattering (CARS) microscopy. Optical-parametric amplification in photonic-crystal fibers is used to generate the required wavelength set for the CARS process. Hence, the generated pump and Stokes pulses for CARS are emitted from a single fiber end, thus being intrinsically overlapped both in space and time. This approach allows for ultra-compact all-spliced fiber setups with direct fiber delivery to the microscope. Moreover, the single-beam output drastically simplifies the alignment requirements for the user.

A narrowband mode-locked all-fiber oscillator, generating ps pulses with low repetition rate was developed. Based on this oscillator an all-spliced and, therefore, completely alignment-free 20ps all-polarization-maintaining fiber source with a repetition rate of 2MHz was realized, emitting pulses around 800nm and 1030nm, simultaneously. High-quality multimodal imaging of biological tissue, using both second harmonic generation and CARS in the CH-stretching band, is presented with this source. Furthermore, ultra-high spectral resolution (down to 1/cm) and wide tuneability (2300-3800/cm and 1200-1900/cm) could be obtained using a similar fiber laser with an additional cw-seed for the generation of 65ps pulses at 1MHz. The narrow linewidth of the laser allows for a very high resonant signal to non-resonant background ratio. Moreover, tuning this laser around 890nm (pump) and 1250nm (Stokes), the imaging of a human aorta section is performed at 2850 and 2930cm-1. This allowed distinguishing between proteins and lipids due to their different ratios of CH2/CH3 functional groups. The compact-size, robust and inexpensive fiber laser concept presented herein opens the door for the application of CARS in clinic environments.

8611-17, Session 4

Tunable picosecond Tm fiber laser centered at 2 µm

Youngjae Kim, Bryan Burgoyne, Alain Villeneuve Jr., Guido Pena, Genia Photonics Inc. (Canada)

Thulium (Tm)-doped fiber lasers have generated a lot of interest due to characteristics such as their eye-safe 2 ?m wavelength, broad gain bandwidth (between 1.8 ?m-2.1 ?m) and high power. Numerous applications have been developed with Tm fiber lasers; remote sensing, mid-IR spectroscopy with DFG, LIDAR and pump for optical parametric oscillator (OPO) only to name a few.

Picoseconds tunable lasers around 2 ?m are relevant for the research and development of special optical fibers for supercontinuum generation. Picoseconds tunable Tm fiber lasers offer all the advantages of fiber lasers (stability, robustness) plus short pulse duration and fast wavelengths tunability to optimally pump various OPOs. It is also worth noting that various nonlinear mid-IR spectroscopic techniques are also feasible by using pulsed tunable Tm fiber lasers. As Thulium CW tunable laser, picoseconds fiber laser and femtoseconds tunable fiber laser have been developed and demonstrated in literature, very few has been reporting picoseconds tunable lasers using Tm fiber.

We demonstrate here a fully programmable, rapidly tunable (more than 1 000 000 wavelengths per second) picoseconds Tm fiber laser. We used a chirped fiber Bragg grating (CFBG) as a dispersive element, which has dispersion of -12 ps/nm and reflectivity of 70 % at 1950 nm. FWHM of the CFBG is 100 nm and the center wavelength is 1950 nm. The optical pulse width is 130 ps. Repetition rate is 10 MHz and time average power is 1 W over the whole wavelength range. The results of another laser centered at 2050 nm will be discussed.

8611-18, Session 4

100-fs-level diode-pumped Yb-doped laser amplifiers

Martin Delaigue, Amplitude Systèmes (France); Julien Pouysegur, Amplitude Systemes (France); Sandrine Ricaud, Clemens Hoenninger, Eric P. Mottay, Amplitude Systèmes (France)

Ultrashort pulse lasers with pulse duration on the level of 100 fs can be used for à variety of interesting applications that rely on multiphoton processes or ultrafast dynamics. Up to now, this field was reserved to Ti:sapphire-based laser systems that exhibit a quite complex laser architecture and relatively low laser efficiency. This may be an important reason why such applications could not yet penetrate into large scale industrial applications.

We have realized an Yb-doped tungstate-based regenerative amplifier in innovative amplifier architecture. We succeeded to produce 106-fs-pulses at 70µJ and 140 fs at 40 µJ pulse energy, respectively. The average power is on the level of several Watts. The optimized management and exploitation of dispersive and nonlinear effects during the amplification process inside the regenerative amplifier cavity enabled the generation of such short pulses with excellent temporal quality and in an extremely simple and robust laser architecture that is well suited for industrial environments.

Applying the same amplifier architecture to an Yb:YAG thin disk regenerative amplifier enabled the generation of pulses as short as 360-fs at high pulse energies exceeding 200 µJ and high average powers of more than 30 W.

8611-19, Session 4

A new small-package super continuum light source for optical coherence tomography

Sven Meissner, Peter Cimalla, Universitätsklinikum Carl Gustav Carus Dresden (Germany); Björn Fischer, Fraunhofer-Institut für Zerstörungsfreie Prüfverfahren (Germany); Christopher Taudt, Tobias Baselt, Peter Hartmann, Westsächsische Hochschule Zwickau (Germany); Edmund Koch, Universitätsklinikum Carl Gustav Carus Dresden (Germany)

Broadband light sources provide a significant benefit for OCT imaging concerning the axial resolution. Light sources with bandwidths over 200 nm result in an axial resolution up to 2 microns. Such broad band OCT imaging can be achieved utilizing super continuum light sources. The main important disadvantage of commercial SC light sources is the overall size and the high costs. Therefore, the use of SC light sources in small OCT setups and applications is limited. We present a new small housing and cost-effective light source, which is suitable for OCT imaging. The light source was coupled in a dual band OCT system.

In this test measurement a plastic foil was used as a sample, which is composed of several plastic film layers. Three dimensional images were acquired simultaneous with the dual band OCT setup. The images were acquired at an A-scan rate of 1 kHz. The 1 kHz A-line rate was chosen because so far the optical power of the light source is not optimal for high speed OCT imaging. The source provides 2 mW in the range of 390 nm to 800 nm and 25 mW in the range from 390 nm to 1650 nm.

Nevertheless, we demonstrated that this new small-package and cost-effective light source is very suitable to carry out OCT imaging. The use of this light source can open up new OCT applications, which require OCT setups with very high axial resolution and small footprint.

8611-20, Session 4

Defense of fake fingerprint attacks using a swept source laser optical coherence tomography setup

Sven Meissner, Technische Univ. Dresden (Germany); Ralph Breithaupt, Bundesamt für Sicherheit in der Informationstechnik (Germany); Edmund Koch, Technische Univ. Dresden (Germany)

The most established technique for the identification at biometric access control systems is the human fingerprint. While every human fingerprint is unique, fingerprints can be faked very easily by using thin layer fakes. Because com-mercial fingerprint scanners use only a two-dimensional image acquisition of the finger surface, they can only hardly differentiate between real fingerprints and fingerprint fakes applied on thin layer materials.

A Swept Source Laser OCT system (20kHz) was used to acquire fingerprints and finger tips with overlying fakes. Three-dimensional volume stacks with dimensions of 4.5mm x 4mm x 2mm of the finger tip were acquired. In this feasibility study, approximately 7800 volume stacks of 226 test persons and 10 bodies were acquired. Furthermore, 3000 volume stacks of faked finger prints were taken. The layering arrangement of the imaged finger tips and faked finger tips was analyzed and subsequently classified into real and faked fingerprints.

The manual classification of the acquired data results in 100% accuracy concerning the differentiation between real and faked fingerprints. Additionally, several parameters of the dermatological tissue beneath the finger tip, which al-lows an automatic differentiation between real fingerprint and faked fingerprint, were defined.

We demonstrated that OCT is a very useful tool to enhance the performance of biometric control systems concerning attacks with finger print fakes.

8611-21, Session 5

Fiber amplifier with <300-fs pulses, 55 W average power, and >50 µJ pulse energy

Clemens Hoenninger, Franck Morin, Yoann Zaouter, Eric P. Mottay, Amplitude Systèmes (France)

Femtosecond fiber lasers are interesting because of their high performance and high optical efficiency. Extremely short pulses in the range below 300 fs, pulse energies of several 10 µJ, and excellent beam quality radiation can readily be produced from photonic crystal single mode fibers with large mode areas. Highly efficient compressor architectures allow the production of high average powers that are necessary for industrial applications demanding high throughput.

We have demonstrated an industrial femtosecond Yb-doped fiber laser producing 55 W average power and up to 60 µJ pulse energy. Even higher extracted pulse energies are possible, however, on the expense of a degraded temporal quality of the femtosecond pulses after pulse compression because of overdriven nonlinear effects. Up to a the 60-µJ-level, the pulses are shorter than 300 fs corresponding to a peak power of up to 200 MW. With a pump power of 107 W we could produce 55 W of average output power after the compressor corresponding to an optical efficiency of more than 50%.

The ultrashort pulses could be frequency doubled with a good efficiency of as high as 60%. Thus, 50-µJ pulses of infrared radiation were doubled to 30µJ pulses at 515nm in the green spectral region.

This laser source is ideally suited for high-end industrial applications as e.g. the selective ablation in thin film photovoltaics or comparable applications on delicate materials and substrates.

8611-22, Session 5

3D ultrafast laser scanner

Ata Mahjoubfar, Univ. of California, Los Angeles (United States) and California NanoSystems Institute (United States); Keisuke Goda, Univ. of California, Los Angeles (United States) and California NanoSystems Institute (United States) and Univ. of California, Los Angeles (United States); Chao Wang, Univ. of California, Los Angeles (United States); Ali M. Fard, Univ. of California, Los Angeles (United States) and California NanoSystems Institute (United States); Jost Adam, Univ. of California, Los Angeles (United States); Daniel R. Gossett, Univ. of California, Los Angeles (United States) and California NanoSystems Institute (United States); Ali Ayazi, Elodie Sollier, Omer Malik, Evan Chen, Yaqiao Liu, Rebecca Brown, Niusha Sarkhosh, Univ. of California, Los Angeles (United States); Dino Di Carlo, Univ. of California, Los Angeles (United States) and California NanoSystems Institute (United States); Bahram Jalali, Univ. of California, Los Angeles (United States) and California NanoSystems Institute (United States) and Univ. of California, Los Angeles (United States)

Laser scanners are an essential tool for scientific research, manufacturing, defense, and medical practice. They are used in a variety of applications including light detection and ranging (LIDAR), non-destructive evaluation, geographical survey, machine vision, laser TV systems, endoscopy, and cytometry. Unfortunately, often times the speed of conventional laser scanners (e.g., galvanometric mirrors and acousto-optic modulators) falls short for many applications, resulting in motion blur and failure to capture fast transient information. Here we present a novel type of laser scanner that offers roughly three orders of magnitude higher scan rates than conventional methods. Our laser scanner, which we refer to as the hybrid dispersion laser scanner, performs inertia-free laser scanning by dispersing a train of broadband pulses both temporally and spatially. More specifically, each broadband pulse is temporally chirped in a highly dispersive fiber and further dispersed into space by one or more diffractive elements such as prisms and gratings. As a proof-of-principle demonstration, we perform 1D line scans at a record high scan rate of 91 MHz and 2D raster scans and 3D volumetric scans at an unprecedented scan rate of 100 kHz. The method holds great promise for a broad range of scientific, industrial, and biomedical applications. To show the utility of our method, we demonstrate high-speed imaging, nanometer-resolved surface vibrometry, and high-precision flow cytometry with unique capabilities that conventional laser scanners cannot offer due to their low scan rates.

8611-23, Session 5

10GW diode-pumped femtosecond laser based on Yb:CaF2

Antoine Courjaud, Vincent Clet, Amplitude Systèmes (France); Patrice Camy, Jean-Louis Doualan, Richard Moncorgé, Ecole Nationale Supérieure d'Ingenieurs de Caen et Ctr. de Recherche (France); Eric P. Mottay, Amplitude Systèmes (France)

Among all the numerous applications of ultrafast lasers, some require high peak power, for secondary sources such as THz or Xray generation, or analysis such as LIBS or ICPM [1,2]. Those applications require compact and stable systems, at high repetition rate. Diode-pumped technology is a solution of choice to address those requirements,

Recently, we demonstrated the broad tunability of Yb:CaF2 at room temperature from 1030 to 1065nm in Q-switched regime, with an optimal pulse energy around 1050nm [3]. We report here on an ultrafast laser based on an Yb:CaF2 regenerative amplifier operating in the multi-millijoule regime at a repetition rate around 100Hz.

The laser consists in an ultrafast fiber oscillator delivering pulses with 10nm bandwidth, at a central wavelength of 1053nm, a grating based stretcher, a regenerative amplifier based on a Yb:CaF2 crystal pumped by a CW 15W fiber-coupled laserdiode, and a grating based compressor.

The regenerative amplifier delivers 5mJ pulses at 100Hz repetition rate, and 4mJ at 300Hz, at a central wavelength of 1048nm, with a bandwidth of 6nm. The amplified pulses are subsequently compressed to a pulse duration of 320fs, with a pulse energy of 3,2mJ at 100Hz and 2,7mJ at 300Hz, corresponding to a peak power exceeding 10GW. The beam quality is excellent, and the pulse-to-pulse stability is 0,3% rms. Efficient frequency doubling and quadrupling were performed, corresponding to 524 and 262nm respectively.

8611-24, Session 5

Simultaneous measurement of two ultrashort pulses at different wavelengths using double blind polarization-gate frequency-resolved optical gating

Tsz Chun Wong, Rick Trebino, Georgia Institute of Technology (United States)

Most modern ultrafast-optical labs have more than one pulse that must be simultaneously measured. In addition, these pulses usually have different center wavelengths and complexities. Thus, a device capable of measuring a pair of independent pulses without limitations would be very useful. Here, we demonstrate Double Blind Polarization Gate Frequency Resolved Optical Gating (DB PG FROG) for measuring a pair of independent unknown ultrashort pulses with different center wavelengths and complexities.

DB PG FROG is nearly identical to its well-known cousin, PG FROG, except that, rather than a single pulse gating itself, as in PG FROG, two different pulses enter the device, and each gates the other, generating two FROG traces. Here, we measure a pair of pulses with center wavelengths of 400nm and 800nm, recording the two resulting FROG traces. The DB PG FROG pulse-retrieval algorithm returned the pulses with FROG errors of 0.31% and 0.30% for the 400nm and 800nm pulses respectively. The time-bandwidth product (TBP) of both pulses is about 1.1. We also measured a double pulse at 800nm (TBP = 6) and a simple 400nm pulse. The 400nm pulse was retrieved with 0.83% FROG error, and the 800nm pulse with 0.51% FROG error, indicating good measurements.

Our results show that DB PG FROG is not only capable of measuring unknown pairs of pulses with very different center wavelengths, but also with very different complexities. Future work will focus on measuring a simple pulse and a complex pulse simultaneously on a single shot. This may lead to single-shot measurement of extremely complex pulses, such as super-continuum generated in optical fibers.

8611-25, Session 5

New, simplified algorithm for cross-correlation frequency resolved optical gating

Daniel J. Kane, Mesa Photonics, LLC (United States)

Frequency Resolved Optical Gating (FROG) uses the ultrafast laser pulse to interrogate itself for full characterization; that is, no reference pulse is used to obtain the full intensity and phase of the input ultrafast laser pulse. Cross-correlation FROG (X-FROG) cross-correlates a known ultrafast laser pulse with an unknown ultrafast laser pulse to characterize the unknown pulse allowing wider wavelength ranges of ultrafast laser pulses as well as very complex ultrafast laser pulses to be characterized. The easiest and fastest FROG algorithm (and in some cases the most robust) is the principal components generalized projections (PCGP) algorithm; however, its applications have been limited to only either two FROG geometries (second harmonic generation (SHG) and polarization-gate (PG)) or blind FROG retrievals. Using the PCGP algorithm with a known pulse together with unknown pulse often results in stagnation. Using the blind FROG algorithm for X-FROG applications can result in large errors especially when the pulses are similar in shape and duration. As a result, X-FROG retrieval algorithms are based on the standard generalized projections implementation of the FROG algorithm where the known pulse is an input and held fixed. In this work, we present our recently developed PCGP X-FROG algorithm, its derivation and demonstrate its use. Robust and fast, it is the simplest of all the PCGP FROG algorithms.

8611-26, Session 5

The coherent artifact in modern pulse measurement

Michelle Rhodes, Georgia Institute of Technology (United States); Günter Steinmeyer, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany); Justin Ratner, Rick Trebino, Georgia Institute of Technology (United States)

We simulate multi-shot measurements of unstable pulse trains using a variety of pulse-measurement techniques, including spectral phase interferometry for direct electric-field reconstruction (SPIDER), second-harmonic-generation (SHG) frequency-resolved-optical-gating (FROG), polarization gate (PG) FROG, and cross-correlation FROG (XFROG). Two pulse trains were constructed to have random and nonrandom components of equal energy. The random components of these trains were smoothed by different amounts to yield two trains of different average time-bandwidth products and pulse durations.

We find that SPIDER ignores the random component of the pulses, measuring only the coherent artifact for an unstable pulse train. This result was confirmed by an analytical calculation, and is actually obvious because interferometric methods in general are not sensitive to random phase variations. FROG measurements yield varying pulse lengths, likely a result of the details of the random trains. More importantly, FROG measurements are more likely to yield the actual temporal structure typical of the pulses in the train. In addition, all FROG measurements of these trains have clearly visible differences between measured and retrieved traces, providing an indicator of instability. The only indicator of instability in SPIDER is the presence of background, but background in SPIDER also comes from a variety of benign alignment effects and so is usually ignored. Thus pulse-length claims from SPIDER measurements alone must be re-examined. In summary, only 100% SPIDER fringe visibility (which is very rare) or good FROG trace agreement imply a stable pulse train.

8611-27, Session 5

Temporal self-reconstruction of few-cycle nondiffracting wavepackets

Stefan Koenig, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany); Martin Bock, Susanta K. Das, Alexander Treffer, Ruediger Grunwald, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany)

Recently we demonstrated the generation of programmable, highly localized few-cycle wavepackets from Ti:sapphire laser oscillator pulses by shaping with a reflective phase-only liquid-crystal-on-silicon spatial light modulator (LCoS-SLM). In particular, quasi nondiffracting Bessel-like beams without radial oscillations which we refer to as needle beams can be formed and adaptively corrected for aberrations with such a setup. Because of a number of advantageous properties like excellent temporal transfer and spatial self-reconstruction, needle beams are of growing interest for applications in nonlinear spectroscopy, optical pumping, free-space data transfer, microscopy, metrology and materials processing. Here we report for the first time on the self-reconstruction properties of 6-fs pulsed needle beams in time domain. To study the temporal pulse recovery with low contribution of diffraction, a pulse-lengthening spectral distortion was realized by locally inserting thin (100 micron range) polymer color filters suppressing the blue part of the spectrum. By shading different percentages of the area of particular elements in an array of programmable axicons, a multichannel detection of self-reconstruction under variable conditions was enabled. Pulse duration maps of needle beam arrays were measured with 2D second order autocorrelation with a BBO crystal as nonlinear converter and an EMCCD camera as sensitive detector. Completely distorted pulses had an FWHM pulse duration of > 13 fs. Partially distorted sub-beams were found to undergo a temporal recovery back to pulse durations of about 7 fs. Applications for the temporal encoding of data and other fields are proposed.

8611-28, Session 6

Femtosecond laser writing of lab-on-a-fiber: integrating interferometers and microfluidics

Moez Haque, Kenneth Lee, Univ. of Toronto (Canada); Luís Andre N. A. Fernandes, Univ. of Toronto (Canada) and Univ. do Porto (Portugal); Jason R. Grenier, Kyle Cheng, Peter R. Herman, Univ. of Toronto (Canada)

Biological and chemical laboratory processes are continuously being investigated towards miniaturization and integration of bulky free-space systems to more compact and functional lab-on-chip devices. Chemical analysis and synthesis, sample preparation, mixing and particle sorting are examples that may benefit from further reduction onto a new generation of "lab-on-a-fiber" (LOAF) devices that wrap microfluidic and optical components around the guiding core waveguide of standard optical fiber. The pure silica cladding now widely used in many types of standard and photonic crystal fiber presents an ideal platform that naturally facilitates intimate optical interrogation of microfluidic and micro-reactor components on a large and standard base of existing fiber optics technology.

Device fabrication onto coreless fiber further introduces facile 3D positioning of waveguides to shape directional couplers, Y-splitters, interferometers and Bragg-grating-waveguides for interrogating microfluidic components that we aim to develop inside the fiber cladding towards highly sensitive flow sensors and cytometers. LOAF 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 processing and hydrofluoric acid etching recipes for development of a LOAF Mach-Zehnder interferometer. Coreless fibers were exposed with a focused Yb-fiber amplified femtosecond laser for direct-laser-writing of microfluidic channel, reservoir and waveguide templates. Subsequent hydrofluoric acid etching opened the microfluidic channels and reservoirs that together yielded the integrated optofluidic LOAF device for refractive index sensing of fluids. Such optofluidic fiber devices were successfully fusion spliced with standard optical fiber, offering a simple low cost and highly efficient packaging solution for numerous application directions.

8611-29, Session 6

High aspect ratio nanofiber formation due to sub-surface, high repetition rate, ultrashort laser irradiation of transparent dielectrics

Mark Ramme, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); Arnaud Royon, Thierry Cardinal, Univ. Bordeaux 1 (France); Martin Richardson, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); Lionel S. Canioni, Univ. Bordeaux 1 (France)

Previous studies have reported that surface irradiation of PMMA with an excimer laser has led to the generation of nanofibers. At fluences higher than necessary for surface ablation, free-standing fibers were created with diameters of a few hundred nanometers and lengths of several micrometers. Such fibers were also generated by laser spinning, in which a beam from a CO2 laser is incident on a surface and assisted by a gas jet from a supersonic nozzle.

Focused fs-laser radiation inside the bulk of transparent dielectrics causes nonlinear absorption solely in the focal volume and can lead to the local modification of the material properties. High repetition rate laser irradiation of transparent materials has shown to lead to heat accumulation in the focal volume. This heat accumulation can lead to local temperatures beyond the melting point of the material.

Here we present the formation of nanofibers on different transparent dielectrics (fused silica, soda lime glass) due to sub-surface ultrashort irradiation with high repetition rate lasers, from 1 to 10 MHz. Free-standing fibers, similar to such created by laser spinning, with diameters of about a hundred nanometers and lengths up to hundreds of micrometers, were produced without assistance of any gas jet. The dependence of the fiber-formation on focusing depth and pulse energy has been investigated. We report on the evolution of the heat expansion from the focal volume with respect to the number of pulses and its dependence on the fiber formation. A phenomenological explanation of the formation process will be given.

8611-30, Session 6

Femtosecond laser fabrication of optical sensing circuits in the coreless optical fibers

Jason R. Grenier, Moez Haque, Univ. of Toronto (Canada); Luís Andre N. A. Fernandes, Univ. of Toronto (Canada) and Univ. do Porto (Portugal); Kyle Cheng, James S. Aitchison, Univ. of Toronto (Canada); Paulo V. S. Marques, Univ. do Porto (Portugal); Peter R. Herman, Univ. of Toronto (Canada)

Femtosecond laser direct writing in bulk transparent dielectric materials is an established single-step technique for generating three-dimensional (3D) optical circuit devices that cannot be fabricated with traditional, lithography-based techniques. Fabricating these devices in the cladding of optical fibers to develop highly function integrated optical and optofluidic devices represents a highly attractive direction for expanding the frontiers of ultrafast laser fabrication while extending the range of possible functions available on this compact and highly utilized platform.

In this work, second harmonic (522 nm), high repetition rate (500 kHz) femtosecond laser pulses were tightly focused into optical fibers using oil-immersion optics to avoid spherical and astigmatic optical aberrations and thereby drive stronger interactions that can form low loss waveguides (0.65 dB/cm) including strong Bragg grating responses (35 dB). Directional couplers and Y-splitters of predetermined splitting ratios were optimized inside coreless fibers to enable the simultaneous probing of multiple distributed devices, which was not possible using a single mode fiber (SMF) owing to the dissimilar propagation constants of the core and laser-formed waveguides. The coreless fiber sections were successfully spliced to SMF fiber top present highly efficient packaging opportunities that bypass the complex steps of fiber pig-tailing to otherwise large-sized optical circuits. Microfluidic channels were also laser-defined and opened up with HF etching, permitting light guiding structures to evanescently probe their contents to make sensitive refractive index measurements. The goal is to create compact and functional optical and optofluidic microsystems for sensing by moving towards the integration of complex laboratory diagnostics within the compact optical fiber cladding.

8611-31, Session 6

The influence of distributed rare earth dopant on the performance of waveguide lasers fabricated by the femtosecond laser direct-write technique

Yuwen Duan, Aaron M. McKay, Peter Dekker, Michael Steel, Michael J. Withford, Macquarie Univ. (Australia)

We present a modified model analyzing the propagation of the pump and signal power in an Yb-doped DBR waveguide laser fabricated using femtosecond laser pulses. Conventional gain dynamic models, routinely used to study fibre lasers, use a fixed mode overlap coefficient to define the fraction of the power overlapped with the doped core. This approach is valid when the dopant is confined to the core only. However, these

models are not suitable for femtosecond laser written waveguide lasers because the rare-earth dopants are distributed not only in the waveguide but also in the glass surrounding the waveguide. Consequently, in the modified model, special emphasis was given to the transverse energy distribution along the waveguide in order to investigate how the doped "cladding" influences laser performance. The model was validated with experiments comparing a DBR fiber and a waveguide laser. The model can also be used to determine the parameters that can optimize the laser performance. It was found that additional pump and signal absorption by the doped "cladding" reduces laser output power by up to 15%. The optimal waveguide length for a DBR waveguide laser with and without doped "cladding" was also calculated to be 9 mm and 10 mm respectively for the highest output power and slope efficiency. The laser performance can be further optimized by increasing the refractive index contrast of the waveguide and adjusting the reflectivity of the output coupler to around 55%.

8611-32, Session 7

Volume scattering optics fabrication by ultrashort pulse lasers *(Invited Paper)*

Rafael Piestun, Univ. of Colorado at Boulder (United States)

No Abstract Available

8611-33, Session 7

The underlying structure of ultrashort pulse laser-induced nanogratings

Felix Zimmermann, Sören Richter, Friedrich-Schiller-Univ. Jena (Germany); Anton Plech, Karlsruher Institut für Technologie (Germany); Sven Döring, Matthias Heinrich, Michael Steinert, Friedrich-Schiller-Univ. Jena (Germany); Ulf Peschel, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany); Ernst-Bernhard Kley, Friedrich-Schiller-Univ. Jena (Germany); Andreas Tünnermann, Stefan Nolte, Friedrich-Schiller-Univ. Jena (Germany) and Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

I would like to participate in the student competition.

Sub-wavelength structures are a crucial ingredient for modern optics. A class of ultrashort laser pulse induced, self-organized modifications in bulk transparent materials have attracted particular interest in recent years.

Despite the multitude of potential applications of these so-called "nanogratings", their underlying structure on the nanometer scale has been the subject of intensive debate throughout the decade since their discovery: Are they merely continuous modulation patterns of the material density, or do they consist of a substructure of hollow cavities? As nanogratings are embedded within the bulk material the conventional visualization technique relies on polishing and subsequent etching to excavate the modifications. However, such invasive sample preparation effectively erases sub-100nm features. Moreover, they only provide access to two-dimensional cross sections.

To overcome these limitations, we employed small angle X-ray scattering (SAXS), focused ion beam (FIB) milling and scanning electron microscopy (SEM) to reveal the underlying three-dimensional structure of nanogratings.

Our results show that small cavities are the primary constituents of the nanogratings.

These cavities grow predominantly during the first 100 laser pulses and reach a final size of about 30x200x300 nm?. Prolonged exposure to laser pulses increases the absolute number of cavities. Their three-dimensional arrangement forms characteristic periodic planes of nanogratings.

8611-34, Session 7

Dense arrays of microscopic optical vortex generators from femtosecond direct laser writing of radial birefringence in glass

Arnaud Royon, Lionel S. Canioni, Etienne Brasselet, Univ. Bordeaux 1 (France)

Femtosecond direct laser writing (fs-DLW) has been found useful to fabricate singular micro-optical elements, namely, structures enabling the generation of light fields endowed with phase and/or polarization singularities. Here, we report on the single-point fs-DLW production of radial birefringence in a glassy material with an energy budget that is more than 100 times smaller than previously reported. This is made possible by using photo-thermo-refractive (PTR) glass that has a similar composition as soda-lime glass, apart the presence of silver. Indeed the addition of photosensitive agents, such as silver, allows enhancing the light-induced material modifications while minimizing the energy budget.

The laser-written structures consist in microvoids surrounded by an over-dense shell. The radial birefringence origins from a thermally affected zone surrounding the microvoids. This thermally affected zone is created from pulse after pulse heat accumulation, due to the high repetition rate (10 MHz) of the writing laser.

Moreover, we show that such a light-induced radial birefringence allows for the realization of microscopic optical vortex generators via a spin-to-orbital optical angular momentum conversion process, which mimics the principle of operation of optical vortex generators based on radially ordered liquid crystal droplets. The measured spin-to-orbital angular momentum conversion efficiency ? is on the order of 3?10-3, leading from a simple model to a radial birefringence ?n of about 3?10-4. Since the obtained singular light mode converters are permanently inscribed in glass at predetermined locations, dense arrays of them can be readily achieved and here we report on surface densities up to 10^4 cm-2.

8611-35, Session 7

Birefringence tuning in fused silica waveguides by femtosecond laser-induced stress

Luís Andre N. A. Fernandes, Univ. of Toronto (Canada) and Univ. do Porto (Portugal); Jason R. Grenier, Peter R. Herman, James S. Aitchison, Univ. of Toronto (Canada); Paulo V. S. Marques, Univ. do Porto (Portugal)

Waveguides fabricated with femtosecond laser exposure have been found to have birefringence inherent from anisotropic stress, created by the nonlinear absorption in the material, as well as strong form birefringence arising from nanogratings, with orientations dependent on the polarization of the writing laser. The possibility of tuning the waveguide birefringence in bulk fused silica glass was studied with the fabrication of stress inducing modification tracks that were positioned with different geometries around the waveguides. Femtosecond laser exposures with 300 fs pulse duration, 500 kHz repetition rate and 522 nm center wavelength were applied with different pulse energies and polarizations to vary the strength of the stress inducing laser modified tracks as well as the alignment of nanograting structures. Polarization splitting of Bragg grating waveguides revealed that the waveguide birefringence was tunable over a widely useful range of ~0 to 4.35?10^{-4} with a precision of 4?10^{-6}. This waveguide birefringence modification did not appear to arise from the local material stress or nanograting generated form birefringence inside the stress tracks, but rather from a longer range stress that either enhanced or diminished the inherent waveguide birefringence which was 6.6?10^{-5} and 1.87?10^{-4}, respectively, for nanograting alignments that were oriented perpendicular or parallel to the waveguide direction. This range of birefringence tuning can possibly enable great flexibility in designing polarization dependent devices, like waveguide retarders and polarization beam splitters into more compact devices, as well as the possibility of

making polarization independent devices by reducing polarization mode dispersion.

8611-36, Session 8

Adaptive control of pulse front tilt, the quill effect, and directional ultrafast laser writing

Patrick Salter, Richard D. Simmonds, Martin Booth, Univ. of Oxford (United Kingdom)

The "quill effect" describes a curious directional phenomenon frequently encountered during ultrafast fabrication of subsurface continuous structures. Even in a homogeneous and isotropic material, such as fused silica, the fabrication regime experienced can be dependent on the direction of motion relative to the optic axis. The directionality has been attributed to a tilt of the pulse front relative to the incident wavefront, leading to a spatiotemporal asymmetry in the focal plane. Here we use a liquid crystal spatial light modulator (SLM) to demonstrate and control the quill effect when using a femtosecond laser for bulk fabrication of fused silica. A pulse front tilt can be introduced to the fabrication beam by applying a blazed grating to the SLM, and tuned by varying the grating periodicity. As a result, the fabricated features generated when moving the substrate in opposite directions relative to the tilt are different. Reversing the blazed grating switches the effect, confirming the fabrication dependence on the pulse front tilt. However, it is additionally shown that inhomogeneous pupil illumination can cause similar directionality in the fabrication, through a simple spatial asymmetry in the focal intensity distribution. We show that the pupil illumination profile can likewise be controlled adaptively by the SLM and that directional effects can be dynamically introduced during fabrication. Further possibilities are considered for higher order control of ultrashort pulses using combinations of adaptive optical elements.

8611-37, Session 8

Femtosecond Laser Ablation Properties of Transparent Materials: Impact of the laser process parameters on

the machining throughput

Victor V. Matylitsky, Juerg Aus-der-Au, High Q Laser, a Newport Corp. Brand (Austria); Frank Hendricks, High Q Laser a Newport Corp Brand (Austria)

Ultrafast laser systems, with pulse duration in the femtosecond time range, have proven their potential in many material processing applications. The unique advantages of the ultrafast lasers i.e. high ablation efficiency and accuracy of ablated structures on metal as well as on dielectric targets were demonstrated in many studies. Although the achieved processing quality meets industrial demands, processing speed should be improved in order to satisfy an economical industrial use. Therefore, ultrafast laser systems with high average power and repetition rate are required in order to overcome this problem. Additionally, ultrashort pulse lasers have to be compact and industrially reliable.

A one-box commercial SpiritTM laser system based on an Yb-doped chirped pulse regenerative amplifier provides flexible repetition rates up to 1 MHz with pulses as short as 400fs. An average power of 2, 4 and 8 W is achievable all within the same compact housing. Additionally, single pulse and burst energies can be dialed freely without the usual first pulse effects. The newest generation of SpiritTM lasers permits fully automated control of the pulse duration between ~400 fs and ~10 ps. In this paper, we will give an overview of actual applications for ultrashort pulse lasers for industrial micro-processing. The study on the impact of the laser processing parameters on the removal rate for chemically strengthened transparent substrate using femtosecond laser pulses will be presented. In particular, examples of micro-processing of Corning Gorilla glass machined with SpiritTM ultrafast laser will be shown.

8611-38, Session 8

Wavelength dependence of femtosecond laser interactions confined inside bandgap solids

Stephanie Leyder, David Grojo, Philippe Delaporte, Maxime Lebugle, Lasers, Plasmas et Procédés Photoniques (France); Wladimir I. Marine, CINaM - Ctr. Interdisciplinaire de Nanoscience de Marseille (France); Nicolas Sanner, Marc L. Sentis, Olivier P. Utéza, Lasers, Plasmas et Procédés Photoniques (France)

In the past decade, direct writing with focused femtosecond laser pulses at fundamental wavelength has emerged as a technique for microfabrication inside transparent dielectrics. To develop similar technologies for semiconductors, it is required to work with longer wavelength femtosecond lasers.

We perform an experimental study of the multiphoton-avalanche absorption yields and thresholds with tightly focused femtosecond laser beams over a wavelength range of 1300-2200nm. We concentrate on silicon (BG=1.1 eV) which remains the basis materials for microelectronics and telecommunication applications. For comparisons, we repeat the same experiments in a large bandgap material: fused silica (BG=9eV). The number of photons required to span the band gap increases from two to three in silicon and from ten to sixteen in fused silica in this wavelength range. Then we can compare a low order multiphoton interaction situation to highly nonlinear laser interaction experiments.

In the experiments, femtosecond laser pulses from an optical parametric amplifier are tightly focused inside materials. Integrating spheres are used to measure the total transmission of pulses as a function of input pulse energy. Through the measurements, we estimate the intensity threshold above which non-linear absorption is initiated for all conditions tested (material, wavelength). For both materials, we find that the femtosecond laser energy deposition at micron scale is nearly independent on the wavelength. While we concentrate this study on the understanding of laser energy deposition, our work aims at opening a possibility for new laser processing applications inside semiconductors by using mid-infrared wavelength femtosecond lasers.

8611-39, Session 8

Laser erasing of ultrafast laser written optical waveguides in fused silica glass

Satoru Takahashi, Univ. of Toronto (Canada) and The Univ. of Tokyo (Japan); Jianzhao Li, Peter R. Herman, Univ. of Toronto (Canada)

While the underlying laser interaction physics has not yet been fully understood, ultrafast laser induced refractive index modification inside transparent materials, dominated by silica glasses, has enabled the fabrication of numerous 3-dimensional optical devices including optical waveplates, volume diffractive optical elements, interferometer, beam coupler and splitter, and waveguide lasers. Various laser beam tailoring techniques such as spatial and temporal beam shaping have been investigated in order to understand laser-glass interaction physics and also to harness new interaction pathways that can maximize refractive index modification while reducing optical scattering losses. Here we report the study of ultrafast fiber laser direct writing of optical waveguides in fused silica glass by means of double-pulse laser burst trains. Dependence of waveguide formation on energy splitting and polarization of each of the double pulses as well as pulse-to-pulse time delay (150 ps – 5 ns) was systematically investigated. It was revealed that, irrespective of laser polarization, a novel process window exists for erasure of waveguides at combined exposure exceeding the first pulse modification threshold energy of ~25 nJ. The apparent unraveling of the laser modification dynamics of the first pulse occurred when the second pulse was delayed from ~150 ps to over ~500 ps. The window for waveguide 'erasing' further depended on scanning direction. This novel 'erasing'

effect may be attributed to the second pulse inducing a type of thermal annealing at a critical time of transient lattice distortion or stress that was excited by the first pulse. Time-resolved imaging of laser interaction zone is under investigation with the aim to unravel the relevant physics of the dual-pulsed ultrafast laser glass interaction that may facilitate new directions for optimization of 3D photonic devices.

8611-40, Session 8

Direct laser writing of three-dimensional silver nanostructures and applications

Kevin Vora, SeungYeon Kang, Michael G. Moebius, Eric Mazur, Harvard Univ. (United States)

Recent advances in direct laser writing have led to three-dimensional (3D) fabrication of silver nanostructures embedded inside a polymer matrix with sub-300 nm resolution. The technique enables the single-step fabrication of multiple layers of silver nanostructure arrays that are disconnected in three dimensions. We present applications and characterizations of the 3D silver nanofabrication technique.

We induce the photoreduction of silver ions through nonlinear absorption in a thick polymer film doped with silver salts. The laser parameter space to obtain silver growth varies by several orders of magnitude in exposure times as well as pulse energies. We show the dependence between feature resolution and laser exposure. Due to the nonlinear nature of the optical interaction with chemical precursors, silver-ion photoreduction processes are limited to a focused volume smaller than that of the diffraction-limit. We also fabricate and characterize single- and multi-layered diffraction gratings composed of silver dots. We obtain optical properties of silver nanostructures and show that the fabrication process is suitable for applications in metamaterials.

8611-41, Session 8

Dynamic band collapse in photonic graphene

Giacomo Corrielli, Andrea Crespi, Giuseppe Della Valle, Stefano Longhi, Politecnico di Milano (Italy); Roberto Osellame, Istituto di Fotonica e Nanotecnologie (Italy)

The honeycomb structure of graphene, together with the presence of external electromagnetic driving field, leads to a great variety of intriguing phenomena such as the photovoltaic Hall effect, metal-insulator transition, valley-polarized currents and photo-induced quantum Hall effect. So far, many of these phenomena have only been predicted theoretically and never been observed directly in solid state graphene. For this reason, the possibility to create and simulate the physics of graphene has recently attracted a great interest. Experimentally accessible model systems of graphene with controllable parameters (cold atoms in optical lattices and acoustic simulators among others) have already permitted to observe and demonstrate few of the above mentioned effects.

In our work we realize a photonic simulator for the single electron dynamic in graphene in order to observe partial and complete electronic quasi-energy band collapse induced by the presence of linearly and circularly polarized driving monochromatic electromagnetic field. For this purpose we fabricated several 3D waveguides arrays, arranged in honeycomb structures, with controlled lattice parameter and geometry. The interaction with the AC driving force is simulated via a sinusoidal or a helical bending of the arrays along the paraxial propagation direction and the temporal electronic dynamic is mapped into the spatial evolution of light into the arrays. Such engineered waveguide structures, whose realization was permitted uniquely by the 3D capabilities of femtosecond laser micromachining, successfully enabled the observation of quasi-energy band collapse and confirmed that photonic simulators are good candidate to visualize hard-to-observe coherent quantum phenomena.

8611-42, Session 9

Time-resolved spectroscopy characterization of femtosecond fiber laser induced plasma

Huan Huang, Lih-Mei Yang, Jian Liu, PolarOnyx, Inc. (United States)

This paper reports the studies on time-resolved space-integrated laser induced breakdown spectroscopy (LIBS) of plasmas produced by femtosecond (fs) fiber laser pulses. The temporal behavior of specific ion and neutral emission lines of different materials (metals, glasses and polymers) has been characterized. Spectroscopic diagnostics were used to determine the time-resolved electron density, as well as the optimal temporal gating for LIBS analysis was investigated for different materials. The decay between the continuum plasma emission and the atomic emission were used as a means to maximize the signal-to-noise ratio of the atomic emission lines for different materials. Detection windows were investigated corresponding to delay times from 20 to 35 ns following the plasma-initiating laser pulse. In comparison with plasmas produced by longer laser pulses, the plasma generated by fs laser pulses exhibits a shorter plasma lifetime and a faster thermalization. Advantages attributed to the fs laser LIBS include minimized background continuum and negligible atmospheric entrainment. This fiber laser based LIBS can lead to a more compact, reliable, low-cost and field-deployable detection system for versatile and rapid analysis of chemical and special explosive materials.

8611-43, Session 9

Study on the influence of repetition rate and pulse duration on ablation efficiency using a new generation of high power Ytterbium doped fiber ultrafast laser

John Lopez, Univ. Bordeaux 1 (France); Rémi Torres, ALPhANOV (France); Yoann Zaouter, Clemens Hoenninger, Amplitude Systèmes (France); Patrick Georges, Marc Hanna, Institut d'Optique Graduate School (France); Eric P. Mottay, Amplitude Systèmes (France); Rainer Kling, ALPhANOV (France)

Ultrafast laser are well known to provide cold ablation on metals at near-threshold fluence and low repetition rate. However increasing the repetition rate from multi-kHz to MHz may produce a heat accumulation in the target depending on both the scanning speed and the material properties. This potentially leads to two effects: enhanced ablation efficiency as well as increased heat affected zone. To identify potentials and limitations while maintaining highest processing quality is the main objective of this paper and a key issue for many industrial applications. We present some comprehensive results on the influence of both repetition rate and pulse duration on the ablation efficiency. This investigation is performed using a new generation of high power Ytterbium doped fiber ultrafast laser with a tunable pulse duration ranging from 350fs to 10ps and with repetition rate going from 250kHz to 2MHz. The output power is up to 40 watt. The effect of both parameters above on ablation efficiency of Al, Cu and Mo is discussed with respect to removal rate measurement and SEM analysis.

8611-44, Session 10

Ultrafast lasers for materials processing in consumer electronics *(Invited Paper)*

Haibin Zhang, Electro Scientific Industries, Inc. (United States)

No Abstract Available

8611-45, Session 10

Micro-structuring of thin titanium films with ultra-short laser pulses

Regina Moser, Tobias Gschwilm, Adrian Zacherle, Gerhard Heise, Heinz P. Huber, Hochschule München für Angewandte Wissenschaften (Germany)

Electron beam guns with approximately 100 kW power are used for drying printing colors. As exit window for the electrons, 15 µm thin titanium films are used, their thickness is at the current limit for industrial rolling processes. Thinner exit windows would increase the electron's transmission and therefore reduce the required acceleration voltage, power consumption, shielding against X-rays and in the end machine and processing costs. The titanium films should locally be thinned to about 5 µm, in the ranges of 3 mm diameter.

Ultra-short laser pulses are well known for high precision micro structuring, as they offer small heat effect zones.

We optimized the processing parameters and the ultra-short laser ablation of thin titanium foils to achieve high manufacturing velocity and quality of the surface structure.

Experiments with different parameters were conducted to find the optimum between the high ablation efficiency and a smooth surface with low roughness and in keeping the structured part of the foil vacuum proofed. Single pulse ablation experiments show no dependency of the thresholds on the laser spot diameter, however a dependency was observed between the spot diameter and the ablation efficiency in ablating three dimensional micro structures.

A theoretical model is assuming a dependency of the ablation efficiency on the threshold behavior but no dependency on the spot diameter. In conclusion this simple model, without regard the heat accumulation in the thin titanium foil, is not able to predict multi-pulse phenomena correctly.

8611-46, Session 10

Transient investigations of the laser lift-off process of thin molybdenum films

Matthias Domke, Stephan Rapp, Jürgen Sotrop, Hochschule München für Angewandte Wissenschaften (Germany); Heinz P. Huber, Hochschule München für Angewandte Wissenschaften (Germany)

Ultra-short pulse laser irradiation of thin metal films on glass substrates enables various applications such as laser scribing, the creation of micro structures, or the laser induced forward transfer (LIFT). For example, glass substrate side irradiation of thin molybdenum films initiates a laser lift-off, enabling high speed scribing of the p-contact of a CIS (copper-indium-diselenide) thin film solar cell.

For the investigation of the underlying physics of the lift-off initiated by a 660 fs laser pulse, a pump-probe microscopy setup is utilized to record movies of the ablation process. The ultrafast dynamics in the femtosecond and picosecond range are captured by ultra-short exposure of the sample with an optically delayed probe pulse of 510 fs duration. The nanosecond and microsecond delay range of the probe pulse is covered by an electronically triggered 600 ps-laser.

In addition, the experimental results are compared to a numerical simulation of the glass substrate side ablation of molybdenum films. The simulation is based on the two temperature model. Above the evaporation temperature of molybdenum, an adiabatic expansion of the evaporated molybdenum is assumed. The generated pressure causes the Mo film to bulge.

Both, results and experiment, suggest that a phase explosion generates a liquid-gas mixture of molybdenum at about 10 ps. Then, a shock wave and gas expansion cause the molybdenum layer to bulge after a few 100 ps, while the enclosed liquid-gas mixture cools and condenses. At about 20 ns, an intact Mo disk shears- and lifts-off, leaving a hole free from thermal damages.

8611-47, Session 11

Ultrastable bonding of glass with femtosecond laser bursts

Sören Richter, Felix Zimmermann, Sven Döring, Friedrich-Schiller-Univ. Jena (Germany); Andreas Tünnermann, Stefan Nolte, Friedrich-Schiller-Univ. Jena (Germany) and Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

I would like to participate in the student competition.

We report on the welding of fused silica with bursts of ultrashort laser pulses. The advantage of this technique is tailored energy deposition into the material, which reduced the maximal induced temperature and allows the relaxation of induced tensions. At conventional high repetition rate laser bonding, breaking resistance of up to 75% of the bulk material has been measured previously. By optimizing the burst frequency and repetition rate we were able to achieve significantly higher breaking stress of up to 96%. Thereby reduced stress in the surroundings of the laser induced weld seams is the main reason for this stability increase, which is proven by measurements of the stress-induced birefringence.

To compare the obtained modifications, we investigated the particular dimensions of molten structures in burst and high repetition rate regimes at similar applied powers. Thereby we found longer modifications when the pulse number within the bursts increases. This can be attributed to stronger heating and a subsequent stronger influence of temperature dependent material properties (diffusivity), which is in good agreement with our thermodynamic simulations of the laser melting and bonding process. The different shape of the modifications influences the induced tensions.

To conclude, by using optimized processing parameters enables both low laser induced stress and high molten volume at the interface of the bonded samples. Thus a breaking stress as high as the bulk material can be achieved of laser bonded glass samples.

8611-48, Session 12

Influence of ambient pressure on the hole formation process in ultrashort pulse laser deep drilling

Sven Döring, Sören Richter, Tobias Ullsperger, Friedrich-Schiller-Univ. Jena (Germany); Andreas Tünnermann, Stefan Nolte, Friedrich-Schiller-Univ. Jena (Germany) and Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

We investigate the influence of the ambient pressure on the hole formation process during percussion drilling of silicon by applying an in-situ imaging technique. In this study the pressure is varied from atmospheric conditions down to medium vacuum of 10 µbar. Drilling was performed using an ultrashort pulse system providing 8 ps pulses with up to 125 µJ at 1030 nm. At this wavelength, the ablation behavior of silicon is comparable to metals. At the beginning of the drilling process, we observe an increased drilling efficiency by 40% already for a moderate pressure decrease to 100 mbar. The formation of an ideally shaped hole lasts for approximately 200 pulses instead of only 100 as for atmospheric conditions and therefore leads to 3 times the depth at this point. The effect can be enhanced by increasing the pulse energy, but not by decreasing pressure further. However, the number of pulses till the end of the drilling process is extended by decreasing the pressure further. For a low ambient pressure of 10 µbar, this is accompanied by an increase of the maximum achievable depth of more than 100%. Simultaneously the hole shape changes from a few ends and bulges at atmospheric conditions to numerous branches over the complete lower part of the hole at low pressure. This drilling behavior can be attributed to a better removal of ablated particles from the hole capillary with decreasing pressure, which leads to lower scattering losses for the pulse propagation inside the hole.

8611-49, Session 12

Spatio-temporal dynamics of femtosecond Bessel beams for high-aspect ratio nanochannel drilling in dielectrics

Jinggui Zhang, Univ. de Franche-Comté (France); Francois Courvoisier, Institut Femto ST (France); Arnaud Couairon, Ecole Polytechnique (France); John M. Dudley, Univ. de Franche-Comté (France)

The fabrication of high-aspect ratio nano-channels is a particularly important challenge for nanofluidics and nanophotonics. We have previously reported a novel approach based on femtosecond Bessel beams to process nanochannels in glass with unprecedented aspect ratio (100:1) with a single laser shot. Although this effect was experimentally well-characterized by post-mortem analysis, the specific effect of high conical angle on the Bessel pulse and plasma generation were unknown. Here, we report the results of a detailed numerical study based on the nonlinear Schrödinger equation (NLSE) coupled to a rate equation describing the generation of an electron-hole plasma. We show that the extended light/matter interaction length of Bessel beams compared to Gaussian beams provides very high sensitivity to the ionization dynamics. We also show for the first time to our knowledge that this beam configuration allows the generation of a plasma nanochannel (typically 400 nm in diameter, 40 µm in length) with a density higher than the critical density at which plasmas become opaque and where the ionization degree can reach more than 90% with only a 1 µJ pulse. This explains the high degree of control on the nanochannel parameters that was observed experimentally. In addition, we show that the propagation dynamics is close to stationary such that Kerr-induced spatial and spectral dynamics is reduced even though the intensity can locally exceed extreme values (>1014 W/cm2). Interesting effects of pulse self-compression are also observed due to the rapid buildup of the plasma.

8611-50, Session PTue

Protein profile studies of tissue homogenate in diagnosis of cervical cancers using HPLC-LIF: a preliminary report

Maheedhar Kodali, Vidyasagar M.S., Vadhiraja B. M. M.D., Donald J. Fernandes M.D., Manipal Univ. (India)

Cervical cancer is the most common malignancy among women. Paptest and Colposcopy the existing screening methods are shown to be prone to false positive / negative results. High Performance Liquid Chromatography with high sensitivity Laser Induced Fluorescence (HPLC-LIF) was used to study protein profiles of the tissue homogenates from healthy volunteers and cervical cancer subjects. Seven biopsies from malignant subjects and four biopsies harvested from regular hysterectomy (controls) were recruited in the study. Tissue homogenate prepared in saline and standardized by 6 strokes with each revolution time of 30 seconds. In this study we have explored feasibility of classifying chromatograms of cervical tissue homogenates using Principle Components Analysis (PCA) as multivariate statistical tool. PCA is a data reduction technique where large amount of spectral data is described in terms of small number of independent variables called 'eigenvectors' or 'factors' or 'principal components' and the scaling constants used to reconstruct the spectra are known as 'scores'. Scores of factors is widely used parameter for classification of tissue types. Our findings suggest that PCA of derivative chromatograms give better discrimination. In our analysis first derivative chromatograms in the 1250-2700 seconds region with 5 factors yielded best results. Our finding suggests that HPLC-LIF instrument is not only suitable for detection of femto/subfemto moles of proteins but also data can be analyzed by multivariate statistical tools inorder to achieve objective diagnosis. Prospectively, by recruiting larger data set further study may yield better results with high specificity and sensitivity.

8611-52, Session PTue

Laser time-of-flight measurement based on multi-channel time delay estimation

Chao Li, Qian Chen, Guohua Guand, Tian Man, Nanjing Univ. of Science and Technology (China)

Laser time-of-flight (TOF) measurement is an active sensing technique widely used in laser ranging, laser imaging radar and other laser direct detection applications. The time resolution of TOF measurement determines the precision of laser ranging and the definition of laser imaging radar, so it is of importance to measure the laser flight time accurately [1-3]. Laser TOF measurement system measures the time interval between the transmitted laser pulse signal (start) and the received laser pulse signal (stop).

The basic problem of laser TOF measurement employing time delay estimation is to determine the time delay between the transmitted signal and the received signal. Restricted by the conversion rate of ADC device, the precision of laser TOF measurement is restricted no more than the ADC sampling period [4]. In order to solve this problem, a novel method based on cross-correlation analysis, multi-channel time delay estimation with linear fitting correction is proposed.

The paper is organized as follows: Section II discusses the principle of the method based on cross-correlation analysis, multi-channel time delay estimation with linear fitting correction. Section III discusses the laser TOF measurement system design and performance results of the experiment. Section IV discusses conclusions and future work.

8611-54, Session PTue

Characterization of femtosecond laser filament-fringes in titanium

Md. Shamim Ahsan, KAIST (Korea, Republic of) and Khulna Univ. (Bangladesh); Fadia Dewanda, KAIST (Korea, Republic of); Farid Ahmed, Martin B. G. Jun, Univ. of Victoria (Canada); Man Seop Lee, KAIST (Korea, Republic of)

In this paper, we characterize the femtosecond laser filament-fringes in titanium. In order to fabricate regular arrays of filaments in titanium sample, we place either a pinhole or a beam shaper in the optical path of the femtosecond laser beam that originates linear diffraction of the laser beam. As a consequence, the intensity distribution of the laser beam is modulated and fringe type of filament distributions is evident in titanium. The suitable control over the size of the diaphragms (pinhole or beam shaper) leads us to adjust the shape, orientation, and number of filaments in each irradiated spots. By properly adjusting the diameter of a pinhole that was placed in the optical path, we are successful in forming a single filament in titanium. By using these single filaments, we fabricated high aspect ratio periodic holes in the titanium surface by moving the translation stage in both horizontal and vertical directions. The period of the holes in the horizontal direction is controlled by varying the scanning speed, whereas the period in the vertical direction is controlled by varying the vertical scanning step. We strongly believe that, filamentation technology described in this paper will have applications in forming a variety of micro/nano-structures in various materials.

8611-55, Session PTue

Liquid jet generated by thermocavitation bubbles within a droplet

Juan Pablo Padilla-Martinez, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); Darren Banks, University of California in Riverside (United States); Julio-Cesar Ramirez-San-Juan, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); Guillermo Aguilar, University of California in Riverside (United States); Ruben Ramos-Garcia, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

Recently, the collapse of cavitation bubbles within droplets has attracted attention due to its potential applications for the formation of water jets, spray cooling, emulsion formation, 3D micro-printing, and more. In the past, short pulsed lasers or electrode spark-discharge have been the most common methods to produce cavitation within a droplet. The present paper reports the use of continuous wave (CW) optical thermocavitation in order to achieve the same goal. In contrast with the two techniques described above, CW thermocavitation is simpler and cheaper since it only requires the use of an inexpensive low power CW laser focused on a highly absorbent solution. To demonstrate the simplicity of CW thermocavitation, we employed a hemispherical droplet (5µL volume) of a saturated solution of CuNO4 dissolved in water (? =135 cm-1 at ?=975 nm) confined to a 5 mm diameter by a thin lip in form of a circular pool on a glass slide. An infrared laser (?=975 nm) was focused from underneath the glass slide, 400 µm above the solid-liquid interface, which produced the largest bubble in our experiments and, therefore, the strongest pressure wave upon it collapses leading to the ejection of a thin liquid jet from the droplet.

8611-56, Session PTue

A multi-GPU implementation of nonlinear schrödinger equation for the propagation of USPL and its interaction with matters

Mohammad R. Zunoubi, State Univ. of New York at New Paltz (United States); William P. Roach, Air Force Research Lab. (United States)

In this research, we present the first multi-GPU implementation of nonlinear Schrödinger equation (NLSE) for the propagation of high-power ultrashort pulse laser (USPL) and its interaction with materials. The extended form of the NLSE that includes the effects of diffraction in transverse plane, group velocity dispersion, self-phase modulation, self-steepening, multi-photon ionization, plasma effect, and delayed Raman effect along with the nonlinear rate equation is discretized using a combination of the higher-order Runge-Kutta and 2-step higher-order compact (2SHOC) finite-difference methodologies. The computations are ported into multiple graphical process units (GPUs) by using the computed unified device architecture (CUDA) application programming interface (API). The Open-MP API is utilized to synchronize the operation of GPUs and their corresponding CPUs. By taking advantage of CUDA programming model, we present a unique implementation of the NLSE that exploits the memory hierarchy of GPUs which includes the global, texture, and shared memory, enabling us to tackle problems that are otherwise computationally prohibitive. Practical results will be presented along with a measure of speedup factors achieved when using multiple GPU cards.

8611-58, Session PTue

Laser-induced structural modifications in glass using a femtosecond laser and a CO2 laser

Takayuki Tamaki, Keigo Nakamura, Shunsuke Ono, Nara National College of Technology (Japan)

In this paper, we present the investigation results on laser-induced structural modifications in a BK7 glass sample (OHARA, S-BSL7) by use of a femtosecond laser and CO2 laser system. A femtosecond fiber laser system (wavelength: 1.06 µm and pulse duration: 200 fs) generates 1 MHz ultrashort laser pulses with a pulse energy up to 2 µJ, and a CO2 laser system generates CW (continuous wave) laser beam with a wavelength of 10.6 ?m. Both laser beams were simultaneously irradiated on a glass substrate (30 mm ? 5 mm ? 0.7 mm thick) with a 0.56-NA (numerical aperture) aspheric lens. The structural modifications regions were created by translating the glass sample perpendicular to the laser axis with a distance of 1 mm and a scan speed of 0.65 mm/s. The dependence of structural modifications on laser parameters including laser energies of femtosecond and CO2 laser beams and sample scanning speeds were investigated. The results have demonstrated that the refractive index change region with the width of 3 ?m was created with simultaneously irradiation of two laser beam although the structural modification regions, which were produced with femtosecond laser pulses, were scattering damage. And the scattering damage regions were changed to the refractive index change regions as the energy of CO2 laser beam increased.

8611-59, Session PTue

Defect detection in laser powder deposition components by laser thermography and laser ultrasonic inspections

S. P. Santospirito, Kingston Computer Consultancy Ltd. (United Kingdom); Rafal Lopatka, Polkom Badania (Poland); Kamil S?yk, Bin Luo, Kingston Computer Consultancy Ltd. (United Kingdom); Donatella Cerniglia, University of Palermo (Italy); Dorothée Panggabean, John Rudlin, TWI Limited (United Kingdom)

Laser Powder Deposition (LDP) techniques are being adopted within aerospace and automotive manufacturing to produce innovative precision components. Non-destructive techniques (NDT) for detecting and quantifying flaws within these components enables performance and acceptance criteria to be verified, improving product safety and reducing on-going maintenance and product repair costs.

In this work, software enabled techniques are presented for in-process analysis of NDT Laser Ultrasonic signals and pulsed Laser Thermography images of sequential metallic LPD layers. LPD tracks can be as thin as 200µ while deposited at a rate of 500 mm/min, requiring ultrafast inspection and processing times. The research developed analysis algorithms that allow senior engineers to develop inspection templates and profiles for in-process inspection, as well as an end-to-end, user friendly interface for engineers to perform complete manual Laser Ultrasonic or Laser Thermographic inspections.

Statistical models have been built for both NDT approaches to analyse individual deposition layers as well as to integrate each layer sequentially into the entire LPD component. This allows the evaluation of defects at an intra-layer level as well as tracking the effect of sequentially deposited defects within the entire component.

Several algorithms are offered to quantify the flaw sizes and severity. The identified defects are imported into the sentencing engine which then automatically compares analysis results against the user defined acceptance criteria so that the manufacturing products can be verified. Where both Laser Ultrasonic and Laser Thermographic NDT data is available further statistical tools increase the confidence level of the inspection decision.

8611-60, Session PTue

Substrate optimization of a nanostructured plasmonic transfection device

Sebastien D. Courvoisier, Harvard School of Engineering and Applied Sciences (United States) and Univ. of Geneva (Switzerland); Jun Chen, Harvard School of Engineering and Applied Sciences (United States) and Nanjing Univ. of Science and Technology (China); Lucy Chen, Harvard School of Engineering and Applied Sciences (United States); Luigi Bonacina, Jean-Pierre Wolf, Univ. of Geneva (Switzerland); Eric Mazur, Harvard School of Engineering and Applied Sciences (United States)

The efficient and safe introduction of genetic vectors into mammalian cells is the first step to develop novel approaches for gene therapy, regenerative medicine, and to modify gene expression. Our research aims to develop a very efficient, low toxicity and high throughput transfection method by using a laser to excite a plasmonic substrate that creates highly localized electric fields. By patterning a metal film surface, the electromagnetic energy from an input laser beam can be focused into very small volumes, below the diffraction limit. In this scheme we use a femtosecond laser to excite plasmon modes at the metal-dielectric interface to create these “hot spots”. The phospholipid bilayer membrane of a cell close enough to a hot spot experiences a local electric field greater than the original incident optical field. Beyond a certain threshold, chemical or thermodynamic perturbation of the membrane results in localized disruption of the cell membrane. The resulting poration of the plasma barrier membrane allows a subsequent influx of charged molecules like naked DNA via diffusion.

In this presentation, we focus our attention on the design of the plasmonic substrate. First, to maximize the contrast between the hot spots and the surrounding area, we optimized some promising geometries around a modified pyramid array using Finite-Difference Time-Domain method. Second, we fabricated the thin gold structured films from best simulation candidates using a template stripping method. Third, we characterized the fabricated substrate by Near-Field Scanning Optical Microscopy, two photon fluorescence and Scanning Electron Microscope.