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Contents

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6451-01, Session 1

Continuous wave Praseodymium solid-state lasers

G. Huber, A. Richter, E. Heumann, Univ. Hamburg (Germany)

Pr3+ is an interesting ion for the realization of efficient solid-state lasers in the visible spectral range because its energy level scheme offers several transitions in the red, orange, green, and blue spectral regions. In addition, a single step of nonlinear frequency conversion like intracavity frequency doubling yields reliable and compact continuous wave UV lasers between 260 nm and 360 nm. We review Pr-doped laser materials (like Pr:LiYF4, Pr:BaY2F8), their spectroscopic properties (absorption, emission spectra) and relevant laser parameters (upper laser level lifetimes, cross sections, gain), as well as recent developments in visible continuous wave lasing of Pr3+- lasers. In particular, the first GaN-diode pumped solid-state lasers were realized with Pr3+:YLiF4 (pump laser diodes at ~442 nm / 444 nm with 20mW / 350 mW power). So far, we obtained maximum output power of ~0.6 W at the 720-nm, 640-nm, and 520-nm transitions of Pr3+YLiF4 using a 1.6-W optically pumped semiconductor laser as excitation source at 479 nm. With LiB3O5 as nonlinear material ~0.32 W of ultraviolet 320 nm radiation has been also demonstrated by intracavity frequency doubling.

We wish to acknowledge the support of Coherent GmbH, Branch Luebeck, Germany.

6451-02, Session 1

UV generation by intracavity frequency doubling of an OPS-pumped Pr:YLF laser with 500 mW of cw power at 360 nm

V. G. Ostroumov, W. R. Seelert, Coherent Luebeck GmbH (Germany); L. E. Hunziker, C. Ihli, Coherent, Inc.; A. Richter, E. Heumann, G. Huber, Univ. Hamburg (Germany)

Trivalent Praseodymium ions (Pr3+) are very interesting for realizing lasers in the visible spectral range, because the energy level scheme of Pr3+ enables several transitions in the blue (~490 nm), green (522 nm), orange (607 nm) and red (640 nm, 697 nm, 720 nm) spectral regions. Furthermore, several wavelengths in the UV can be achieved using a single step of second harmonics generation, which would require in case of Nd3+ two nonlinear processes. The former lack of suitable pump sources for Pr-doped materials at 444 nm or 479 nm has been overcome due to recent progress in GaN-based pump diodes operating at 444 nm and optically pumped semiconductor lasers (OPS) operating at 479 nm. These developments enable Pr3+-doped crystals as gain media for compact and efficient solid-state lasers.

In this paper, we report on 500 mW of cw UV radiation at 360 nm, obtained by intracavity frequency doubling of an end-pumped Pr:YLF laser. As pump source, an OPS laser operating at 479 nm with an output power of about 1.8 W was used. Results, obtained with different Pr3+-doped fluorides, will be presented and discussed.

6451-03, Session 1

522/261 nm cw generation in a Pr3+:LiYF4 laser pumped by an optically pumped semiconductor laser

V. G. Ostroumov, W. R. Seelert, Coherent Luebeck GmbH (Germany); L. E. Hunziker, C. Ihli, Coherent, Inc.

Among the transitions of trivalent Praseodymium ions (Pr3+) in the visible spectral range (red at 720 nm, 697 nm and 640 nm, orange at 607 nm, green at 522 nm and blue at ~490 nm), the green laser transition is very interesting for second harmonic generation, providing continuous-wave (cw) 261 nm laser radiation which is close to the wavelength of the fourth harmonic of Nd:YAG lasers.

Although the 522 nm-transition in Pr:YLF (3P1 μ 3H5) is relatively weak compared to the others in the visible spectral region, it still has a reasonable emission cross section value (σem = 0.5•10-19 cm2). In combination with the small Stokes shift efficient lasing is provided.

In this paper we report on first experiments of an all-solid-state end-pumped Pr:YLF laser. An OPS laser operating at 479 nm was used for pumping. Applying 1.7 W of incident pump power more than 400 mW were obtained at 522 nm with a slope efficiency of 33%. Results of intracavity frequency doubling of the 522 nm radiation will be presented and discussed.

6451-04, Session 1

High-power long term operation of a low noise 355 nm CW diode-pumped monolithic laser

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Low noise CW Diode-Pumped Solid-State UV lasers are needed for many analysis applications in the semiconductor (wafer inspection, micromachining ...) and the biological fields (cell sorting, cytometry ...). Recently the development of monolithic laser structure has led to mW scale UV output power. This crystalline architecture is composed of an amplifying medium (Nd:YVO4), a doubling (KTP) and a tripling (LBO) crystal. These elements produce respectively the 1064 nm, the 532 nm and the 355 nm emissions. The monolithic structure is quite straightforward and is obtained by optically contacting crystals. It doesn't require any alignment reduces the manufacturing costs and improves reliability.

Thanks to the monolithic structure and compared to previously published work on this topic, we present for the first time a long term characterization of the diode pumped CW 355 nm laser. The interplay between pump absorption, cavity length, 1064 mode size, walk off angle, acceptance angle has been optimized. In our experiments, the temperature of each element of the laser could be controlled and UV power, noise and spectra could be monitored versus these temperatures. Optimized UV power beyond 30 mW were measured and with a 2W pump power, the laser could be repeatedly tuned to 20 mW over a short period and could be power controlled over days in the 10 to 15 mW UV power range. The noise level constantly remained below the 1% rms level.

Several lasers were built with the same architecture and more long-term measurements will be presented at the conference. In addition, we believe that the UV output power can still be improved.

6451-05, Session 2

Ultrafast frequency conversion sources for the visible and ultraviolet based on BiB3O6

M. Ebrahim-Zadeh, Institut de Ciències Fotòniques (Spain)

We describe efficient frequency conversion of femtosecond and picosecond pulses into the visible and ultraviolet using the nonlinear material BiB3O6. By deploying techniques based on synchronously-pumped optical parametric oscillators, and single-pass second-harmonic and third-harmonic generation, we have generated femtosecond and picosecond pulses across the ultraviolet and visible, from 240 to 710 nm in a variety

of device configurations. Average powers of up to 1 W, pulse durations from ~120 fs to ~30 ps, conversion efficiencies >50%, and pulse energies >200 mJ have been obtained.

6451-06, Session 2

Frequency tripled and quadrupled air-cooled modelocked Nd:YVO4 laser with greater 6W average power

A. H. Diening, Coherent, Inc.; S. Ahler, S. D. Butterworth, W. R. Seelert, Coherent Luebeck GmbH; O. Mehl, Coherent, Inc.

Compact DPSS UV sources are of interest for replacing Ar-Ion lasers in applications that require cw or quasi-cw emission. One way to generate UV light at 355nm and 266nm is by modelocking an IR Nd:YVO4 laser and converting the ps pulses towards the second, third, and fourth harmonic. The mechanism of choice is passive modelocking using a saturable Bragg reflector (SBR). We have developed an air-cooled system capable of UV output powers in excess of 6W. Laser performance as well as lifetime data will be presented for wavelengths at 355nm and 266nm.

6451-77, Session 2

35 W at 355 nm from a mode-locked Nd:YVO4 MOPA

L. McDonagh, Technische Univ. Kaiserslautern (Germany); R. E. Wallenstein, Univ. Kaiserslautern (Germany); A. Nebel, Lumera Laser GmbH (Germany)

We present a simple, high-efficiency passively mode-locked Nd:YVO4 oscillator pumped at 888 nm, further amplified in a single-pass stage to a 110 W average power at 110 MHz repetition rate, with 33 ps pulse duration output and diffraction-limited beam quality. These laser parameters are especially well suited to obtaining high frequency conversion efficiencies. So far, we have already demonstrated 87 W at 532 nm and 35 W at 355 nm in simple doubling and tripling stages, respectively. We expect that with a more optimal tripler configuration UV power outputs can be increased further to over 40 W.

6451-08, Session 3

Recent advances in optically pumped semiconductor lasers

J. L. A. Chilla, Q. Shu, Coherent, Inc.; H. Zhou, E. S. Weiss, M. K. Reed, Coherent, Inc; L. Spinelli, Coherent, Inc.

Optically pumped semiconductor lasers offer significant advantages with respect to all traditional diode-pumped solid state lasers (including fiber lasers) in regards to wavelength flexibility, broad pump tolerance, efficient spectral and spatial brightness conversion and high power scaling. In this talk we will describe our recent progress in the lab and applying this technology to commercial systems. Results include diversified wavelengths from 460 to 570nm, power scaling to >60W of CW 532nm, and the launch of a low cost 5W CW visible source for forensic applications.

6451-09, Session 3

Power-scaling of optically pumped semiconductor lasers

L. E. Hunziker, Q. Shu, C. Ihli, G. J. Mahnke, M. Rebut, J. L. A. Chilla, A. L. Caprara, H. Zhou, E. S. Weiss, M. K. Reed, Coherent, Inc.

Optically-pumped semiconductor lasers can be scaled to tens of Watts output by increasing device size and using multiple chips within the resonator cavity. We present methods for producing high beam quality, IR and visible output, with powers exceeding 50W.

6451-10, Session 3

New wavelengths in the yellow orange range between 545 nm and 580 nm generated by intracavity frequency-doubled optically pumped semiconductor lasers

S. Hilbich, W. R. Seelert, V. G. Ostroumov, C. Kannengiesser, R. von Elm, J. Mueller, Coherent Luebeck GmbH (Germany); E. S. Weiss, H. Zhou, J. L. A. Chilla, Coherent, Inc.

Diode pumped frequency doubled Optically Pumped Semiconductor lasers (OPS) have proven to be a reliable source of laser radiation in the blue and blue-green wavelength range between 460 nm and 505 nm. One of the major advantages of using semiconductors as the gain medium is the possibility to design the emission wavelength by means of band gap engineering.

Here we report new OPS materials emitting in the wavelength region between 1090 nm and 1160 nm and the implementation of frequency doubled lasers between 545 nm and 580 nm. Laser performance with output powers of up to several W in the yellow spectral range as well as efficiency and lifetest data will be presented.

6451-11, Session 3

Pulsed Yb:YAG thin disk laser with 100 W at 515 nm

G. Hollemann, P. Heist, S. Heinitz, J. Symanowski, T. Eidam, JENOPTIK Laser, Optik, Systeme GmbH (Germany); C. Stolzenburg, A. Giesen, Univ. Stuttgart (Germany)

Pulsed lasers with high average output power in the green spectral range are of interest for laser annealing applications. In this paper an efficient pulsed diode-pumped Yb:YAG thin disk laser with intra-cavity frequency doubling is presented.

The Yb:YAG laser crystal disk has a thickness of 180 μm and a diameter of 10 mm and is pumped by a laser diode stack at a wavelength of 938 nm. The disk is soldered to a water-cooled Cu-W heat-sink and exhibits a nearly perfect spherical surface. The folded resonator is dynamically stable with a beam quality factor of $M^2 = 5$ and which is matched to the requirements of the application. Acousto-optical and electro-optical switches are investigated to operate the laser in the cavity dumping mode. An average output power of 100 W at 515 nm is achieved. The diode-to-green efficiency is about 20%.

A critically phase matched LBO crystal is used for intra-cavity second harmonic generation. We show that stable pulsing is obtained from 10 kHz to 100 kHz. The pulse width can be varied from 200 ns to 500 ns by control of the high-loss period of the switching element.

The experimental results are compared with theoretical modelling of the system and first application results are discussed.

6451-12, Session 3

Thin disk Yb:YAG laser with Q-switching and frequency doubling for the generation of strong pulses at 515 nm with excellent beam properties

C. Petermann, G. E. Hummelt, ELS Elektronik Laser System GmbH (Germany)

The thin disk laser technology is ideal for the generation of very high cw powers with excellent beam quality. We report an Yb:YAG Thin Disk Laser for Q-switched operation with frequency doubling to 515 nm. New performance levels are attainable both for pulse energy and average power without compromising spatial and spectral beam properties. Design considerations and performance data will be presented.

6451-72, Session 3

Advances in power scalable, tunable and mode-locked semiconductor disk lasers

O. G. Okhotnikov, A. Härkönen, E. J. Saarinen, J. Rautiainen, M. Guina, Tampere Univ. of Technology (Finland)

We present new approaches for power scaling and tunability in semiconductor disk lasers. The novel concepts allow for reduced thermal load of the gain material, increasing the threshold of rollover and extending the capability for boosting the output power without degradation in the beam quality. Tunable high-power Sb-based disk laser operating at 2-μm is demonstrated using efficient low-loss approach for spectral control. The potential of disk lasers for high repetition rate ultrashort pulse generation using harmonic mode-locking is also discussed.

6451-13, Session 4

888-nm pumping of NdYVO4 for high-power high-efficiency TEM00 lasers

L. Mc Donagh, Univ. Kaiserslautern (Germany)

Nd:YVO4 is a widely used gain medium in commercial lasers providing up to several tens of Watts in a diffraction limited beam. Its high gain favors high repetition rate and short pulses in nanosecond Q-switched and picosecond mode-locked regimes. However, output power is limited by strong thermo-optical effects leading to an aberrated thermal lens and ultimately the crystal's fracture. In this contribution, we present the optimized pumping of vanadate at 888 nm, benefiting from polarization-independent absorption, reduced quantum defect and very low absorption coefficients compared to the common pump wavelengths of 808 and 880 nm. After a presentation of the principle and the characterization of the key parameters in a high power fiber-coupled end-pumped multimode oscillator, a series of systems based on this pumping technique will be presented. A compact 60 W high efficiency TEM00 CW oscillator first proves the potential for high power high beam quality systems. Q-switched and cavity-dumped Q-switched oscillators providing 50 W of average power with 5 ns long pulses at all repetition rates were investigated. High repetition rate mode-locking of an oscillator providing over 50 W of output power was achieved with a saturable absorber mirror. Finally, a high power oscillator was amplified in a power amplifier based on the same pump/crystal configuration. The high seed power available from the oscillator allowed an efficient extraction in the amplifier stage, even in a single-pass. The wide range of systems demonstrated illustrates the simplicity and flexibility of 888 nm pumping for extending the benefits of vanadate in the higher power range.

6451-14, Session 4

High-power 885-nm end-pumped Nd:YAG laser

M. Frede, Laser Zentrum Hannover e.V. (Germany)

In diode pumped Nd:YAG lasers the quantum defect is the most important parameter determining the thermal load of the laser crystal. This can be dramatically reduced by pumping into the upper laser level. Therefore a high power end-pumped Nd:YAG laser with direct pumping into the upper laser level will be presented. An 8 bar stack with central wavelength of 885 nm and a spectral width of 2.5 nm was used to pump a diffusion bonded Nd:YAG crystal with total length of 62 mm and 5 mm in diameter. With an absorbed pump power of 438 W an output power of 250 W was realized. This results to an optical to optical efficiency of 57 %. To the best of our knowledge this is the first demonstration of high output power and slope efficiency by using 885 nm pumping. Further investigations on thermal load and thermal optical effects will be presented.

6451-15, Session 4

Lightweight, 100 mJ 1064 nm laser designator

J. C. McCarthy, R. C. Day, P. A. Ketteridge, K. J. Snell, E. P. Chicklis, BAE Systems North America

We describe the performance of a 100 mJ, end-pumped, 1064 nm laser in a simple oscillator-amplifier configuration. The efficient, end pumped design uses only 18 QCW pump diode bars (200 Wpeak per bar), uses no active thermal control and weighs 3.7 lbs (including batteries). Laser performance for typical military operating temperatures is detailed.

6451-16, Session 4

Diode pumped Nd:YGG laser for direct generation of pulsed 935 nm radiation for water vapour measurements

J. Löhring, K. Nicklaus, N. Kujath, H. Hoffmann, Fraunhofer-Institut für Lasertechnik (Germany)

A resonator setup applying a double-sided diode end-pump configuration and an electro-optical Q-switch for efficient generation of 4 mJ pulses (< 60 ns fwhm) at 935 nm from Nd:YGG is presented, to our knowledge for the first time. The optical-optical efficiency is 11% (absorbed pump light to laser out). High quality crystals have been investigated, showing high damage threshold, high efficiency and good optical properties permitting Q-switched mode of operation. Experimental small signal gain data coincide with spectroscopic measurements. For vapour detection frequency stable single mode operation is required. Injection seeding with a single frequency cw-signal has been successfully achieved. Frequency control mechanisms are currently under investigation. The direct generation of 935 nm radiation simplifies future LIDAR systems significantly compared to current approaches based on OPO, Raman or Ti:Sa technology.

6451-28, Session 4

Nd:GSAG laser for water vapor detection by lidar near 942 nm

F. Kallmeyer, S. G. Strohmaier, D. Schmidt, H. J. Eichler, Technische Univ. Berlin (Germany); R. Treichel, EADS Astrium (Germany); S. Nikolov, EADS ASTRIUM (Germany)

For weather forecast, especially for civil protection from high-impact weather events, measuring the three-dimensional distribution of water vapour by DIAL techniques is a fundamental concern. Especially for development and evaluation of atmospheric models, knowledge of water vapour distribution is important. The wavelength regions around 935 nm, 942 nm and 944 nm have been identified by the "WALES" program of the European Space Agency (ESA) as the most suitable wavelength ranges for the water vapour DIAL. For these regions there are more or less well established technologies such as the optical-parametric-oscillator-laser (OPO), the Raman-laser and the Ti-Sapphire laser. But these systems suffer from a low efficiency and a complex set-up due to the need of two or more frequency conversion steps. In contrast the Nd:GSAG laser can be directly pumped with 808 nm laser diodes. Which supports the realisation of an efficient and compact laser system. For the development of a laser the knowledge of the stimulated emission cross section has a vital importance. The measurement of the gain cross section in a Nd:GSAG laser crystal from 941-944 nm and the laser performance around 942 nm will be presented in this talk. In addition the frequency stabilisation of the laser to a water vapour absorption wavelength by injection seeding is discussed.

6451-20, Session 5

Fe:ZnSe passive q-switching of 2.8-μm Er:Cr:YSGG laser cavity

A. R. Gallian, A. Martinez, P. Marine, V. V. Fedorov, S. B. Mirov, The Univ. of Alabama at Birmingham; V. V. Badikov, Kuban State Univ. (Russia); D. M. Boutoussov, M. Andriasyan, BIOLASE Technology, Inc.

The use of Fe:ZnSe crystals as passive Q-switches for the Er:Cr:YSGG laser operating at 2.8μm is introduced. Fe:ZnSe samples with 1-7cm^-1 coefficients of absorption were prepared using thermal diffusion of chromium in CVD grown polycrystalline ZnSe.

A flashlamped pumped room temperature Er:Cr:YSGG laser with a plane-plane cavity of 25-cm length and variable (40-80% reflectivity) output coupler (OC) was used as a test bed for passive Q-switching. Using a 90% initial transmission Fe:ZnSe placed at Brewster angle we obtained a single giant pulse lasing with a pulse duration of ~120ns and the output energy of 5 and 3-mJ for 80% OC, 11.5-J pump and 40% OC, 9.5-J pump, respectively. The ratio of energy of single giant pulse to the respective free-running energy was ~20% and could be further increased with improvements of Fe:ZnSe quality. Multi-pulse (19 pulses) output was obtained with 85-mJ total output energy at a pump energy of 30-J with a 40% OC. Utilization of a folded cavity design yielded 13-mJ output energy using a 40% OC and 25-J pump energy.

The Q-switched output of the Er:Cr:YSGG laser was used for saturation studies of Fe:ZnSe. The saturation curve of Fe:ZnSe was measured. Its fitting with the Frantz-Nodvick equation results in absorption cross section of 6.0x10-18cm^2, which is of the same order of magnitude as the absorption cross-section obtained from spectroscopic measurements (1.0 10-18cm^2). The described Fe-doped ZnSe crystals are very promising as room temperature solid state passive Q-switches for mid-IR lasers operating over 2.5-4.0μm spectral range.

6451-21, Session 5

ZnSe:Cr2+ laser crystal grown by Bridgeman technique: characteristics and laser performance

P. Koranda, H. Jelínková, Czech Technical Univ. in Prague (Czech Republic); M. E. Doroshenko, General Physics Institute (Russia); J. Šulc, M. Nemec, Czech Technical Univ. in Prague (Czech Republic); T. T. Basiev, General Physics Institute (Russia); V. K. Komar, M. Kosmyna, Institute for Single Crystals (Ukraine)

ZnSe:Cr2+ crystals grown by the Bridgeman technique from the melt in inert gas (argon) under pressure were characterized and utilized as effective laser active material.

Large crystalline boules with a necessary concentration of Cr2+ ions 1019 cm-3, practically homogeneously distributed throughout the crystal bulk (50 mm in diameter and up to 100 mm in length), were prepared. For the laser evaluation the ZnSe:Cr2+ samples in the form of 6 mm thick blocks were polished.

ZnSe:Cr2+ laser was longitudinally coherently pumped either with flashlamp-pumped Er:YAP laser radiation (wavelength 1.66 um) or with diode-pumped Tm:YAP laser (wavelength 1.97 um).

In the first case the ZnSe:Cr2+ laser was pumped with radiation of Er:YAP laser working in free-running regime (pulse length 200 ms, pulse energy 200 mJ, repetition rate 1 Hz). The maximal obtained ZnSe:Cr2+ laser pulse energy was 14 mJ (slope-efficiency 70%). With the help of dispersive prism inside the resonator, the output laser radiation was broadly tunable from 2.15 um to 2.6 um.

In the second case the ZnSe:Cr2+ laser was pumped with radiation of DPSS Tm:YAP working in pulsed or cw regime. For cw regime the maximal obtained ZnSe:Cr2+ laser output power was 200 mW (slope-efficiency 66%). The spectrum of generated radiation covered the range from 2.1 um to 2.4 um. The temporal profile and spatial structure of laser beam were measured.

ZnSe:Cr2+ crystal grown by the Bridgeman method was demonstrated as efficient broadly tunable laser active material generated in the mid-infrared spectrum.

6451-22, Session 5

Properties of Ho3+ -doped PbWO4 as laser active and stimulated Raman scattering active crystals

I. S. Mirov, V. V. Fedorov, I. S. Moskalev, The Univ. of Alabama at Birmingham; S. Beloglovsky, S. Burachas, Y. Saveliev, A. Tseitline, North Crystals

The major objective of the study is to develop an effective solid state laser system operating at room temperature at ~2.5μm for medical and trace gas analysis applications. Two important ideas are combined for realization of an acceptable laser system. First, the fiber-bulk (Tm-fiber - Ho-laser) hybrid laser approach of direct laser pumping of the 5I7 manifold featuring a long fluorescence lifetime that allows for the high energy storage capability of Ho and the effective (up to 85%) conversion of the CW pump 1.9μm into a Q-switched 2.1μm radiation was used. Second, PbWO4 (PWO) Raman crystal was used as a host for Ho ions. It could provide an effective self-stimulating Raman lasing at 2.5μm.

All of the PWO crystals were grown by a Czochralski method with Ho concentration varied from 0.2% to 4%. Polarized optical absorption, emission and kinetic of fluorescence were measured over 20-300K temperature and over 0.2-8μm spectral ranges. The measured Stark energy levels of the 5I8 and 5I7 manifolds were similar to those in Ho:YLF, but with a smaller quantum defect and with the strongest absorption and emission lines of the 5I8-5I7 transitions at 1.96 and 2.04μm, respectively. The luminescence decay of Ho(4%):PWO sample revealed an exponential dependence with a lifetime of 12.5 ms at 300K. Absorption and luminescence cross-section were calculated from the spectroscopic data.

We also report on the experiments of 2.5μm Raman shifting in PWO and discuss self-Raman laser power scaling approaches.

6451-71, Session 5

Progress in mid-IR transition metal lasers

K. L. Schepler, Air Force Research Lab.

No abstract available

6451-73, Session 5

Novel infrared Q-switch materials

C. N. Pannell, Optronic Labs., Inc.; J. Ward, Gooch & Housego PLC (United Kingdom); T. E. Stenger, Cleveland Crystals, Inc.; R. K. Shori, Naval Air Warfare Ctr.

High intensity mid to far infrared lasers have generally been limited to long pulse or CW operation due to the lack of suitable Q-switches. The limitations of existing technologies will be compared with newer electro-optic and acousto-optic devices and materials, which have the capability to extend Q-switched operation to lasers operating from the mid to far infrared. Particular emphasis will be placed on recent results for a new Q-switch for Er-based lasers operating near 3um.

6451-23, Session 6

Bragg grating improves characteristic of resonantly diode-pumped Er:YAG, 1.65-mm DPSSL

I. Kudryashov, D. Z. Garbuzov, Princeton Lightwave Corp.; M. A. Dubinskii, Army Research Lab.

Bragg Grating feedback is widely used for spectrum narrowing of GaAs-based pumping systems. Spectrum narrowing is even more desirable in the case of InP -based 1470 nm and 1532 nm pumps since their spectrum full with half maximum is wider than that for GaAs-pumps by factor 3. In this paper we demonstrated an improvement of characteristics of Er (0.5%):YAG slab DPSSL, achieved using 1532 nm Bragg Grating. For some special design of the slab DPSSL we plan to pump it throw the long 60 mm facet (polished and AR coated for 1650 nm). In this case the width of the slab were limited by ingot growth condition and it was 15 mm. The slab thickness is 2.5 mm and slab was In bonded to water cooled copper heatsinks for CW operation. Pumping radiation from a 1530 nm diode laser stack after collimation was coupled into the rod end through a dichroic plano-plano mirror M1. At one side, mirror M1 had an anti-reflective coating for pumping radiation. The coating on the other mirror side provided transparency greater than 95% for pumping radiation and higher than 99.8% reflection for SSL radiation in the wavelength range of 1605-1670 nm. The highest SSL output powers were obtained using a flat output couplers with a transparency of 4-7%?

With optical path for pumping radiation of 15 mm only 37% 1530 nm radiation was absorbed by the slab. After placement of Bragg Grating between pumping stack and slab, the absorption of the pumping radiation increases up to 62%. As the results the threshold incident power reduced by factor 2.5, Slope efficiency increased by factor 1.7 and CW power have reached 51 W compared to 31W without Bragg spectrum narrowing .

6451-24, Session 6

Room temperature, multi-wavelength operation in Er:YALO3

S. Sharma, C. L. Vergien, R. K. Shori, O. M. Stafsudd, Univ. of California/Los Angeles

Simultaneous, orthogonally polarized lasing output at 1.662 μm and 1.673 μm was demonstrated in 1% Er:YALO3. Combined output energy at the two wavelengths was measured to be greater than 200 mJ. Using an intra-cavity polarizer with its orientation aligned along the a-axis or the c-axis, the lasing can be forced to occur at either 1.662 μm or 1.673 μm.

6451-26, Session 6

Microchip Nd:YAG laser for safe laser applications

H. Jelínková, J. Šulc, M. Nemec, J. Koranda, J. Pašta, K. Nejezchleb, V. Škoda, Czech Technical Univ. in Prague (Czech Republic)

No abstract available

6451-17, Session 7

Multi ten-watt, ultra-stable and tuneable Innoslab-based single frequency MOPA

M. Höfer, M. Traub, R. Kleindienst, H. Sipma, H. Hoffmann, Fraunhofer-Institut für Lasertechnik (Germany); P. Weßels, P. Burdack, InnoLight GmbH (Germany)

Reliable high power narrow bandwidth single frequency laser sources in the range of multi ten watt have many applications in the field of laser based metrology like lidar or precision interferometry and will surely enable new fields of application. Together with resonant external cavities, such systems are also highly interesting for non linear optics like SHG, DFG or OPO processes.

Other scientific applications, like laser cooling of atoms or gravitational wave interferometry, are also demanding ultra stable, tuneable single frequency laser sources. Besides high average power and excellent beam quality, especially characteristics like long term frequency, pointing and power stability and a low level of relative intensity noise are needed in this special field of application.

We present a long term stable single frequency MOPA with 34 W output power and M^2 < 1.2 consisting of an ultra-stable 1 W non-planar ring cavity oscillator with outstanding single frequency characteristics and one Innoslab amplifier stage. The partially end pumped Nd:YVO4 Innoslab amplifier is set up in a folded single pass configuration. A 30 GHz tuneable spectral bandwidth of 1kHz/100ms and a relative intensity noise (RIN) of < 1E-5 Hz^-1/2 (>10kHz) was measured in free-running mode. Together with an active intensity noise suppression electronics a RIN of < 5E-7 Hz^-1/2 (>10kHz) was achieved. A comprehensive discussion of experimental data is given. The theoretical modelling of the amplifier stage and further power scaling will be discussed.

6451-29, Session 7

Seeded single-frequency q-switched laser: new approach

A. I. Khizhnyak, V. Markov, MetroLaser, Inc.

We proposed and experimentally realized a new approach for a seeded wavelength Q-switched laser that can oscillate without adjustment of cavity resonances and seed emission carrier frequency. The oscillated laser pulse is easy to time-synchronize to the external processes.

Single-frequency tunable short-pulse lasers with reproducible pulse duration and ability of time-synchronization to external processes are of great utility for a variety of practical applications. Injection seeding is the technique most frequently used to generate a single-longitudinal mode nsec range reproducible output from the pulsed lasers. Traditionally it is assumed that the laser cavity must be in the resonance with the frequency of the seed source when the cavity Q-switch is turned on, and pulse build-up or ramp-and-fire techniques are most commonly used for this purpose. However both these methods fail to perform reliably when the time-synchronized operation is of interest.

The primary issue with our approach is in filling up the cavity with seed radiation to the level that significantly exceeds the level of spontaneous emission, purely on the first round-trip since the Q-switch is turned on. In this regime the Q-switched laser operates as a multi-passes amplifier of seeded radiation and doesn't require matching between the cavity resonance and seeded light wavelengths. Maximal cavity quality (with high-reflectivity mirrors) is an optimal cavity configuration for addressing this problem. The cavity damping regime, timed to the moment when the intracavity pulse reaches a maximum energy, is effective for a high-energy output, and controlling the damping time allows for the output pulse shaping.

6451-30, Session 7

Single-frequency stabilization of frequency tripled nanosecond Ti:sapphire laser injection seeded for silicon atom optics

Y. Shiomi, T. Yamamoto, H. Kumagai, A. Kobayashi, Osaka City Univ. (Japan)

Among a variety of chemical elements for atom optics, we have focused on silicon, which plays important roles in modern semiconductor industries. The required laser wavelength for the laser cooling of a silicon atom is 252.41 nm in the deep-UV region, which is resonant with the 33P1 - 43P0 cyclic transition of the silicon system. The linewidth of the ns pulsed

light source which has the high frequency-conversion efficiency into the deep UV is broader than the frequency separation (estimated at about 800 MHz) of the isotopes 28Si, 29Si and 30Si, even if it includes some dispersion optics such as prisms and an intracavity etalon. Therefore, we adopted the injection-seeding technique, which is a convenient and reliable method for achieving the single-mode laser operation.

In this study we have developed an injection-seeded nanosecond pulsed deep-UV light source, which is comprised of a single-mode cw Ti:sapphire laser as a seed laser and a ns pulsed DUV laser as a slave laser. The seed laser brings the injection-seeding effects which can narrow the linewidth whenever the cavity frequency of the slave laser matches with the longitudinal mode of the seed laser. If the pulsewidth and the linewidth of the ns Ti:sapphire laser satisfy the Fourier-transform-limit relation by the injection seeding, the linewidth of the THG becomes approximately 33 MHz. We examined the change of the build-up time of the pulse in the ns Ti:sapphire laser and then maintained the cavity frequency for the stable injection seeding.

6451-31, Session 8

Cryogenically cooled Ti:sapphire regenerative amplifier

S. Fournier, Coherent France (France); J. Heritier, G. J. Germann, B. Resan, A. Fry, Coherent, Inc.

Cryogenic cooling of Ti:Sapphire is a well known technique for improving its thermal performance in laser systems. In particular the dramatic improvement in thermal conductivity, temperature dependence of the index of refraction and thermal expansion around 77 K virtually eliminates the thermal lensing. This allows a significant increase in output power thru a better pump efficiency, and having much better beam quality over a wider range of operation. As an example we demonstrate a single-stage regenerative amplifier that is capable of delivering output powers in the 8-10 W range from 1-10 kHz.

6451-32, Session 8

A high-average power femtosecond laser for synchrotron light source applications

R. B. Wilcox, R. W. Schoenlein, Lawrence Berkeley National Lab.

We describe a 30W, 70fs, 10kHz titanium sapphire CPA laser using cryogenically-cooled regenerative and power amplifiers, currently operating at the Advanced Light Source at LBL. The system consists of an oscillator, a 20 kHz regenerative amplifier, and two power amplifiers to produce two output beams, each at 30W. Each power amp can be pumped by two 90 Watt, 10 kHz, diode-pumped, doubled YLF lasers simultaneously (for 10 kHz) or interleaved in time (for 20 kHz). The regen is pumped at 20 kHz and 60W, producing 8W output which is split between the power amps. To maintain the crystals near the thermal conductivity peak at ~50 LK, we used 300 Watt cryorefrigerators mechanically decoupled from the optical table. Beam position instability is a few percent of the beam width, despite large motions of the decoupled refrigerators. Pulses are compressed in a quartz transmission grating compressor, to minimize thermal distortions of the phase front typical of gold coated gratings at high power density. Transmission through the compressor is >80%, using a single 100 x 100mm grating. One of the 30W output beams is used to produce 70fs electron bunches in the synchrotron light source. The other is delayed by 300ns in a 12-pass Herriot cell before amplification, to be synchronized with the short light pulse from the synchrotron.

6451-33, Session 8

High-power operation of cryogenic Yb:YAG

K. F. Wall, P. F. Moulton, Q-Peak, Inc.

No abstract available

6451-34, Session 8

Innovative high-power CW Yb:YAG cryogenic laser

D. C. Brown, J. M. Singley, E. Yager, J. W. Kuper, B. J. Lotito, L. L. Bennett, Snake Creek Lasers, LLC

No abstract available

6451-35, Session 9

Extended tunability of Ti:sapphire lasers in CW and quasi-cw operation

I. MacGillivray, A. S. Bell, G. Friel, Coherent Scotland Ltd. (United Kingdom)

Advances in the output powers and beam quality of DPSS lasers have provided tens of watts of green pump power in a reliable and compact form. This paper describes advances in the performance of both single frequency CW and femtosecond modelocked ti:sapphire lasers using such high power pump lasers. Short wavelength performance below 660 nm for the CW system is described as well as single frequency tunability beyond 1100 nm. Continuous tunability of the modelocked system of over 400 nm will be presented and power performance for different output coupling and pump levels described. The applicability of these high performance systems to demanding new applications will also be described.

6451-36, Session 9

Pulse shaping, characterization and phase compensation system for enhanced ultrafast laser performance

B. Resan, W. M. Tulloch, S. Fournier, G. J. Germann, J. Heritier, A. Fry, Coherent, Inc.

A novel device designed for pulse shaping, characterization and phase compensation in ultrashort laser systems is described. The pulse shaper exhibits low transmission loss and is widely applicable to lasers with spectral bandwidth from 10 nm to over 400 nm. Pulse characterization and phase compensation is fully computer controlled in a closed loop via MIIPS method. This system is designed to enhance performance of ultrafast oscillators and ultrafast amplifiers including terawatt lasers and cryogenically cooled amplifier systems. Seed laser spectral amplitude shaping results in increased bandwidth while preserving the output power in ultrafast regenerative amplifiers. Subsequent phase compensation enables the robust delivery of output pulses within couple of percent of transform limit. Numerous applications are discussed including MPE microscopy, CARS, and more general coherent control experiments.

6451-37, Session 9

Noncryogenic 10-kHz Ti:sapphire amplifier

G. Matras, Univ. Jean Monnet Saint-Etienne (France) and Thales Laser SA (France); E. Baubeau, Thales Laser SA (France); N. Huot, E. Audouard, Univ. Jean Monnet Saint-Etienne (France)

In an international scientific context dealing more and more with micro- and nano-technologies, ultrashort laser sources have sparked a great deal of interest for precise machining of materials. Most ultrashort laser sources are based on all-solid-state Ti:sapphire systems. The main limitation of such systems is the repetition rate. Indeed, the higher the repetition rate, the greater the thermal effects in the laser crystal.Short thermal focal lengths induced in the laser crystal make it difficult to build a stable cavity at high repetition rates, especially above 5 kHz. Cooling the crystal at very low temperature under 273°K by using Peltier or cryogenic devices

is a solution commonly used in scientific studies and by laser manufacturers. These techniques increase the thermal conductivity of the crystal and reduce its dependence on the optical index, resulting in decreasing greatly thermal lensing. Nevertheless such techniques are generally difficult to be set up, expensive and voluminous.

We will present two solutions of non-cryogenic 10 kHz Ti:sapphire amplifiers. The first one is based on a classical chirped pulse amplification (CPA) system architecture : a stretcher, a regenerative cavity, a double-pass amplifier and a compressor. The second one is also based on a CPA system architecture but with an innovative and single non-cryogenic regenerative amplifier which produces after compression up to 350-μJ and 60-fs pulses at a 10 and 15 kHz repetition rate.

6451-38, Session 9

Amplification of ultrashort pulses to 0.5TW at 5Hz with a flashlamp pumped Cr:LiSAF gain medium

R. E. Samad, G. E. C. Nogueira, S. L. Baldochi, N. D. Vieira, Instituto de Pesquisas Energéticas e Nucleares (Brazil)

Cr:LiSAF crystals show very attractive spectroscopic properties for a gain medium, such as a long upper laser level lifetime (~67 us), three broad absorption bands and a emission band ranging from 650 nm to 1050 nm that overlaps with the Ti:Sapphire emission band. Flashlamp-pumped Cr:LiSAF ultrashort pulse CPA amplifiers reached peak powers up to 8.5 TW, but the operation repetition rates were always confined to low values due to the poor thermal properties of the LiSAF host, in order to avoid cracking due to thermally induced stress. Besides, the lifetime of the Cr:LiSAF laser transition is strongly temperature dependent, dropping from ~67 us at room temperature to half this value at 69C due to thermal quenching, and if the crystal temperature rises above ~25C, the nonradiactive decay generates more heat, increasing the nonradiactive decay rate, in a catastrophic process that reduces the crystal energy storage capacity and can lead to fracture. For rod shaped Cr:LiSAF gain media, amplification to the TW region was always limited under 1 Hz repetition rate.

We report the development and construction of a two-flashlamp pumping cavity for a Cr:LiSAF rod, using an approach that minimizes the crystal thermal load by decreasing the heat reaching the gain medium and being generated inside it, by the use of intracavity filters. This approach allowed a gain in excess of 3.5 per pass at 1 Hz and over 3 at 5 Hz. A four-passes multipass amplifier was built using this cavity, and it was integrated to a CPA Ti:Sapphire system, and gain over 150 was obtained, resulting in pulses with peak power of 0.5 TW.

6451-75, Session 9

Semiconductor saturable absorbers with recovery time controlled through band-gap design and growth condition

M. Guina, Tampere Univ. of Technology (Finland) and RefleKron Ltd. (Finland); P. Tuomisto, O. G. Okhotnikov, Tampere Univ. of Technology (Finland)

We discuss new concepts for shaping the temporal response of saturable absorption in semiconductors. A robust start-up of mode-locking and efficient pulse formation mechanism require a proper balance between the fast and slow components of the absorption recovery time. We achieve this by using carrier-trapping reach GaAsN layers, in-situ irradiation with ions produced by N-plasma and incorporation of N directly into the absorption region. Semiconductor saturable absorber mirrors prepared with an advanced control of the absorption recovery time have been used in Yb- and Bi-doped mode-locked fiber lasers.

6451-39, Session 10

Power scaleable reimaging waveguide laser

I. T. McKinnie, Lockheed Martin Coherent Technologies

No abstract available

6451-40, Session 10

The InnoSlab laser, extending the parameter range for industrial and scientific applications

H. Hoffmann, Fraunhofer-Institut für Lasertechnik (Germany)

No abstract available

6451-74, Session 10

J-HPPSL Nd:YAG ceramic ThinZag laser program

A. E. Mandl, D. E. Klimek, Textron Systems

Activities at Textron Systems related to the on-going development of high power diode pumped solids state lasers will be presented. This work will include improved methods of thermal management using Textron's ThinZag™ technology, which uses thin slabs of Nd:YAG ceramic gain material. The greater [Nd] uniformity and index of refraction uniformity achievable in ceramic, as compared to crystal, allows more uniform optical pumping, which leads to better thermal uniformity and translates to better medium quality. Medium and beam quality measurements will be presented. Results of scaling of a single laser module to ~15 kW of CW laser power will be presented, along with our plans for scaling to higher powers.

6451-76, Session 10

Emerging fiber laser developments

M. Neice, High Energy Laser Joint Technology Office; W. Fink, California Institute of Technology; D. D. Seeley, High Energy Laser Joint Technology Office

No abstract available

6451-41, Session 11

Laser performance of Yb3+:YAG ceramic microchip lasers

J. Dong, A. Shirakawa, K. Ueda, The Univ. of Electro-Communications (Japan); H. Yagi, T. Yanagitani, Konoshima Chemical Co., Ltd. (Japan); A. A. Kaminskii, Institute of Crystallography (Russia)

Ceramic laser materials fabricated by the vacuum sintering technique and nanocrystalline technology have gained more attentions as potential solid-state laser materials in recent years. The optical properties of Yb:YAG ceramic doped with different Yb concentrations are presented. The absorption coefficient at peak absorption wavelength of 940 nm increases linearly with Yb concentration in Yb:YAG ceramics. There is concentration quenching in highly doped Yb:YAG ceramics. Low-threshold and highly-efficient continuous-wave (cw) laser-diode end-pumped Yb:YAG microchip ceramic laser with near-diffraction-limited beam quality was demonstrated at room temperature. Slope efficiencies of 79%, 67% and optical-to-optical efficiency of 60%, 53% at 1030 nm and 1049 nm, respectively were achieved for 1-mm-thick Yb:YAG ceramic plate (CYb = 9.8 at.%) under cw laser-diode pumping. Dual-wavelength operation at 1030 nm and 1049 nm with 5% transmission of the output coupler was achieved by varying pump power intensity. 1049 nm laser operation was automatically obtained by using 5% transmission output coupler when absorbed pump power is higher than 1 W. The lasers operate in multi-

longitudinal-mode, the effect of pump power on the laser emission spectra for both wavelengths is addressed. The laser wavelength around 1030 nm shifts to short wavelength at low pump power region and then to red with increase of the absorbed pump power, while the laser wavelength around 1049 nm does not change with the pump power. Excellent laser performance indicates Yb:YAG ceramic laser materials could be potentially used in high-power solid-state lasers operating at 1030 nm, 1049 nm, or both wavelengths simultaneously.

6451-42, Session 11

Thermal and mechanical stress analysis of ceramic YAG crystals with different Nd concetrations

N. Kenar, G. Oke, A. Esendemir, Middle East Technical Univ. (Turkey)

Numerical heat and stress analysis of rod shaped laser crystals were performed. Relation between the Nd concentration and resulted stress in the crystal were investigated by considering laser diode pumping structure and mechanical boundary conditions of the crystal. Results of heat and stress analysis were used to calculate the focal length of laser crystal.

6451-43, Session 11

Modeling visible and infrared stimulated emission from Tb3+ in TbAlO3

K. L. Nash, J. B. Gruber, R. M. Yow, The Univ. of Texas at San Antonio; U. V. Valiev, National Univ. of Uzbekistan (Uzbekistan); D. K. Sardar, The Univ. of Texas at San Antonio

With recently developed diode-lasers to resonantly pump solid-state crystalline lasers, new opportunities arise for systems such as Tb^{3+} as an activator ion in different host matrices. For example the observed fluorescence from $^5D_4 \rightarrow {}^7F_5$ transition (540 to 560 nm) of Tb^{3+} in $TbAlO_3$ represents such a possibility. There is little fluorescence quenching in this crystal involving this transition, and the measured lifetime is approximately 4 ms, long enough to sustain sufficient population for stimulated emission. The quantum efficiency is better than 50 percent as measured in this material. For this same transition, others have reported room-temperature pulsed laser operation at 544 nm for Tb:YLF, where the lifetime is comparable. Mid- and long wavelength infrared laser emission has been observed for Tb^{3+} in chalcogenide glass fibers that complement our spectroscopic findings for Tb^{3+} in pedestal-grown Y_2O_3 and YAG fibers. We have identified the infrared transitions that lase as transitions between different manifolds within the ^7F_J multiplet. In the present study we first evaluate the various visible experimental findings with a Judd-Ofelt analysis of Tb^{3+} in $TbAlO_3$. We predict a radiative lifetime of 3.9 ms for the excited $^5D_4$ manifold to the ^7F_J manifolds with more than 50% of the emission represented by the $^5D_4 \rightarrow {}^7F_5$ transition. To account for the visible stimulated emission, we report transition probabilities for $^5D_4 \rightarrow {}^7F_J$ transitions and for diode-pumped infrared transitions we report similar spectroscopic properties for transitions within the ^7F_J multiplet. We comment on possible infrared transmitting hosts that have superior optical qualities in the wavelength region where the Tb^{3+} ion exhibits infrared stimulated emission.

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6451-44, Session 11

Continuous-wave diode-pumped Yb:LuVO4 lasers

J. Liu, V. P. Petrov, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany); J. Wang, J. Wang, M. Jiang, Shandong Univ. (China); U. Griebner, F. Noack, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany)

We studied several crystals of Yb-doped LuVO4 with different orientations (a-cut and c-cut) in order to evaluate the potential of this new laser material for high power continuous-wave operation using simple hemispherical cavities, longitudinally pumped by a fiber coupled diode-laser module. We achieved substantial improvement of our initial results in terms of output power and slope efficiency. The highest output power and optical efficiency were obtained for the p-polarization using a-cut samples. Under certain conditions, polarization switching and/or bistability of the input-output power characteristics in terms of a hysteresis loop were observed. Both effects are associated with increase of the crystal temperature. Significant intensity fluctuations have also been observed in a small operational region near the critical point (up-threshold) of the bistable region. The heating of the crystal is less in the lasing state when stimulated emission keeps the part of the radiative relaxation high in comparison to the nonradiative relaxation processes.

6451-45, Session 11

Determination of Cr:LiSAF crystals ablation thresholds on the 20-ps regime using a diagonal scan

R. E. Samad, S. L. Baldochi, N. D. Vieira, Instituto de Pesquisas Energéticas e Nucleares (Brazil)

The usual method to determine the ablation threshold of solid samples by ultrashort laser pulses is done by focusing the laser beam on the samples surface by a known lens, requires the knowledge of all the geometrical parameters (lens focus, beam propagation parameters, beam quality, sample position), and a series of measurements for different pulse energies.

We present here a simpler method for determining ultrashort laser pulses ablation threshold for solid samples. The method uses a focusing lens, and requires only the knowledge of the pulse power, employing a diagonal translation of the sample through the laser beam waist, resulting in a pattern etched on the sample surface. The ablation threshold is obtained measuring only one dimension of this pattern and a straightforward mathematical relation, There is no need to know any other geometrical parameter of the laser beam or of the lens used.

The technique was employed to determine the ablation threshold of pure and Cr doped LiSAF samples for 20 picoseconds pulses, and a dependence with the Cr concentration was observed.

6451-46, Session 11

Time-resolved pump-probe measurements of new cerium-doped BaY2F8 UV materials

H. Liu, D. Spence, D. Coutts, Macquarie Univ. (Australia); M. Tonelli, A. Toncelli, Univ. di Pisa (Italy)

We present an results of an investigation of the spectroscopic properties of Ce:BaY2F8 (BYF), which is a potential laser material with emission wavelength range from 320nm to 360nm. The BaY2F8 single crystals, doped with various amount of Ce3+ ions, were grown by the Czochralski technique, in an oxygen-free high-purity Argon atmosphere.

Like other cerium doped UV materials (Ce:YAG, Ce:LiCAF, Ce:LiLuF, Ce:KYF), excited-state absorption (ESA) and color centres formation in Ce:BYF are the two main factors that can affect laser performance, and may even prevent laser action. We will present the results of experiments investigating the potential for laser action in Ce:BYF.

We have employed a time-resolved pump-probe technique to look for net gain in Ce:BYF. We used a Ce:LiCAF laser emitting 3 ns pulses at 290 nm to pump the crystal, and a Ce:LiLuF laser emitting sub nanosecond pulses at 327 nm to probe the net gain or loss in the centre of the Ce:BYF emission band. Measurements were made for all combinations of pump and probe polarisations; the effective emission cross-section and rate of colour centre creation are found to be strongly polarisation dependent. We observe strong absorption from colour centres with millisecond and second lifetimes that will certainly prevent high rep rate laser action with these

crystals, although it may be possible for low rep rate laser action to be achieved.

6451-19, Session 12

Detailed single-shot spectral measurements of Q-switched solid state lasers

C. Veltkamp, A. B. Petersen, J. D. Kafka, Spectra-Physics

A system has been developed to measure energy and longitudinal mode characteristics of single Q-switched pulses from TEMoo Nd:YVO4 lasers operating at up to 100 kHz. Design and operation of the system is discussed along with statistical results for four representative lasers. Differences are shown between single pulse and time-averaged spectra.

6451-47, Session 12

High-power DPSS laser hosted on a HMW-THS

M. Checchetti, Microptronics Srl (Italy)

The Hollow Metallic Winglets / HMW-THS, a turbo engine optimised for cooling electronics, handles large flows of energy, gas and air. Its heat exchanging shell, of huge area, tops the pressurised Can; a window fits the bottom. The hosted machine can integrate the main gas ducts and the inner structures. Considering the power levels, the ducting ease of both outer air flows is important and cuts noise.

Two banks of Laser Diodes, monolithic or hybrid, side feed each lasing Z-slab, thin and exposed to the cooling gas, flowing fast on both sides. The least path to reach the cooling gas minimises dT; to cut the thermal lensing effects, cooling can copy the heating density. The simplest layout is preferable but the current schemes and materials seem suitable; where required, the slab ends etc can be Brewster cut etc.

The pressure affects mildly only the outer window. Compactness and more degrees of symmetry lead to a natural athermal behaviour; a MOPA configuration ensures a good coherence.

The neuter, clean He sports a top CP and flows easily; speed and pressure increase the heat removal rate and reduces dT; the fast cycle can be important. H2 would spoil the HT / HR coatings, the electronics and generates water. Note that He was used to cool the largest AC generators.

Dedicated turbo stages can generate colder flows to cool better some hotter spots or to exploit better the weak elements.

6451-48, Session 12

Autostabilization of generations of solid state laser with nonlinear transparency absorber

A. S. Kuchyanov, Institute of Automation and Electrometry (Russia)

It well known that the inserting of nonlinear transparency absorber (NTA) with relatively high initial optical density into the laser resonator leads to a generation of one or several short pulses. Usually, the mode locking regime obtained by the technique has low reproducibility of one ultra-short pulse in axial period from flash to flash.

In this work we have found that the dynamics of generation this kind of laser under proper conditions may differ from common laser situation.

We have experimentally proved that in YAG:Nd laser with nonlinear transparency absorber (NTA) 3274u when the level of pumping closed to the threshold and when intercavity radiation is focused into the cell with NTA, autostabilization of generation can be easily obtained.

Duration of the laser generation is increased and it reached of 10-12 microsecond. It was found that the intensity of the generation of this laser is almost constant. Note, that the reproducibility of a single picosecond pulse in axial period achieved the level of 100% under mentioned above condition.

We propose the following explanation of this phenomenon. At the beginning of the generation the developing of the intensity of radiation in NTA is closed to the level of absorbtion saturation (it is because the radiation is focused into NTA). Due to this condition, the rate of intracaviy field growth is increased and it approaches the rate of inversion population accumulation which is controlled to be at minimum. It is clear that under this condition the intensity of laser radiation becomes constant. A long period of interaction of NTA with intracavity radiation leads to significant (up to the 100%) growth of reproduction of one ultra-short pulse in axial period from flash to flash.

6451-49, Session 12

1.44 um giant pulse generation

J. Šulc, H. Jelínková, P. Arator, K. Nejezchleb, V. Škoda, Czech Technical Univ. in Prague (Czech Republic)

No abstract available

6451-51, Session 13

Lasers in confocal imaging - standard applications and new trends

E. Simbuerger, Carl Zeiss Jena GmbH (Germany)

Confocal mircroscopy depends on the use of lasers as a light source due to the prinicple of this imaging method. Apart from using this light source just for imaging fluorescent dyes, several years back researchers started to use UV laser light to release chemically modified substances which then allowed to directly investigate the effects of theses molecules onto living cells and tissue. In addition the discovery and use of fluorescent porteins as intrinsic markers for specific cell structures boosted the direct observation of molecular processes in living cells or cultured tissue explants. This requested the use of specific and more powerful lasers to enable the manipulation of these fluorescent proteins and to allow high speed imaging which is essential for the study of protein dynamics. Besides standard confocal microsopy using all kinds of visible lasers the use of utrafast lasers for multiphoton excitation has become a preferred tool for high resolution imaging of fluorescently labelled cells and cell structures in tissue and even in living animals. This underlines the prominent trend to study function and dynamics of labelled molecules in living organisms instead of just the amount and distribution of molecules in fixed and conserved preparations. Both, the availabilty and variety of laser sources and the development of flurescent labels within the biomedical research have enabled a tremendous amount of imaging techniques providing new insights into the dynamics of life.

6451-52, Session 13

Industrial microprocessing with advanced solid state lasers

J. Stollhof, S. Weiler, D. Sutter, J. Kleinbauer, M. Kumkar, TRUMPF Laser GmbH & Co. KG (Germany)

Trumpf Laser has developed an advanced solid-state q-switched laser, designed specifically to meet the requirements of industrial micro-processing. Pulse energies exceeding 4 mJ, pulse durations adapted to the application and a diffraction limited beam ($M^2 < 1,2$) are essential for micro-machining. A novel feature of the laser ensures its particularly high performance and overall stability. The technical concept is based on a power oscillator, where the output power is not set by adjusting the pump power, but rather by precise switching and attenuation of the pulses outside of the resonator. This leads to a high stability and a fixed concentric beam profile, independent of the actual output power of the system.

In the field of micro processing, laser light is primarily used for the precise ablation of various materials. High intensities almost 1 GW/cm^2 enable the development of new laser processing strategies, e.g. sublimation-cutting and -drilling. High stability in terms of beam quality, beam location (pointing stability < 10 μrad) and pulse energy allows for both the improvement of well known laser processes as well as pushing forward

new applications. Additionally, the repetition rate of up to several hundred kilohertz and the high average power emphasizes the high performance of the developed system, particularly with regard to the competition with alternative manufacturing strategies.

Further potential to increase the precision and to minimize the heat affected zone (HAZ) is given by the application of ultrashort picosecond and femtosecond pulses. Trumpf Laser has already demonstrated a CPA-free, diode-pumped all-solid-state thin-disk laser, delivering ps-pulses with an average power of 50 W.

6451-53, Session 13

Advances in laser processing of microelectronics

B. W. Baird, R. F. Hainsey, S. Peng, P. Y. Pirogovsky, Electro Scientific Industries, Inc.

Current trends in advanced laser processing of microelectronics require development of a diverse array of pulsed solid state laser sources. The range of laser processes for advanced semiconductor memory, including dynamic random access memory (DRAM) and flash memory, span 355 nm to 1343 nm and demand pulse repetition frequencies greater than 50 KHz from laser sources with excellent fundamental spatial mode performance. Advanced high speed laser micromachining of semiconductors, ranging from logic devices to solar cells, demand high average power and high pulse repetition frequencies, and a broad range of wavelengths and laser pulsewidths. Implications for advanced pulsed solid state laser architectures and microelectronic laser processes will be discussed.

6451-54, Session 13

Frequency stabilization of q-switched Nd:YAG oscillators for airborne and spaceborne lidar systems

K. Nicklaus, V. Morasch, M. Höfer, J. Luttmann, M. Vierkoetter, H. Hoffmann, Fraunhofer-Institut für Lasertechnik (Germany); M. Ostermeyer, Univ. Potsdam (Germany); J. Höffner, Leibniz-Institut fur Atmospharenphysik e.V. (Germany)

Lidar Systems for the measurement of three-dimensional wind or cloud and aerosol formations in the earth atmosphere require highly stable pulsed single frequency laser systems with a narrow line width. The lasers for ESAs ADM-Aeolus and EarthCARE missions require frequency stabilities of 4 and 10 MHz rms at a wavelength of 355 nm and a line width below 50 MHz at 30 ns pulse duration. Transferred to the fundamental wavelength of the laser systems the stability requirement is 1.3 and 3 MHz, respectively. In comparison to ground based lidar systems the vibrational load on the laser system is much higher in airborne and spaceborne systems, especially at high frequencies of some hundred Hertz or even some kHz. Suitable frequency stabilisation methods have therefore to be able to suppress these vibrations sufficiently. The often used Pulse-Build-up method is, due to its very limited capability to suppress vibration frequencies of the order of the pulse repetition frequency, not suitable.

In this study the performance of three frequency stabilisation methods in principle capable to meet the requirements, the cavity dither method, the modified Pound-Drever-Hall method and a modified Ramp-Fire method - named Ramp-Delay-Fire - is theoretically and experimentally investigated and compared.

The investigation is performed on highly efficient, passively cooled, diode end-pumped q-switched Nd:YAG oscillators, which are breadboard versions of the A2D (ADM-Aeolus) and possible ATLAS (EarthCARE) oscillators. They deliver diffraction limited output pulses with up to 10 mJ pulse energy at a pulse duration of 30 ns and 100 Hz pulse repetition rate.

6451-55, Session 13

The injection laser system on the National Ignition Facility

M. W. Bowers, S. C. Burkhart, S. J. Cohen, G. V. Erbert, J. E. Heebner, M. R. Hermann, D. R. Jedlovec, Lawrence Livermore National Lab.

The National Ignition Facility (NIF) is currently the largest and most energetic laser system in the world. The main amplifiers are driven by the Injection Laser System comprised of the master oscillators, optical preamplifiers, temporal pulse shaping and spatial beam formatting elements and injection diagnostics. Starting with two fiber oscillators separated by up to a few angstroms, the pulse is phase modulated to suppress SBS and enhance spatial smoothing, amplified, split into 48 individual fibers, and then temporally shaped by an arbitrary waveform generator. Residual amplitude modulation induced in the preamplifiers from the phase modulation is also pre-compensated in the fiber portion of the system before it is injected into the 48 pre-amplifier modules (PAMs). Each of the PAMs amplifies the light from the 1 nJ fiber injection up to the multi-joule level in two stages. Between the two the pre-pulse is suppressed by 60 dB and the beam is spatially formatted to a square aperture with pre-compensation for the nonuniform gain profile of the main laser. The input sensor package is used to align the output of each PAM to the main laser and acquire energy, power, and spatial profiles for all shots. The beam transport sections split the beam from each PAM into four main laser beams (with optical isolation) forming the 192 beams of the NIF. Optical, electrical, and mechanical design considerations for long term reliability and availability will be discussed. Work performed under the auspices of the U. S. Department of Energy under contract W-7405-Eng-48.

6451-56, Session 14

A consideration of the requirements for laser devices used in countermeasure applications

D. H. Titterton, Defence Science and Technology Lab. (United Kingdom)

Laser device technology has developed rapidly in the laser few years and it is used in many applications spanning the civil and military sectors. The military operational use of laser technology has been responsible for highly significant improvements in many weapon systems, such as guidance accuracy. Recent developments in solid-state laser technology, in terms of its efficiency and size, have lead to an interest in the use of this technology for countermeasure applications.

This paper will consider the current status of a number of classes of laser technology and its potential application to countermeasure systems. This review will also outline approaches to defining a laser-based system so that the device is compatible with the whole system. The importance of an integrated approach to system design will be emphasised.

6451-57, Session 14

Narrow linewidth coherent beam combining of optical fiber amplifier arrays

T. M. Shay, Air Force Research Lab.

The techniques for combining multiple high power fiber amplifiers into a single high brightness beam will be presented. The techniques which reduce system weight will be discussed.

6451-58, Session 14

CALIPSO on-orbit lidar performance

W. S. Luck, Jr., NASA Langley Research Ctr.

The CALIPSO satellite is a joint NASA and CNES (Centre National d'Etudes

Spatiales) ESSP (Earth System Science Pathfinder) mission that will provide unique new measurements, from space, of Earth's clouds and atmospheric aerosols. The CALIPSO payload consists of the following three co-aligned, nadir-viewing instruments: the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP), the Imaging Infrared Radiometer

(IIR), and the Wide-Field Camera (WFC). The CALIOP and WFC were both developed for and with the cooperation of NASA by Ball Aerospace, and the IIR is provided by our French counterparts at CNES. CALIPSO and CloudSat were both successfully launched into space from a Delta II rocket on April 28, 2006. CALIPSO will then undergo a nominally 45-day commissioning phase prior to a nominally 45-day assessment phase from which point the Payload engineering team will have completed hand over of the Payload to science mission operations team for the remainder of the 3-year mission. This paper will briefly describe the CALIPSO Payload before proceeding to describe the on-orbit engineering performance, through assessment phase (nominally 90 days after launch), of the CALIPSO payload with particular focus on the Lidar and the Wide-Field Camera and their signal-to-noise performance.

6451-59, Session 14

High resolving power tunable filter for spaced-based lidar applications

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A novel photonic-crystal-based Fabry-Perot filter has been developed capable of producing sub-angstrom spectral resolution, high throughput, and a broad (~several nanometers) tuning range. The materials, size, mass and power requirements are suitable for use in space-based optical systems. Theory, design and recent test results are presented.

6451-50, Poster Session

Super-Gaussian pumping profiles for solid state lasers

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For a diode end-pumped solid state laser, the pump beam is described as a Gaussian profile initially and then as a flat-top profile. In fact, the fiber-coupled pump beam is more accurately fit by a super-Gaussian beam. With the same beam waist, different beam profiles can be obtained with different m. It is a Gaussian profile if m = 1; and it is a flat-top profile if m is infinite. The super-Gaussian beam should be normalized before it is used to characterize the thermal and optical properties of a solid state laser. With this normalized super-Gaussian pump beam, the corresponding analysis on thermal temperature, thermal radial and tangential stresses, refractive index changes, OPD, birefringence, depolarization loss, and rate equations are modeled more accurately. At the meantime, as the progress of diode laser echnology, powerful and narrow line width diodes are becoming available. It is possible to directly pump nonlinear crystals such as KTP, LBO for second harmonic generation using diode laser. Nonlinear conversion efficiency is discussed. Thermal properties for a super-Gaussian beam (with different m) on nonlinear crystal are analyzed using finite element analysis.

6451-62, Poster Session

Five simultaneously q-switch mode-locked passive laser modulators

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

Five types of passive Q-switched as well as simultaneously Q-switch mode-locked modulators: plastic dye sheets (Kodak 9850 cellulose acetate dye sheets), lithium fluoride crystals containing F2- color centers (LiF: F2-), chromium doped yttrium aluminum garnet crystals (Cr4+:YAG), ionic color filter glass (Schott RG1000 color filter glass) and the single crystal semiconductor wafers (GaAs, Fe doped InP, Zn doped InP, S doped InP, etc.) used for the modulation of the Nd:hosted(Nd:YAG, Nd:YVO4, and Nd:LSB) lasers have been investigated in detail in our researches. We have also investigated into the applications of the Q-switch mode-locked pulses train for the development of higher resolution solid state laser range finder.

6451-64, Poster Session

Ultra-narrow-linewidth combined CW Ti:sapphire/dye laser for atom cooling and high-precision spectroscopy

S. M. Kobtsev, Novosibirsk State Univ. (Russia); V. I. Baraoulya, V. M. Lunin, Tekhnoscan JSC (Russia)

Presented is a new combined CW single-frequency Ti:Sapphire/Dye laser with horizontal ring cavity and with improved stability of output frequency. Short-term output line width does not exceed 10 kHz for the Ti:Sapphire laser and amounts to 90 kHz for the Dye laser, output frequency drift being less than 30 MHz/hour.

In this paper we present an original and relatively simple transformation of Ti:Sapphire laser configuration suggested by S.Bourzeix et al. (Opt. Commun., 99, 89-94, 1993) into a single-frequency ring dye-jet laser. Given are the test results of the combined Ti:Sapphire/Dye laser in the passive and active modes of frequency stabilisation, as well as at different levels of pump power. We also analyse particulars of the smooth automatic scanning of the output frequency of the combined laser important for its applications.

It is shown that the vertical position of the dye solution jet in the Dye laser with horizontal ring cavity does not affect negatively the laser generation parameters. Efficient suppression of typical jitter of the output line is demonstrated at frequencies up to ~100 kHz by way of specially designed actuators based on thin PZT which allowed to avoid using an electro-optical modulator in the frequency stabilisation system. The combined laser features relative high output efficiency: the maximum output power with a 10-W pump (532/515 nm) exceeds 2 W for the Ti:Sapphire configuration and is > 1.6 W for the Dye one.

6451-65, Poster Session

A compact remote-controlled underwater lidar system

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Lidar is an important equipment for the accurate detection of underwater targets. In this paper, a compact and remote-controlled lidar system is described. The system contains four modules which are Q-switchen Nd:YAG pulse laser module, optical detect module, data collector module and remote-controlled module. All of the modules are put into a hermetic container. The lidar system can be in operation under the water and carried by a underwater carrier such as ROV (Remotely Operated Vehicle). The operator controls the lidar and downloads the data from the system through a fiber. The system can automatically eliminate the return signal due to the surface wave. The system has been used in underwater bubble detection. A brief description of the lidar system and its operation is present in the paper. The experiment results of underwater bubble measurement are discussed.

6451-66, Poster Session

Optimization of q-switch performance of Co2+ by crystal-field tuning of the stark levels in the absorber host crystal for the resonantly pumped Er:YAG laser (1.6 μm)

B. Zandi, Army Research Lab.; J. B. Gruber, The Univ. of Texas at San Antonio; A. S. Nijjar, nLight Corp.; M. R. Kokta, Saint Gobain Crystals; D. K. Sardar, K. L. Nash, The Univ. of Texas at San Antonio

Currently the saturable absorber Co2+ in the spinel matrix (MgAl2O4) is a popular Q-switch for stimulated emission in the infrared, eyesafe region involving the transitions of Er3+ (4I13/2 to 4I15/2) in hosts, including the garnets and phosphate glasses. A little known property of the spinel phase diagram not yet exploited for its potential as a Q-switch matrix, is that the spinel system is a series of related congruent compounds with Co2+ as a dopant that can be expressed as Mg(1-x)Cox AlBOC where B = 2,4,6, and C = 4, 7, 10, with x representing the amount of Co2+ that substitutes for Mg2+ in tetrahedral sites of Td symmetry. The point group symmetry of Co2+ does not change across the phase diagram of variable stoichiometric compositions, but the strength (magnitude) of the crystal field at the Co2+ site does change as the ionic separations between ionic charges change to accommodate minimum energy considerations. As a consequence, the spectroscopic properties including the wavelengths of absorption and emission, the cross sections of the vibronic/electronic transitions, and the lifetimes of Co2+ change as a function of wavelength for the absorbing 4T1 manifold observed between 1.5 and 1.8 microns (the manifold involved as the saturable absorber for the Er3+ laser). Holding the concentration of Co2+ constant, we first optimize the spectroscopic properties of Co2+ to the specific wavelength of stimulated emission of Er3+ in different hosts the as a function of Mg and Al concentrations across the phase diagram from MgAl2O4 to MgAl4O7 to MgAl6O10. Secondly, we vary the concentration of Co2+ and carry out additional optical studies to optimize Q-switch performance relative to a specific laser cavity configuration.We have carried out spectroscopic measurements as well as Q-switch modeling studies on optimized compositions of these spinels doped with Co2+ as the saturable absorber for Q-switched Er:YAG and Er,Yb: glass microchip lasers. Our findings indicate that a more efficient Q-switch can be obtained for either laser by tuning the wavelength of the absorber through compositional variations in Mg and Al. To predict the relative performance of each absorber so designed for optimized performance, we have developed multi-dimensional coupled rate equations that involve a set of quasi-three level gain and four-level absorber rate equations. It is possible to maximize Q-switch performance to the several individual wavelengths of stimulated emission in Er:YAG by this method of tuning the crystal field of the Co2+ ion.

6451-67, Poster Session

Spectroscopic performances and diode-pumped lasing of calcium-niobium-gallium garnets (CNGG) and sodium-gadolinium tungstates (NGW) doped with Tm3+ ions

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The crystals CNGG (Ca3Nb1.67Ga3.2 0.11O12) and NGW (NaGd(WO4)2) have initially disordered structure. Application of the crystals with the disordered structure doped with TR3+ ions, gives a number of advantages before crystals having regular structure at using the laser diode pumping. First, the best agreement of diode-pumped radiation spectra and absorption spectra of the TR3+ ions is provided. Second, the wide inhomogeneous broadening of TR3+ ions luminescence spectra are enabling of smooth returning of lasing wavelength, and also realizating of ultrashort generation pulses in mode-locked. Third, the crystals with disordered structure are exceeding the industrial laser glasses in the mechanical and thermophysical properties.

The emission cross-sections of Tm3+ ions laser transition 3F4-3H6 was calculated by Fuhtbauer-Ladenburg technique at the first time in the CNGG:Tm3+ and NGW:Tm3+ crystals. The highest possible value of emission cross section was em(λ=1860 nm)=0.4*10-20 cm2 Π em(λ=1800 nm)=1.9*10-20 cm2 for the CNGG and NGW crystals correspondingly. The ratable lifetime of excited state 3F4 in accordance with the data of kinetics decay from the state 3F4 was no more than 7.6 ms (CNGG) and 1.5 ms (NGW). The inhomogeneous broadening of the luminescence band in the 1.90-2.02 μm spectral range makes possible to achieve lasing and tunable in the range of wavelength. Diode-pumped free-running lasing was obtained in the 1.98-2.0 μm spectral range. The achieved slope efficiency of this lasing made 10%. The crystal improving and composition optimization will allow increase both the generation spectral range and the output laser performances.

The work is supported by RFBR No. 04-02-16479.

6451-68, Poster Session

A promising new Yb-doped oxyorthosilicate laser crystal Yb:Gd2SiO5

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A new Yb-doped oxyorthosilicate laser crystal, Yb:Gd2SiO5 (Yb:GSO), and mixed crystals such as Yb:(Lu1-xYx)2SiO5 and Yb:(Gd1-xYx)2SiO5 have been grown by the Czochralski method.Compared with Yb:YSO,Yb:LSO oxyorthosilicate crystals[1], Yb:GSO is monoclinic symmetry with space group of P21/c[2]. Ytterbium experiences quite a strong crystal-field interaction in GSO host and the overall splitting of the 2F7/2 manifold reaches about 1076 cm-1, which is one of the largest known values and larger than those of oxyorthosilicates.Yb:GSO appears as an interesting laser medium approaching a quasi-four-level laser scheme, which results in easy population inversion and a low threshold value. Particularly, the emission band at 1088 nm possesses the largest branching ratio and the largest emission cross section, for the smallest thermal populating of the terminal laser level which brings about smallest re-absorption losses.

Tunable continuous-wave,passively Q-switched and mode-locked laser actions of Yb:GSO pumped by LD have been demonstrated. Through the preliminary laser experiment, a slope efficiency up to 86%. a low threshold of 77mW and 639fs mode-locked pulses were achieved for a continous wave Yb:GSO laser at 1092.5nm. For the Q-switched output, the laser operated at 1047.5nm with an InGaAs saturable absorber. The pulse repetition rate was from 20kHz to 36kHz and was increased with the pump power.

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6451-69, Poster Session

Characteristics of Q-switched Er:YALO3 operating at eye-safe wavelengths

K. Rogers, S. Sharma, R. K. Shori, O. M. Stafsudd, Univ. of California/Los Angeles

No abstract available

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6452-09, Session 1

Dispersive elements for enhanced-laser gyroscopy and cavity stabilization

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We analyze the effect of a highly dispersive element placed inside a modulated optical cavity on the frequency and amplitude of the modulation to determine the conditions for cavity self-stabilization and enhanced gyroscopic sensitivity. We find that group indices with magnitudes larger than the phase index (both normal and anomalous dispersion) are found to enhance the sensitivity of a laser gyroscope to rotation, whereas group indices with magnitudes smaller than the phase index (anomalous dispersion only) can be used to self-stabilize an optical cavity. Our results indicate that atomic media, even coherent superpositions in multilevel atoms, are of limited use for these applications, because the amplitude and phase filters work against one another, i.e., decreasing the modulation frequency increases its amplitude and vice-versa, with one exception: negative group indices whose magnitudes are larger than the phase index result in negative, but enhanced, beat frequencies. On the other hand, for optical resonators the dispersion reversal associated with critical coupling enables the amplitude and phase filters to work together under a greater variety of circumstances than for atomic media. We find that for single over-coupled resonators, the absorption and normal dispersion on-resonance increase the contrast and frequency of the beat-note, respectively, resulting in a substantial enhancement of the gyroscopic response. For the application of cavity self-stabilization, we propose the use of a unique variety of induced transparency that is accompanied by anomalous dispersion.

6452-11, Session 1

Nanojet-induced modes in 1D chains of microspheres

A. M. Kapitonov, V. N. Astratov, The Univ. of North Carolina at Charlotte

We report on the light transport phenomena in linear chains composed of several tens of touching spherical microcavities. A new optical mode type, namely nanojet-induced modes (NIMs) is directly observed. These modes result from the optical coupling of microspheres acting as a series of micro-lenses, which periodically focus propagating wave into photonic nanojets. Theoretically, formation of periodic nanojets has been predicted in (Z. Chen, A. Taflove, and V. Backman, Opt. Lett. 31, 389 (2006)).

The chains were formed by means of the self-assembly directed by micro-flows of water suspension of polystyrene microspheres. The standard size dispersion of spheres in each particular chain was below 3%, while mean size of spheres was varied in the 2-10 micron range. To couple light to NIMs we used built-in emission sources formed by several locally excited dye-doped microcavities from the same 1-D chain. The coupling of external plane waves is also feasible. Conversion of modes emitted by the light source into the NIMs results in losses of several dB per sphere in the vicinity (first few tens of spheres) of such sources. At longer distances we found an attenuation rate as small as 0.5 dB per sphere, that reveals low intrinsic propagation loss for NIMs.

The NIMs have potential applications for coupling of light in and out of spherical cavities characterized by extremely high quality (Q) whispering gallery modes and for guiding of emission in compact arrays of such microcavities.

6452-15, Session 1

Dynamically-tuned microresonator complexes

M. L. Povinelli, S. Sandhu, S. L. Fan, Stanford Univ.

We describe recent theoretical work exploring the use of dynamic modulation of microresonators to achieve slow and stopped light in photonic crystals and microring-resonator structures. In systems of many coupled resonators, we show that refractive index tuning can be used to achieve dispersion-free time delays limited only by residual loss. Dynamic tuning of simpler systems of two microresonators coupled to waveguides is predicted to lead to a range of trapping, filtering, and frequency conversion effects. Further, we show how interference between multiple coupled resonators can greatly reduce the radiation loss values in photonic-crystal slab systems, yielding enhanced modal quality factors.

6452-23, Session 1

Field confinement and atom manipulation with optical nanofibers

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

Optical resonators have widely been used in quantum optics to manipulate quantum electrodynamic effects associated with the confinement of the electromagnetic fields. Recently, thin optical fibers with subwavelength diameters, termed as optical nanofibers, have attracted considerable attentionsin a similar context. We discuss how the optical nanofibers may open new approaches for manipulating single atoms and single photons with great flexibilities, which offer new tools for quantum optics, especially for quantum information technology. We demonstrate theoretically that spontaneous emission of atoms may be strongly enhanced around nanofibers and an appreciable amount of fluorescence photons may be emitted into a single guided mode of the nanofibers. Furthermore, we show that two distant atoms on the nanofiber surface may be entangled through the guided mode. Novel atom trapping schemes are also proposed using optical nanofibers. We experimentally demonstrateuse using laser-cooled Cs-atoms how optical nanofibers can work for manipulating and probing single-atom fluorescence. We show that fluorescence photons from atoms around the nanofiber are measured efficiently by observing photons through the fiber guided mode. We show also that due to the inherent nature of the nanofiber method the fluorescence excitation spectrum strongly reflects the effect of van der Waals interaction between atoms and nanofiber surface.

6452-46, Session 1

Beam-quality-enhancement in multi-kW rod-based lasers by use of radially-polarized light and phase-front correction

I. Moshe, S. M. Jackel, A. Meir, Y. Lumer, G. Machavariani, S. Rosenberg, Soreq Nuclear Research Ctr. (Israel)

High-power rod-based solid-state lasers have been widely-used for many years. Switching from flashlamp to diode pumping resulted in a jump in beam-quality, but performance was still modest. M2 value of 70-100 were achieved. We here demonstrates a further dramatic improvement in the beam quality of multi-KW CW Nd:YAG lasers by use of radial-polarization and aberration compensation. To date, we have achieved M2 on the order of 10, and the road-map for achieving M2 2 is clear.

Rod based lasers have the advantage of simplicity. Unfortunately, rods suffer from thermal effects that degrade beam quality as power increases. The main degradation factors are thermally induced bifocusing and spheri-

cal aberration (SA). Non-radially-symmetric pump distributions cause non-radially-symmetric aberrations.

For unpolarized or linear polarizations, bifocusing is the worst degradation factor. We bypass this aberration by using radially or azimuthally polarized beams, as these polarizations interact with just one bifocal-lens axis. Thermal SA in laser rods has a positive sign, opposite to the negative SA of convex spherical lenses. We exploit this fact to produce a SA compensator based on two plano-convex positive lenses in a relay-imaging telescope. Non-radially symmetric aberrations are compensated using two rotated pump-chambers.

We applied these compensation techniques in a Master-Oscillator-Power-Amplifier laser. A radially polarized beam was generated in an oscillator and was amplified in an amplifier chain. Most of the power was added to the beam with Soreq manufactured 2kW amplifiers. Output power was >2KW with M2<10 (beam-parameter-product <3.3mm•mrad). Light-light efficiency of the last amplifier was about 30%.

Improvements to this system now focus on a new pump chamber designed for excellent radial symmetry, on application of higher order aberration correction elements, and on coherent wavefront manipulation to transform the a TEM01* radially polarized output beam into a linearly polarized TEM00 beam (we have shown that output M2 can be improved by 1.93x).

6452-01, Session 2

Diffractive gradient mirror as an effective intracavity element for TEM00 mode shaping of the Nd:YAG laser

A. I. Plekhanov, A. S. Kuchyanov, A. G. Poleshchuk, V. V. Cherkashin, Institute of Automation and Electrometry (Russia)

One of the effective methods of controlling of the space and energy characteristics of laser radiation is the usage of mirrors with variable reflection coefficient on radial co-ordinate as intracavity elements. In this paper, we report on the diffractive optical ele-ment as intracavity gradient mirror for the Nd:YAG laser in order to produce single transverse mode oscillation with large volume. The main feature of this element is using of zero order diffraction. We have used a mirror with the reflection coefficient described by super Gaussian function R(r) = R_0*exp [-2(r/w)^8], where R is the reflection coeffi-cient in the center of mirror (R_0 = 50% in our experiment), w is the parameter of mir-ror? radius. The reflection coefficient is determined by the duty cycle of circular diffrac-tive structure. The dielectric cover has been made for the increasing of reflection coeffi-cient Elaborated technology allows us to create the assigned diffractive structure on a fused quartz with 5-10 J/cm^2 damage threshold. In our laser with the gradient mirror and with full aperture of active element the divergence of one-mode radiation of laser became 1,5*10^(-4) rad and the output energy of the Nd:YAG laser with gradient and ordinary mirror did not differ essentially from each other and it was 30 mJ.

6452-02, Session 2

Accuracy of laser beam parameters and beam propagation from real-time Hartmann-Shack experiments

B. Schäfer, K. R. Mann, Laser-Lab. Goettingen e.V. (Germany)

Experiments in laser physics often require more comprehensive information about a beam than can be extracted from single spatial profile measurements alone. In particular, the determination of irradiance and phase distribution at locations were measurement is difficult as well as the accurate measurement of important 2nd order moment based beam parameters, as e.g. M^2, divergence or Strehl-ratio, are quite often essential for a wide class of laser applications.

Here we compare Hartmann-Shack results of numerical beam propagation and parameter estimation to camera based profile measurements and the standard ISO 11146 procedure, respectively. Laser beams of various complexity, reaching from He-Ne fundamental mode beams (with and without aberration) over high-energy Q-switched Nd:YAG nanosecond pulses to ultra-broadband laser pulses with a spectral bandwidth of >190 THz were investigated. For spatially coherent, high to moderate quality beams (M^2<2) the numerically propagated and measured beam profiles are in good agreement and 2nd order moment beam parameters differ by less than 5% for the standard method and Hartmann-Shack.

Drawbacks and opportunities of the Hartmann-Shack technique for means of propagation prediction of laser beams are discussed.

6452-04, Session 2

Improvement and commissioning of a novel technology for the measurement of laser-beam profile

S. R. G. Hall, S. D. Knox, A. Bridge, National Physical Lab. (United Kingdom); D. A. Robinson, H. Yang, Arden Photonics Ltd. (United Kingdom)

Measurement of the laser beam propagation factor M2 is essential in many laser applications including materials processing, laser therapy, and lithography. In this paper we describe the characterisation of a prototype device using a distorted diffraction grating known as an Image Multiplex (IMP®) grating, to measure the M2 value of laser beams. The advantage of the IMP® grating instrument lies in its ability to simultaneously image nine positions along the beam path. This enables beam propagation parameters to be calculated both for pulsed lasers and lasers with rapidly changing propagation characteristics. This is in contrast to the scanned technique recommended by the ISO, which is relatively slow and in practice can only be easily used with cw sources. The characterisation was accomplished by comparison of results from the IMP® grating device with those obtained using the accepted methodology described in the ISO 11146 series of standards. The scope of the work also included provision of a traceability route to international standards, and an uncertainty budget, to allow the intended user community to have confidence in measurements obtained when using the device, and to enable them to use it as part of their quality framework.

6452-05, Session 2

Beam profiling at focus- the search for the Holy Grail

L. I. Green, Spiricon, Inc.

Electronic laser beam profiling is now a widely accepted method to measure the mode quality and spatial profile of a laser beam. For the most part, profiling has been limited to the unfocused or ‘raw’ beam, because the energy density or irradiance in the vicinity of focus is high enough destroy almost any measurement device. Recent developments in measuring technology now enable users to make beam profiling measurements at and near the focus of many lasers. We discuss this new design and show examples of how it functions.

6452-45, Session 2

Beam quality measurements with Shack-Hartmann wavefront sensor and M2-sensor: comparison of two methods

J. V. Sheldakova, A. V. Kudryashov, V. Y. Zavalova, Moscow State Open Univ. (Russia); T. Cherezova, M.V. Lomonosov Moscow State Univ. (Russia)

In both scientific and industrial laser beam applications is essential for users to know what could be expected from the laser beam. That is why analysis of the laser beam parameters is very important during laser use in various industrial and scientific applications. To describe the beam one can use a beam quality factor M2 that characterizes the degree of imperfection of a laser beam.

There are many methods of beam quality determination. The most common way is to use a device based on techniques described in the International Standard ISO11146 “Test methods for laser beam parameters: Beam widths, divergence angle and beam propagation factor”. For example we can use M2-sensor that we design and produce in our Lab.

The measurement of the beam quality factor according to ISO11146 is not a simple procedure and might take a long time. And for some applications fast beam quality determination is needed. Moreover sometimes it is not necessary to know the exact value of M2, only estimation of M2 is just needed. And for the beam quality estimation we suggest to use Shack-Hartmann wavefront sensor. With this sensor we can easily and fast measure the wavefront of the beam and then according to the wavefront calculate M2.

The comparison of two sensors is presented. Advantages and disadvantages are pointed out.

6452-03, Session 3

Adaptive wavelets applied to mode-structure stability in diode-laser arrays

K. J. Jones, Rice Univ.

Progress in laser resonators and beam control requires new criteria for laser beam characterization, especially with spatial and longitudinal modes which tend to oscillate and are critical to their role as high power pump sources in solid state lasers. Previous papers by the author (K. J. Jones, 2005), (K. J. Jones, 2006) have applied wavelet phase extraction and adaptive wavelets to distortion correction in laser diode arrays. Adaptive optics aims at achieving greater dynamic stability in laser systems. This investigation examines multiple spatial and longitudinal modes in diode laser arrays and applies wavelets, first to determine the phase of the oscilating modes and adaptive wavelets to minimize mode distortion.

Wavelet-based phase determination. A series of 1-D profiles are taken of the perpendicular profile of a diode laser array. The 1-D signals are plotted. The Morlet wavelet transform of the signal is taken and plotted as a spectrogram. The ridge extraction algorithm may then be applied to determine the phase of the signal and plotted on the spectrogram. These show the high complexity of the oscillatory mode in the perpendicular profile.

Adaptive wavlet distortion correction is based on filter banks and echo cancellation. The phase determined above contains both signal and noise. High frequency noise is easily eliminated. The challenge comes in breaking down the phase with filter banks and selectively cancelling noise in an approach analogous to echo cancellation.

This investigation will continue prior work applying adaptive wavelets to suppress mode distortion in diode laser arrays.

6452-06, Session 3

Adaptive optics control of solid state lasers

W. Lubeigt, G. J. Valentine, D. Burns, Univ. of Strathclyde (United Kingdom)

Thermally-induced distortions are a major impediment to power scaling in solid-state lasers. These aberrations severely limit the transverse mode quality and efficiency of the laser. Although the spherical component of the thermal lens can be accounted for in the cavity design, there is no simple, effective way of compensating against the effects of the non-spherical component. The thermal distribution in the gain medium is also responsible for the time taken to reach full brightness.

Our work focuses on using adaptive-optics elements to control/enhance the laser capabilities. A closed-loop system was constructed featuring a fitness sensor to determine laser performance, and a PC hosting the optimisation algorithm control software to search for the optimal shape of an intra-cavity deformable membrane mirror. This system was used to successfully improve the brightness of a Nd:GdVO4 grazing-incidence laser.

A variant of this control methodology has also been exploited during the transient phase immediately following the turn-on of the laser in order to reduce the time for the laser to reach both its maximum power and full brightness.

Further enhancements, including the use of movable standard optical components (e.g. mirrors and lenses) have also been incorporated to extend the enhancement potential of these intra-cavity control systems. These developments have proved useful in investigations relating to large-mode lasers as a means to brightness enhancement.

In this paper, the elements of the control loop will be fully described; the results of our brightness enhancement, transient optimisation, and investigations on large-mode design will all be discussed.

6452-07, Session 3

Thick-waist bi-top-hat coherent beams generated by diffractive optical elements

M. A. Golub, Tel Aviv Univ. (Israel)

Thin beam waist and a Gaussian intensity spread prevents the Gaussian beams from filling the entire volume of the laser cavity and result in a lower power output in a single-modal, compared with multimodal, laser regime. We present a new class of “bi-top-hat” coherent beams which may exist as modes of laser cavities with especially designed mirrors. The complex eikonal method which combines physical optics propagation with geometrical ray-tracing is used as a base for derivation of the coherent beams minimizing the diffraction spread. The goal is to find a phase function that is defined within the lateral dimensions in a cross section of the top-hat beam and leads to a similar top-hat type intensity distribution at the Fourier plane. We used well known solutions of diffractive spot array generators for achieving nearly top-hat intensity distribution both in the spatial and Fourier domain of bi-top-hat beams. Computer simulations prove existence of a beam which has lateral dimensions essentially limited to few diffraction limits and a slowly oscillating nearly top-hat intensity distribution in several cross sections along its optical axis. Implementations of the bi-top-hat beams by special aspherical and diffractive mirrors are evaluated. Applications for single modal lasers with a high beam quality are discussed.

6452-08, Session 3

Odd-mode separation in hemispheric resonator with biprism like element

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

New methods of laser metrology (interferometry and microscopy) based on application of beams with special structures provide increased resolution and efficiency. To generate a beam with linear singularity (dark beam) we recently proposed a method for intracavity shaping with the help of a bi-prism-like element within the resonator. There we have studied resonators that are traditionally designed to oscillate on the principal mode (range of configuration parameters).

In the present work we extend the approach and show that the choice of specific configurations, outside the above range of configuration parameters, can lead to much better results for our application. This is the case in particular for an approximately hemispherical cavity (g ~ 0).

The physical mechanism of mode selection is similar to that for coupled cavities. It shows double-peaked distribution of intensity in the first even mode and the requirements are satisfied when the mode with an antiphase superposition of oscillations has the higher quality factor. The optimal dark beam is obtained for a bi-prism angle about twice that obtained for the earlier configurations. For this case the difference between the losses of the first odd mode and other modes is 012-0.15, that is adequate for oscillation on this mode in lasers with any types of active media.

6452-10, Session 3

Experimental and theoretical study of a coaxial, hybrid-stable-unstable resonator for high-power lasers

J. Deile, B. Ehlers, S. S. Sumrain, V. Granson, V. Negoita, TRUMPF Photonics

Presented is a study of a coaxial, hybrid-stable-unstable resonator for high power lasers and in particular the design of the stable direction for best beam quality and minimized alignment sensitivity as well as the optimization of the instable direction for even heat load on the mirrors. Experimental results are compared to simulations performed with different software packages.

Especially interesting are resonator characteristics resulting from the coaxial configuration allowing the realization of the outcoupling and rear mirror in one mechanical structure and using an axicon with retroreflective characteristics as a folding mirror.

Since hybrid-stable-unstable resonators require external beam shaping for most applications, influences on the farfield and farfield position need to be understood, too. Two of the main influences are the change in length of the resonator and changing thermal load on the mirrors.

6452-44, Session 3

Far field laser intensity distribution formation by means of intracavity adaptive optics

A. V. Kudryashov, Moscow State Open Univ. (Russia); I. G. Ilyina, T. Cherezova, M.V. Lomonosov Moscow State Univ. (Russia)

No abstract available

6452-12, Session 4

Bound whispering gallery modes in circular arrays of dielectric spherical particles

A. L. Burin, G. S. Blaustein, Tulane Univ.

Low-dimensional ordered arrays of optical particles can possess bound modes having an extremely high quality factor depending on the material used. If these arrays consist of metal particles, then they cannot have a high quality factor because their light absorption restricts performance. In this paper we address the following question: can bound modes be formed in dielectric systems where the absorption of light is negligible? Our investigation of circular arrays of spherical particles within the framework of the multisphere Mie scattering theory in the simplest dipolar-like approach shows that (1) high quality modes in an array of 10 or more particles can be attained at least for a refractive index n > 2, so optical materials like TiO2 or GaAs can be used; (2) the most bound modes have nearly transverse polarization perpendicular to the circular plane; (3) in a particularly interesting case of TiO2 particles (rutile phase, n = 2.7), the quality factor of the most bound mode increases almost by an order of magnitude with the addition of 10 extra particles, while for particles made of GaAs the quality factor increases by almost two orders of magnitude with the addition of ten extra particles. The consideration of higher multipole contributions has demonstrated that error of the dipolar approach does not exceed one percent if the refractive index n is greater than 2. We hope that this preliminary study will stimulate experimental investigations of bound modes in low-dimensional arrays of dielectric particles.

6452-14, Session 4

How to simulate the whispering-gallery modes of axisymmetric dielectric microresonators using FEMLAB/COMSOL

M. Oxborrow, National Physical Lab. (United Kingdom)

It will be demonstrated how COMSOL Multiphysics can be configured to calculate, in a most straightforward and numerically efficient manner, the frequencies, electromagnetic-field patterns, mode volumes, filling factors, radiation losses,...of the whispering-gallery modes (WGMs) of axisymmetric optical microresonators. The approach exploits COMSOL's rather nice ability to accept the definition of solutions to Maxwell's equations in so-called "weak form". As no transverse approximation is imposed, it remains accurate even for so-called quasi-TM and -TE modes of low, finite azimuthal mode order, as are relevant to applications in nonlinear/quantum optics. The approach's utility will be exemplified by simulating microresonators is the form of dielectric toroids and disks.

6452-16, Session 4

Polarization-discrimating spectra of a fiber-microsphere system

S. Takeuchi, H. Konishi, H. Takashima, H. Fujiwara, K. Sasaki, Hokkaido Univ. (Japan)

Polarization-discriminated spectra of a fiber-microsphere system is acquired. We have succeeded in developing a single-mode tapered fiber capable of maintaining the polarization of the probe beam. The spectra acquired from this system discriminated between transverse electric and transverse magnetic modes.

We will also briefuly discuss the possiblity to use this type of polarization-discrimated fiber-microsphere system for quantum gates for photonic qubits.

6452-17, Session 4

Lasing eigenvalue problems: the electromagnetic modeling of microlasers

T. M. Benson, The Univ. of Nottingham (United Kingdom); A. I. Nosich, M. Balaban, M. Balaban, Institute of Radiophysics and Electronics of Ukraine NAS (Ukraine); P. Sewell, The Univ. of Nottingham (United Kingdom)

Comprehensive microcavity laser models should account for several physical mechanisms, e.g. carrier transport, heating and optical confinement, coupled by non-linear effects. Nevertheless, considerable useful information can still be obtained if all non-electromagnetic effects are neglected, often within an additional effective-index reduction to an equivalent 2D problem, and the optical modes viewed as solutions of Maxwell's equations. Integral equation (IE) formulations have many advantages over numerical techniques such as FDTD for the study of such microcavity laser problems. The most notable advantages of an IE approach are computational efficiency, the correct description of cavity boundaries without stair-step errors, and the direct solution of an eigenvalue problem rather than the spectral analysis of a transient signal. Boundary IE (BIE) formulations are more economic that volume IE (VIE) ones, because of their lower dimensionality, but they are only applicable to the constant cavity refractive index case. The Muller BIE, being free of 'defect' frequencies and having smooth or integrable kernels, provides a reliable tool for the modal analysis of microcavities. Whilst such an approach can readily identify complex-valued natural frequencies and Q-factors, the lasing condition is not addressed directly. We have thus suggested using a Muller BIE approach to solve a lasing eigenvalue problem (LEP), i.e. a linear eigenvalue solution in the form of two real-valued numbers (lasing wavelength and threshold information) when macroscopic gain is introduced into the cavity material within an active region. Such an approach yields clear insight into the lasing thresholds of individual cavities with uniform and non-uni-

form gain, cavities coupled as photonic molecules and cavities equipped with one or more quantum dots.

6452-31, Session 4

Long-distance photon transfer between two individual nanoparticles via whispering-gallery modes

S. Goetzinger, Stanford Univ.; S. Kuehn, V. Sandoghdar, ETH Zürich (Switzerland); L. d. S. Menezes, A. Mazzei, O. Benson, Humboldt-Univ. zu Berlin (Germany)

When two emitters are placed at distances larger than their emission wavelength, optical communication takes place via propagating photons. However, the coupling efficiency drops rapidly as 1/r2. At a distance of 50 μm, the efficiency of one emitter absorbing a photon radiated by the other is merely 3x10-13. A way to enhance the interaction is to use microcavities, since the emitted photon circulates many times and has therefore a bigger chance to get absorbed. Additionally the field per photon becomes large in a small cavity, resulting in a much stronger coupling between the emitter and the photon field. Furthermore, resonators can influence radiative processes leading to an even stronger coupling.

We report controlled cavity-mediated photon transfer between two single nanoparticles over a distance of several tens of micrometers. First, we show how a single nanoscopic emitter attached to a near-field probe can be coupled to high-Q whispering-gallery modes of a silica microsphere at will. Then we demonstrate transfer of energy between this and a second nanoparticle deposited on the sphere surface. We estimate the photon transfer efficiency to be about six orders of magnitude higher than that via free space propagation at comparable separations.

6452-18, Session 5

Overview of novel integrated optical ring resonator bio/chemical sensors

X. Fan, I. M. White, H. Zhu, J. D. Suter, H. Oveys, Univ. of Missouri/Columbia

In parallel to a stand-alone microsphere resonator and a planar ring resonator on a wafer, the liquid core optical ring resonator (LCORR) is regarded as a third type of ring resonator that integrates microfluidics with state-of-the-art photonics. The LCORR employs a micro-sized glass capillary with a wall thickness of a few microns. The circular cross section of the capillary forms a ring resonator that supports the whispering gallery modes (WGMs), which has the evanescent field in the core, allowing for repetitive interaction with the analytes carried inside the capillary. Despite the small physical size of the LCORR and sub-nanoliter sensing volume, the effective interaction length can exceed 10 cm due to high Q-factor (10^6), significantly enhancing the LCORR sensitivity. The LCORR is a versatile system that exhibits excellent fluid handling capability inherent to capillaries and permits non-invasive and quantitative measurement at any location along the capillary. Furthermore, the LCORR uses the refractive index change as a transduction signal, which enables label-free detection. Therefore, the LCORR is a promising technology platform for future sensitive, miniaturized, lab-on-a-chip type sensors.

We have carried out extensive research on various aspects in the LCORR bio/chemical sensor development. We will first experimentally and theoretically characterize the LCORR, followed by the demonstration and analysis of sensor integration with waveguides. Applications of the LCORR in biomolecule detection and capillary electrophoresis will also be discussed. Comparison will be made with other types of label-free ring resonator sensors, as well as surface plasmon resonance sensors.

6452-21, Session 5

Photonic clocks and cQED on a silicon chip

K. J. Vahala, California Institute of Technology

No abstract available

6452-22, Session 5

Highly confined cavities for active and passive devices on chip

M. F. Lipson, Cornell Univ.

No abstract available

6452-33, Session 5

The maximum group delay in a resonator: an unconventional approach

A. B. Matsko, A. A. Savchenkov, V. S. Ilchenko, D. V. Strekalov, L. Maleki, Jet Propulsion Lab.

We introduce a definition of group velocity for a system with a discreet spectrum and apply it to a linear resonator. We show that a positive, negative, or zero group velocity can be obtained for light propagating in the whispering gallery modes of a microspherical resonator. The associated group delay is practically independent of the ring-down time of the resonator. We demonstrate “stopped light” in an experiment with a fused silica microsphere.

6452-24, Session 6

Semiclassical dynamics of light beams supported by adiabatically tapered photonic nanowires

M. Sumetsky, OFS Labs.

An optical microfiber with the diameter significantly less than the radiation wavelength ~ 1 micron is often called a nanowire (NW). The fundamental mode of a NW consists primarily of an evanescent field propagating in the ambient medium outside a NW. Any deformation of a NW changes the evanescent field. If a nanowire is thin enough, even a very small deformation may cause dramatic changes of the evanescent field structure. The simplest types of deformation of a uniform NW are bending and tapering. The structure of evanescent field and optics of radiation loss in bent uniform microfibers is understood quite well. It is determined by an effective potential barrier terminated by a caustic surface, which separates the tunneling and classically allowed regions. Tunneling through the barrier determines the radiation loss. Alternatively, for an adiabatically tapered microfiber, called a nanotaper (NT) a similar potential barrier of finite width cannot be introduced. Instead, the radiation loss in a NT takes place in a small neighborhood of a focal circumference of the evanescent field, while a NT is lossless elsewhere. More specifically, it is found that, for a NT, the mentioned caustic surface becomes complex and can intersect real space along certain lines only. These lines are the focal lines where the radiating modes and the guiding mode are split off. As examples, conical and biconical NTs with characteristic shapes are considered. The theoretically predicted interference between the guiding and radiating components of the evanescent field are confirmed by the beam propagation method (BPM) numerical modeling. The derived analytical expressions for radiation loss are in a good agreement with BPM calculations. Finally, it is shown that there exists an exceptional shape of a NT which fundamental mode has the form of an evanescent Gaussian beam. For this NT, the mentioned complex caustic surface becomes real and the structure of evanescent field is determined by an effective barrier, similar to the bent microfibers.

6452-25, Session 6

Ultra-resolution microwave-assisted dispersion measurements in high-Q WGM resonators

N. Morozov, I. V. Solomatine, OEwaves, Inc.; L. Maleki, Jet Propulsion Lab.; V. S. Ilchenko, OEwaves, Inc.

A mode dispersion in high-Q optical resonators is critical for many appli-

cations. Since the dispersion, measured as difference between consecutive ~10 GHz mode spacing, is very small compared to the optical carrier frequency - typically of order of 1 kHz vs. 200 THz, - accurate measurements by optical means are quite complicated. We developed two methods of converting the optical response into microwave band to utilize microwave techniques for precise dispersion measurements and investigation of the resonator mode structure. Both allowed us to obtain modal spacing information by means of RF instruments with uncertainty ~10-50 Hz. For spectrally averaged dispersion measurement we applied “white” light spectroscopy method with direct detection of filtered light. This approach allowed us to measure mode dispersion of the resonators made from fused silica and CaF2. The results, -300 Hz per mode for CaF2, and 3.8 KHz per mode for fused silica, are in good agreement with analytical estimations. For detailed mode-by-mode investigation we utilized modulator tunable laser approach. We observed evidence of mode interaction effect in fused silica resonator that results in disruption of otherwise uniform shift of consecutive modal spacing and amounts to effective dispersion anomaly. Our method allowed us to identify anomaly-free stretches of optical spectra, which is critical for RF oscillator application of WGM resonators.

6452-26, Session 6

Enhancement of spin coherence using Q-factor engineering in semiconductor microdisk lasers

N. Samarth, The Pennsylvania State Univ.

No abstract available

6452-27, Session 6

Sensitivity and progress in bio-chemical sensors with WG-mode resonators

Y. Lin, V. S. Ilchenko, Jet Propulsion Lab.

No abstract available

6452-28, Session 6

Dome-shaped microresonators

J. U. Nöckel, D. H. Foster, Univ. of Oregon

We have performed numerical and analytic studies of the vector electromagnetic fields in plano-concave microresonators. Two important scenarios are (a) the paraxial and (b) the hemispherical limit; example applications are (a) VCSELs with curved top mirrors for lateral mode control and (b) confocal micromirror cavities fabricated by microsphere-assisted templating. We allow for mixed boundary conditions due to different mirror types (metal and Bragg reflectors). Tracing the shape transition from (a) to (b), we describe the lifting of Gaussian-beam degeneracies in analogy to quantum-mechanical spin-orbit coupling. This allows to explain how some, but not all, eigenstates must develop a spatially inhomogeneous polarization even in axially symmetric, near-paraxial cavities. Approaching the hemispherical regime (b), one expects tightly focused spherical-harmonic type modes which in the ray picture correspond to diametral orbits of small axial angular momentum. We find that with a Bragg mirror at the base of the dome, additional types of modes with strong focussing exist, differing from spherical harmonics in that they are essentially field-free outside of a single, narrowly defined, self-retracing diametral ray orbit. To explain how these modes “condense” around one special ray orbit out of an infinite family of similar paths, we invoke a ray dynamical saddle-node bifurcation which is determined by the properties of the Bragg stack. The physical reason why a mere change in the electrodynamic boundary conditions of the cavity can cause a ray bifurcation lies in the Goos-Hanchen shift. The analysis leads to accurate analytical predictions for these exotic modes.

6452-13, Session 7

Low loss WGM transport in 3D networks of coupled cavities

V. N. Astratov, The Univ. of North Carolina at Charlotte

No abstract available

6452-19, Session 7

Efficient generation of truncated Bessel beams using cylindrical waveguides

A. B. Matsko, V. S. Ilchenko, M. Mohageg, A. A. Savchenkov, L. Maleki, Jet Propulsion Lab.

We propose theoretically and demonstrate experimentally a method for generation of beams of light possessing large angular momenta. The method utilizes cylindrical optical waveguides as well as whispering gallery mode resonators that efficiently transform a plane electromagnetic wave into truncated Bessel beams. Generation of the high order beams with well defined angular momenta is demonstrated.

Possible applications of the beams are discussed.

6452-30, Session 7

Photonic molecules made of matched and mismatched microcavities: new functionalities of microlasers and optoelectronic components

S. V. Boriskina, National Science Ctr. Kharkov Institute of Physics and Technology (Ukraine); T. M. Benson, P. Sewell, The Univ. of Nottingham (United Kingdom)

Photonic molecules, named by analogy with chemical molecules, are clusters of closely located electromagnetically interacting microcavities or “photonic atoms”. When the concept of a photonic molecule was first introduced in 1998, it provided a nice illustration of the parallels between behavior of photons in photonic atoms and electrons in either real or artificial atoms, while practical applications seemed elusive. In nine years that followed, the major international research effort in this field not only yielded insights in the new physical and optical phenomena observed in photonic molecules, but also brought rapid advances in their practical applications as semiconductor microlasers, wavelength-selective optoelectronic filters and switches, coupled-cavity waveguides, biosensors, etc.

As two or several microcavities are brought close together, their optical modes interact, and a rich spectrum of photonic molecule super-modes emerges, which depends both on geometrical and material properties of individual cavities and on their mutual interactions. Here, we will discuss ways of controllable manipulation of photonic molecule super-modes, which improve or add new functionalities to microcavity-based optical components without compromising the attractive features of individual cavities, such as, e.g., their high Q-factors. We will present several optimally-tuned photonic molecule designs for lowering thresholds of semiconductor microlasers, producing directional light emission, enhancing sensitivity of microcavity-based bio(chemical)sensors, and optimizing electromagnetic energy transfer around bends of coupled-cavity waveguides. Photonic molecules composed either of identical microcavities or microcavities with various degrees of size, shape or material detuning will be discussed. Microwave experiments on scaled photonic molecule structures are currently under way to confirm our theoretical predictions.

6452-32, Session 7

Confined modes in small photonic structures

J. F. Donegan, The Univ. of Dublin, Trinity College (Ireland)

In this presentation, a review of recent work in our group on confined

modes in photonic structures will be presented. Our work is centred around small spherical microcavities and cylindrical microtubes of size less than 10 microns and quality factor of 10,000 or less. The small size gives rise to a large mode splitting which is studied using a broad band emitter, CdTe nanocrystals, placed on the surface of the microcavities. There is a large evanescent field associated with these small structures and we have observed the formation of a photonic molecule with a clear pattern of mode splitting associated with the lower symmetry of the molecule. We have also observed a modification of the mode pattern in a microsphere with a soft shell due to the effects of radiation pressure from a focussed laser on the tiny sphere. Very recently, we have fabricated a new photonic microstructure, the cylindrical microtube, which exhibits strongly polarised whispering gallery mode emission and amplified spontaneous emission. All of these structures show strong potential for studies of coupled photonic systems, a new and exciting area for resonator design.

6452-34, Session 7

Light coupling and propagation in 3D lattices of spherical cavities

S. P. Ashili, V. N. Astratov, The Univ. of North Carolina at Charlotte

Light propagation effects via coupling between high quality (Q) cavities is attracting an increasing interest in recent years. This interest is determined by the applications of coupled cavities for developing chip scale devices such as delay lines, narrow spectral filters and sensors.

In this work we integrated spherical cavities into 3D closed packed structures with the thickness varying from one monolayer up to ~50 monolayers. The samples were obtained by self-assembly of spheres (with sizes in 2-10 micron range with standard 3% size dispersion) directed by hydro-dynamic flow in a specially designed cuvette placed in ultrasonic bath. The spheres were dye-doped and locally excited to create a built-in source of whispering gallery modes (WGMs). In the scattering spectra of such samples we observed fringes due to light propagation via coupled WGMs. The study of pump dependence of scattering spectra indicated that above WGM lasing threshold the emission is provided in localized modes formed by multiple spheres. This is confirmed by observation of double peak structures, the spectral signature of strong coupling regime between multiple cavities. Although size disorder plays a negative role in the efficiency of such transport, we show that due to existence of multiple paths for photons the optical transport can be very efficient. The study of thickness dependence of scattering spectra indicates that attenuation length of light in such 3D samples exceeds 50 microns. The results show that the optical transport in such systems is provided along particular configurations of cavities according to a principle of minimization of the total WGM detuning.

6452-35, Poster Session

Optical modes in linear arrays of dielectric spherical particles: a numerical investigation

G. S. Blaustein, A. L. Burin, Tulane Univ.

We have investigated bound modes in finite linear chains of dielectric particles of various lengths, interparticle spacings and particle materials. Through a unique application of the multisphere Mie scattering formalism, we have developed numerical methods to calculate eigen-optical modes for various arrays of particles. These numerical methods involve the use of the multisphere scattering formalism as the entries in NxN matrices where N represents the number of particles in the chain. Eigenmodes of these matrices correspond to the eigen-optical modes of interest. We identified the eigen-modes with the highest quality factor by the application of a modified version of the Newton-Rhapson algorithm. We found that convergence is strong using this algorithm for linear chains of up to 500 particles. By comparing the dipolar approach with the more complex approach which utilizes a combination of both dipolar and quadrupolar approaches, we demonstrated that the dipolar approach has an accuracy of approximately 99%. We found that (1) the quality factor Q of the mode increases with the cubed value of the number of particles in chain in agreement with the previously developed theory; and (2) there is an exponential increase of the quality factor Q as the refractive index increases. In addition to the graphic displays of our findings, the effects of disordering of particle sizes and inter-particle distances will be discussed.

6452-36, Poster Session

Comparison of photo-acoustic and optogalvanic effect in CO2 laser frequency stabilization

J. Choi, Honam Univ. (South Korea)

Two kinds of stabilization method are applied to check a frequency stability of RF excited CO2 laser.

The photoacoustic and the optogalvanic effect generated from the laser itself were used to stabilize on the peak of the Doppler broadened gain curve. A condenser microphone built in the resonator was used to convert delicate variations in the pressure into voltage signals to be used as input signals for lock-in stabilizer. The optogalvanic signal is directly coupled from a RF discharge chamber via a capacitor into a detector and a lock-in stabilizer.

As an result of two stabilizing methods for the laser oscillated from P(20) line, the relative stability of the optical frequency were analyzed and compared with each other.

6452-37, Poster Session

Microsphere resonator reflector for fiber laser

K. Q. Kieu, M. Mansuripur, The Univ. of Arizona

We show that a glass micro-sphere resonator can be used as a wavelength-selective mirror in fiber lasers. Due to their high quality-factor (Q ~10^8), microsphere resonators possess a narrow reflection bandwidth. This feature enables construction of single-frequency fiber lasers even when the cavity is long. We also propose and demonstrate an active Q-switched fiber laser using a high-Q micro-sphere resonator as the Q-switching element. The laser cavity consists of an Er-doped fiber as the gain medium, a glass micro-sphere reflector (coupled through a fiber taper) at one end of the cavity, and a fiber Bragg grating reflector at the other end. The reflectivity of the micro-sphere is modulated by changing the gap between the micro-sphere and the fiber taper. Active Q-switching is realized by oscillating the micro-sphere in and out of contact with the taper. Nonlinear effects (such as stimulated Raman lasing) were also observed in our setup at relatively low pump powers

6452-38, Poster Session

Mode selectivity of random lasing in one-dimensional model

S. Takeda, M. Obara, Keio Univ. (Japan)

Since the first theoretical prediction by Lethokov in 1967, many interesting studies on Random Lasing (RL) have been carried out theoretically and experimentally. The RL is different from conventional laser systems in the feedback mechanism. In conventional lasers, photons are coherently confined inside gain medium using reflectors, resulting in the coherent feedback. In the RL system, photons are subject to multiple scattering in disordered gain medium, and the feedback is realized. According to the degree of disorder in the system, some sharp spikes, which indicate the modal oscillation, appear on the emission spectrum. Thanks to the advantages of without any alignment, low price, micro-size, and mode selectivity, the RL is very attractive for potential applications such as spectroscopy and light emitting devices. However, RL's detailed mechanisms on especially the relationship between the mode selectivity and the degree of disorder in the system are not revealed theoretically. If dependence of the number and the kinds of modes on the scattering states of the RL system is solved, the applications for biological spectroscopy or

behavior analysis of Nd:YAG ceramic laser will be further advanced.

In this paper, we demonstrate the selective modal oscillation behavior by one-dimensional RL model. For calculations, we introduced the rate equations into the one-dimensional scattering model, using the optical parameters for Rhodamine 6G and Nd:YAG systems. Using this model, we investigated how the number and the kinds of modes change as the degree of disorder along with the scattering system changes. This solution will be able to evaluate the state of random medium by only observing the experimental RL's emission spectra.

6452-39, Poster Session

Subpicosecond vacuum ultraviolet-laser system for advanced materials processing

S. Kubodera, Y. Taniguchi, A. Hosotani, M. Katto, A. Yokotani, Univ. of Miyazaki (Japan); N. Miyanaga, K. Mima, Osaka Univ. (Japan)

We have been constructing a subpicosecond vacuum ultraviolet (VUV) excimer laser system at 126 nm utilizing a subpicosecond high-intensity laser as a pump source. A low-temperature high-density Ar plasma produced by optical-field-induced-ionization (OFI) process by use of a 100 fs Ti:sapphire laser system should be adequate for the production of the Ar2* molecules. Our kinetics simulation verified that the production of the low-temperature plasma indeed triggered the efficient production processes of the Ar2* molecules. The plasma production was supported by using an Ar-filled optical hollow fiber with a diameter of 250 microns, in which the focused high-intensity Ti:sapphire laser was irradiated and propagated. The use of a hollow fiber extended the plasma length up to 50 cm, which was far beyond the Raleigh length of the laser. By placing a set of multilayer mirrors at both ends of the hollow fiber, i.e. a plasma gain medium, an optical cavity for the 126 nm emission was constructed. As a result of the optical feedback, a one-pass amplification factor of more than fifty was observed by using a mirror at 126 nm, which led to a gain-length product of four. By utilizing this VUV amplifier at 126 nm, a wavelength-converted subpicosecond VUV seed beam at 126 nm will be amplified to realize a 100 fs VUV laser beam with an average output power on the order of 1 mW with a repetition rate of 1 kHz, which would be used for advanced materials processing.

6452-40, Poster Session

Analysis of enhanced local fields within a defect region of a random medium

H. Fujiwara, K. Sasaki, Hokkaido Univ. (Japan)

We have been interested in the potential for the optical confinement effect within a wavelength-scale-disordered (random) structure. As photon diffusion constants are drastically reduced by the multiple light scattering and the interference effect, the random structure can be utilized as a microcavity. In addition to the optical confinement effect, as we have focused on the advantages, which are (1) easiness of the preparation, (2) no limitation of the shape and size, and (3) easiness of introduction of nonlinear materials, we have expected the paint-like highly efficient and small functional devices will be easily developed such as surface emission device and photo-chemical/physical reaction sites. However, due to the randomness, it is difficult to induce or prepare intended resonant conditions. To this end, we propose a simple method to control the resonant condition, by which we deliberately make the defect region where no scatterer is set and work as a photoreaction site. Due to the average reflectance of the emsamble of dense scatterers, only when the reflection band matches the resonant condition determined by the defect size, we can expect that only the resonant modes localized at this defect region can be inducded and the other non-resonant modes are eliminated by the surrounding scatterers. In the presentation, we will present the characteristics of the defect mode using a two-dimensional finite-difference time-domain method including a rate-equation.

6452-41, Poster Session

Real-time measurement of laser beam quality factor (M^2) by imaging transverse scattered light

K. C. Jorge, R. Riva, N. A. S. Rodrigues, M. G. Destro, Instituto de Estudos Avancados (Brazil)

This method based on scattering allows estimating the M^2 quality of factor with a single lateral view of the laser beam. In the device, the laser beam is focused into a scattering cell and the laterally scattered light is imaged on to a CCD camera allowing a complete view of the laser beam diameter evolution. The M^2 is a key parameter for most of the laser applications and it is obtained after measuring the beam diameter in several longitudinal positions. There are many different techniques for laser beam diameter measurements. In these methods, the M^2 parameter is not assessable since many measurements of the beam width through the laser beam pathway are necessary, not allowing the laser beam characterization in one single shot. To overcome this problem we proposed a method based on light scattering that allows estimating the laser beam quality with only one measurement. The main idea of the method is that the light scattered by tiny randomly oriented molecules can be easily imaged by an optical system allowing a complete lateral view of the laser beam. On image plane each point is proportional to the intensity of the actual laser beam at equivalent location on object plane. Using a single image to measure M^2 parameter of a single mode He-Ne beam laser we obtained $M^2=1.1\pm0.1$ that agrees very close with the value obtained by others methods.

6452-42, Poster Session

Acoustic measurement method in investigation of optical phenomena in a modulated CO2 laser plasma

D. A. Wojaczek, E. F. Plinski, L. Rosinski, R. Trawinski, Politechnika Wroclawska (Poland)

The paper describes the results of investigations of optical phenomena on an RF excited slab-waveguide CO2 laser. The experiments are performed in two optical arrangements: two-mirror resonator and three-mirror one. The main purpose of the experiments is to check possibilities to observe the optical phenomena using a microphone. The laser plasma is modulated with a self-mixing signal in the three-mirror resonator. The response of the microphone is observed and analyzed. Detection of the laser signature phenomenon with the microphone is experimentally considered. The experiments are done at cw regime of the laser. The investigations are performed at pulse operation of the laser, as well. The response of the microphone is analyzed. It is checked how the laser pulse is reconstructed at a profile of the microphone signal. The output laser pulse with a mapped laser signature in the laser pulse profile is compared to the microphone signal shape. The presence of the laser signature at the acoustic signal is investigates.

Conference 6453: Fiber Lasers IV: Technology, Systems, and Applications

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6453-01, Session 1

Photonic crystal fibers: opportunities and challenges

P. S. J. Russell, Univ. of Erlangen (Germany)

No abstract available

6453-02, Session 2

High-peak-power and high-energy fiber amplifiers

J. Minelly, Aculight Corp.

High peak power and high energy fiber lasers are of increasing interest for a number of applications such as materials processing, ranging and imaging, free-space communications and medicine. Pulsed fiber lasers have advantages in efficiency over other diode-pumped solid state lasers. Obtaining high energy or high peak power while retaining beam quality requires either multimode fibers under low order excitation or large mode area single mode fibers. In recent years Yb fibers have been pushed to pulse energies of 6mJ in near diffraction limited beam and peak powers of several MW challenging the accepted self-focusing limit in silica. Frequency conversion of Yb fiber lasers is opening up new application space in for example semi-conductor processing and undersea communications and imaging. Er doped fibers operating in the eye-safe regime have not yet been scaled to such dramatic energy and peak power values due to spectroscopic and material issues. However new fiber techniques and amplifier designs are rapidly closing this gap.

6453-03, Session 2

Super powerful QCW fiber lasers with elevated peak power

V. P. Gapontsev, IPG Photonics Corp.

Over last few years huge progress was achieved both in CW and pulsed fiber lasers for different scientific and industrial applications. Right now kWatts power level single mode and 10‘s of kWatts multimode CW industrial grade fiber lasers are available and utilized at many industrial sites. But still, there are many applications that, due to process specific or economic, requires not only high average power but also a high peak power.

Recent progress in developing such a lasers as well as application specifics would be described and discussed in this presentation.

6453-04, Session 2

High-peak-power pulsed amplifiers in a monolithically integrated all-fiber configuration

S. Caplette, C. A. Delisle, F. Séguin, N. Holehouse, ITF Optical Technologies, Inc. (Canada)

With the recent improvements in fiber design and manufacturing combined with the advent of fiber-coupled high-brightness pump diodes, fiber lasers and amplifiers have become prime candidates for applications where high power and excellent beam quality are required. While the tight confinement is advantageous for achieving high gain, it also lowers the threshold power for nonlinear optical effects and optical damage. Power scaling is therefore a matter of increasing the effective area of the core, which will also increase the saturation energy and therefore the extractable energy. However, quasi-single-transverse-mode operation should be maintained at the same time for good beam quality.

In few-moded large-mode-area (LMA) fibers, however, preservation of the fundamental LP01 mode is challenging. We report on the characterization of all-fiber power amplifiers with fiber core diameters of 20μm and 30μm, which significantly reduce the onset of nonlinear optical effects and damage threshold. In excess of 1.5mJ of output energy has been achieved while maintaining excellent beam quality. A directly modulated diode laser followed by two single-mode fiber amplification stages is used to seed the power amplifier. The complete system is monolithically integrated in an all-fiber configuration with the exception of the isolators. This MOPA design provides maximum flexibility with reconfigurable pulse width, repetition rate and seed energy. A polarization-maintaining version of the amplifier was also assembled using all-fiber PM combiners. The power scaling potential of the device from a reliability point of view was demonstrated by carrying out environmental aging tests on package optimized for mechanical stress and thermal dissipation management.

6453-05, Session 2

High-peak-power pulsed single-mode linearly polarized LMA fiber amplifier and Q-switch laser

V. Khitrov, B. N. Samson, D. P. Machewirth, D. Yan, K. Tankala, A. Held, Nufern

Pulsed single-mode fiber lasers and amplifiers emitting multiple-kW peak powers and average powers in 10-20W range are looking to address many of today’s more demanding applications. Such fiber-based devices have numerous advantages over other types of lasers, such as flexible pulse durations and repetition rates, compactness, maintenance-free operation, robustness and high efficiency.

There is a great interest in linearly polarized single-mode fiber devices. Although non-polarized single-mode 10-20W devices have been successfully demonstrated, developing high-power linearly polarized single-mode pulsed devices is challenging due to non-linear effects and polarization control problems in the fiber at high powers.

Here we report our recent progress in the design and manufacturing of completely monolithic linearly-polarized pulsed fiber amplifiers and Q-switched lasers, with more than 10kW peak power, 20W average power in a diffraction-limited, linearly polarized and stabilized narrow-linewidth output beam operating at 1064nm. The significant practical advantage of the demonstrated design is its monolithic laser cavity consisting of an optimized coil of polarization maintaining large mode area (PM-LMA) fiber with 30μm-core and other fiber components. Linearly polarized output is achieved due to a polarization-mode selectivity of a coiled PM-LMA fiber.

Such linearly polarized, spectrum-stabilized and single-transverse mode output from a compact and robust package is particularly suitable for a number of applications: driving high-power nonlinear wavelength conversion processes in a variety of nonlinear materials, LIDAR and etc. Further power scaling results will be presented at the meeting.

6453-06, Session 3

Ultra-large mode-area fibers: approaches and realizations

S. Ramachandran, OFS Labs.

The recent past has seen an explosion of interest in nonlinearity-resistant fibers that can stably propagate light in increasingly large effective areas (Aeff). To date, four distinct approaches have been considered.

The straightforward and conventional means to achieve large Aeff is to scale the fiber dimensions. The tradeoff is that this makes them multimoded, leading to poor output beam quality . Nevertheless, hero

demonstrations using this approach have achieved Aeff as large as 2000 μm2, though they required great precision in input-coupling and fiber-handling .

An alternative approach uses microstructured optical fibers (MOF). They offer additional design flexibility by selectively leaking higher order modes. Thus, Aeff up to ~ 1400 μm2 have been demonstrated in fibers that can be spliced and packaged.

A variant of MOFs, a rigid glass rod, has gained much recent attention, since a straight light-guide can clearly afford scaling of Aeff. Modal areas up to 4500 μm2 have been achieved, but, such structures are limited to short lengths, need free-space coupling, and are in fact conceptually closer to solid-state rod lasers, though they offer better thermal management.

A fourth approach was recently demonstrated - instead of using the conventional fundamental mode, a single higher-order mode (HOM) is efficiently excited in an intentionally few-moded fiber. HOMs are inherently more robust to mode coupling and bend distortions, yielding a vast design space for tailoring Aeff. Modal areas up to 3200 μm2 with stable light-propagation over lengths exceeding 20 meters have been demonstrated with this approach.

This talk will review and contrast the different design methodologies currently envisaged for achieving fibers with ever increasing modal areas for combating nonlinearities in high-power lasers and amplifiers.

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J.S. Wong et al, “Breaking the limit of maximum effective area for robust single-mode propagation in optical fibers,” Opt. Lett., vol. 30, p. 2855, 2005.

J. Limpert et al, “Extended single-mode photonic crystal fiber lasers,” Opt. Exp., vol. 14, p. 2715, 2006.

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6453-07, Session 3

Photonic crystal fiber designs for power scaling of single-polarization amplifiers

B. G. Ward, U.S. Air Force Academy; C. Robin, M. A. Culpepper, Air Force Research Lab.

Photonic crystal fiber designs for power scaling of single-polarization amplifiers are presented. These fibers incorporate a core with a refractive index slightly lower than that of pure silica and borosilicate stress rods embedded within the photonic crystal lattice. They are realizable as rod-type as well as conventional photonic crystal fibers. The core index change results in a fundamental mode profile that is flattened relative to that of standard photonic crystal fibers. A continuum of mode profiles ranging from approximately Gaussian to approximately top-hat can be achieved in this manner. The modal birefringence and effective area both increase as the core index is lowered. For high birefringence, the fibers are polarizing, allowing only a single polarization mode to propagate with low loss. The optimal parameters of these designs depend on the desired coiling radius, birefringence, and mode area. Preliminary experimental results are presented.

6453-08, Session 3

Yb-doped LMA triple-clad fiber for power amplifiers

P. Laperle, C. Paré, H. Zheng, Y. Taillon, A. Croteau, Institut National d’Optique (Canada)

High-energy pulsed narrow-linewidth diffraction-limited ytterbium-doped power amplifiers in the 1030 to 1100 nm wavelength range and in the nanosecond regime require large mode area (LMA) fibers to mitigate stimulated Brillouin scattering (SBS). However, LMA fibers with core diameters larger than 20 um are inherently multimode. To achieve a diffraction-limited output, several techniques are available such as low core numerical aperture, fiber coiling and selective doping. The triple-clad fiber design takes advantage of the three techniques. The first clad located next to the core allows a reduction and a better control of the effective numerical aperture for high ytterbium doping that is difficult to achieve with the standard double-clad fiber design. Also, the thickness of the first clad gives an extra degree of freedom that allows either a nearly bending-insensitive output or mode filtering through bending losses. Incorporating to the triple-clad design an optimized selective rare-earth doping of the core not only favors the fundamental mode over higher-order modes by the gain differential, but also favors an increase of the SBS threshold by reducing the overlap between optical and acoustic field distributions. An ytterbium-doped polarization-maintaining LMA triple-clad fiber with a large first clad and selective ytterbium doping is tested in a power amplifier configuration. The pulse width is 10 ns with a repetition rate of 100 kHz at 1064 nm. The fiber is characterized for gain, energy, polarization extinction ratio, M2, mode-field diameter and SBS threshold. The fiber performance and power scalability are discussed for power amplifier and laser applications.

6453-09, Session 3

Numerical modeling of self-focusing beams in fiber amplifiers

R. L. Farrow, G. R. Hadley, A. V. Smith, D. A. V. Kliner, Sandia National Labs.

We have numerically investigated the behavior of the fundamental mode of a step-index, multi¬mode (MM) fiber as the optical power approaches the self-focusing limit (Pcrit). The analysis includes the effects of gain (applicable to fiber amplifiers) and bending (applicable to coiled fibers). We find that at powers below Pcrit, power-dependent stable solutions exist, in contrast to some previous results that exhibited large-amplitude oscillations in beam waist along the fiber. For the first time, to our knowledge, we show that in a MM fiber amplifier seeded with the low-power funda¬mental eigenmode (LP01), the transverse spatial profile will adiabatically evolve into that of the fundamental stationary mode as the beam is amplified toward Pcrit. For a given value of the nonlinear index, Pcrit is found to be nearly the same in the bulk material and in a step-index fiber. These conclusions hold for both straight and bent fibers, although the quantitative details are somewhat different.

6453-10, Session 4

Nonlinear optics and frequency conversion - fiber lasers in IR, VIS and UV

J. R. Taylor, B. Cumberland, A. Ferin, A. Rulkov, J. C. Travers, S. V. Popov, Imperial College London (United Kingdom)

Nonlinear optical techniques provide several efficient routes to wavelength extension of doped fibre laser systems and in many cases retain an all-fibre fully integrated format. Here we describe our various experimental programmes generating tunable sources from the ultra violet to the near infra red.

Direct frequency doubling of Yb and Yb:Er as well as frequency mixing of these fundamental sources both in pulsed and cw modes in periodically poled materials has yielded average powers up to 8W, 50W and 3.5W respectively and conversion efficiency up to 85%, single pass. The frequency doubled Yb:Er based system has also been cascaded in a sequential SHG to the uv generating up to 6 W cw at 387nm, albeit in a bulk LBO crystal.

In the visible and near infra red greater wavelength tunability can be achieved using the fundamental fibre lasers as pumps for high power Raman laser schemes. A 23W polarization maintaining Raman fibre laser MOPFA configuration pumped by a cw 40W Yb fibre laser has been frequency doubled to generate over 3W at 589nm. This approach can be generally applied to produce selectable outputs from 560nm to 700nm.

In the near infra red Tm pumped heavily Ge-doped Raman lasers can provide tunable fundamental sources above 2 μm.

For some applications, broad wavelength coverage is required simultaneously. This is the regime of the high power supercontinuum source. Pumped by the rare earth lasers described above both in cw and in pulsed format, spectral power densities of up to 50mW/nm can be achieved covering the wavelength range from UV to 2.1micron. Recent results obtained using long length tapered PCF allows short wavelength extension to around 300 nm where average power densities of up to 5mW/nm have been recorded.

6453-11, Session 4

High-power and highly efficient mid-infrared fiber lasers

S. D. Jackson, The Univ. of Sydney (Australia)

Mid-infrared fibre lasers with operating wavelengths in the 2 micron region have reached the 100 W output level. In this talk I will discuss the important processes that have led to the very high efficiencies and power scaling opportunities for both 2 micron and 3 micron fibre lasers. I will also discuss the recent work associated with mid-infrared Raman fibre lasers and I will offer an outlook for future research and development in this area

6453-12, Session 4

Broadly tunable high-power, pulsed fiber laser system for mid-IR applications

V. V. Ter-Mikirtychev, J. B. Paul, J. J. Scherer, NovaWave Technologies, Inc.

A broadly tunable, mid-infrared fiber laser-based system has been demonstrated at room temperature. The laser system consists of two high peak power pulsed fiber lasers along with difference frequency generation (DFG) in Periodically Poled Lithium Niobate (PPLN). Both fiber lasers were operated with a 200 ns duration and a 20 kHz Pulse Repetition Rate. The Pump laser was continuously tunable in the 1050 - 1080 nm region with a bandwidth of <16 GHz, and produced up to 280 mW of average power (70W of peak power, 14 μJ/pulse). The Signal laser wavelength was fixed 1556 nm, and the laser featured a linewidth of <50 MHz and produced up to 150 mW of average power. Both lasers were combined into a single polarization maintained fiber using a fiber wavelength-multiplexer, and then coupled into a NovaWave Technologies commercial DFG conversion head to produce a rugged all-fiber-coupled assembly. By changing only the Pump laser wavelength, continuously tunable radiation in the spectral range 3300 - 3480 nm was generated with a maximum average power of 9 mW (2.25 W of peak power). The demonstrated DFG conversion efficiency of 0.2 W/W2 (20%/W) is ~100 times higher than that of CW operation. By simultaneously changing the crystal temperature along with the Pump laser wavelength, the tuning range was increased to 3235 - 3545 nm (310 nm). Further scaling of the IR power should be readily accomplished. In particular, by using MgO:PPLN along with Large Mode Area gain fibers, the generation of mid-IR power in the multi-watt regime is possible.

6453-13, Session 4

Fiber-based laser with tunable repetition rate, fixed pulse duration, and multiple wavelength output

P. E. Schrader, R. L. Farrow, Sandia National Labs.; D. A. V. Kliner, Sandia National Labs; J. Feve, N. Landru, Teem Photonics SA (France)

We report a pulsed, fiber-amplified microlaser providing widely tunable repetition rate (7.1-27 kHz) with constant pulse duration (1.0 ns), pulse energy up to 0.41 mJ, linear output polarization, diffraction-limited beam quality, and < 1% pulse-energy fluctuations. The output wavelength was varied from 213 nm to 4.4 μm by harmonic generation and optical parametric generation, with Watt-level output powers. The laser system employs a simple architecture and is therefore suitable for use in practical applications.

6453-14, Session 4

Watt level high-repetition-rate, mid-infrared pulses generated by wavelength conversion of an eye-safe fiber source

F. Di Teodoro, S. Desmoulins, Aculight Corp.

We report on a mid-infrared (mid-IR) source consisting of a 1.54micron-wavelength pulsed fiber source pumping an optical parametric oscillator. From this source, we obtained average power in excess of 1 W in the 3.8-4.0micron wavelength range at pulse repetition frequency = 100 kHz. With a slightly different setup, we also achieved an average power 0.25 W at 4.5micron wavelength. To our knowledge, these values represent the highest mid-IR power obtained through wavelength conversion of an eye-safe fiber source.

6453-15, Session 5

Fibers with resonant mode suppression

J. M. Fini, Fitel USA Corp.

Noise can limit the power in a fiber amplifier by competing with the signal for gain. Distributed filtering offers a way of overcoming current high-power limitations by selectively removing noise before it is amplified. Resonant mode suppression is a flexible strategy for wavelength filtering as well as suppression of unwanted transverse modes.

An Yb-doped gain fiber with distributed filtering of stimulated Raman scattering (SRS) was demonstrated in a cladding-pumped amplifier. Substantial suppression of SRS was demonstrated in this fiber, with a core and resonant Ge-doped ring made using standard solid-fiber fabrication.

Simulations explore generalizations to large-mode-area and filters with multiple band-stop features.

6453-16, Session 5

Frequency agile, electronically tunable, high-power ytterbium-doped PM LMA fiber laser

J. Ding, The Pennsylvania State Univ.; A. R. Geiger, Akamai Physics, Inc.

We report on an electronically tunable continuous-wave Ytterbium doped polarization maintaining fiber laser with more than 50 nm tuning range and more than 10 W linearly polarized single spatial mode laser output. The polarization maintaining Ytterbium doped large mode area (LMA) double cladding (DC) fiber features a 25 micron diameter core with 0.06 numerical aperture (NA) and a 250 micron diameter inner cladding with 0.46 numerical aperture. The relatively bigger core diameter permits bigger saturation energy and higher laser output power. With appropriate coiling, the fiber was able to output single spatial mode beam, thanks in part to its relatively smaller core NA. The panda-shaped polarization maintaining fiber structure increases the ratio between the fiber core to the pump-guided inner cladding and results in more efficient pump absorption. The specially designed Acousto-Optical Tunable Filter (AOTF) has an integrated compensation prism and enables continuous tuning without any mechanical moving parts. By changing the RF driving frequency on the intra-cavity AOTF, the ytterbium doped fiber laser can randomly hop to any wavelength between 1032 and 1080 nm in less than 50 microsecond. With a 2m ytterbium doped LMA DC fiber pumped from both ends by two high power fiber-pigtailed 976 nm laser diodes, the ytterbium doped fiber laser generates more than 10 W linearly polarized Gaussian beam, continuously tunable from 1032 to 1080 nm.

6453-17, Session 5

Low-photodarkening single cladding ytterbium fiber amplifier

B. Morasse, S. Chatigny, C. Hovington, É. Gagnon, J. De Sandro, CorActive High-Tech Inc. (Canada)

A single cladding ytterbium doped fibre amplifier pumped at 980 nm that exhibits negligible amount of photodarkening over a long period of time is demonstrated. The output power as a function of time decreased by a very small factor compared to standard single mode ytterbium fibres. To achieve this photodarkening resistant amplifier, a special ytterbium doped fibre has been developed and photodarkening was characterized by comparing the amount of excess loss created by core pumping of the single cladding fibres at high intensity at 1047 nm and 980 nm. Photodarkening was found to be directly proportional to the excitation of the ytterbium ions, with 980 nm core pumping of the single clad ytterbium doped fibre amplifier representing the worst case scenario for photodarkening. Engineering ytterbium fibres for low darkening is therefore critical in pulsed amplification where short length of fibre with high doping level is required as demonstrated in our experiments from a 6 um core single cladding ytterbium fibre pumped with 200 mW of power at 980 nm. Different glass composition and co-dopants have been investigated to reduce this unwanted phenomenon. Codoping with other rare-earth such as erbium is shown to decrease the multi-excitation of ytterbium and thus to lower photodarkening.

6453-18, Session 5

Tapered fused-bundle splitter capable of 1kW CW operation

F. Seguin, A. Wetter, ITF Optical Technologies, Inc. (Canada); M. J. Lovelady, SPI Lasers plc (United Kingdom)

Tapered fused bundle (TFB) combiners play an increasingly prevalent role in fiber laser integration. Power handling and environmental robustness are key to the successful implementation of reliable devices for field deployment. A metallic package was optimized for thermal dissipation of optical power loss, while preserving optical performance during qualification testing. Specially instrumented TFB packages were developed to establish the relationship between bond temperature and case temperature. This was used to predict the inner temperature of non-instrumented devices by tracking the device surface temperature.

In order to test power-handling performance at 1kW, a special splitter component had to be developed to make use of available sources. A 1X7 TFB splitter using 1.00mm core diameter 0.22NA input fiber coupled to seven 400 micron core 0.22 NA output fibers was tested up to 860W CW at 976nm. Surface temperature rise was measured to be less than 15°C with active heat sinking. The above results suggest that minimizing thermal barriers is the key to the multi kW components, and demonstrates that reliable kW-level operation is possible. An extensive series of long term environmental tests have also been performed and demonstrate the environmental stability of this design.

6453-19, Session 5

Fused fiber components for fiber lasers and amplifiers

A. Robertson, Sifam Fibre Optics Ltd. (United Kingdom)

The current intensive development of both fiber lasers and fiber amplifiers has resulted in a requirement for novel fused fiber optical branching components. While the generic benefits of fiber lasers are well known (e.g. efficiency and compactness), the power scaling of these devices, especially in the pulsed regime, places extremely high demands on component operation and design. In this contribution, we discuss fused optical branching component requirements and address the practical issues of achievable performance and manufacturability. Required components can be classed in two distinct groups. The first group are single mode devices whose function relies on cladding coupling based on fused biconical tapers and these include tap couplers, wavelength combiners/splitters, and filters. The second group includes multi-mode devices, primarily used for the power combining of multi-mode pump diodes. We describe the latest developments in state-of-the-art fused fibre components, including the increasing use of Large Mode Area (LMA) Double Clad fibers in pulsed amplifier systems and the component requirements for these systems.

6453-20, Session 5

Diode-bar side-pumping of double-clad fibers

S. W. Moore, J. P. Koplow, D. A. V. Kliner, A. Hansen, G. Wien, Sandia National Labs.

A formatted, fiber-coupled diode bar is currently the preferred pump source for high-power fiber lasers and amplifiers. The main drawbacks of this source are cost, complexity, and an inevitable tradeoff between coupling efficiency and brightness; the net coupling efficiency from the diode bar into double-clad fiber (DCF) is typically 50-60%. In this paper, we present results showing direct coupling of the unformatted output of a 10-emitter diode bar into an array of glass-clad fibers using the technique of embedded-mirror side pumping. We achieved a net coupling efficiency of 84% of the raw diode-bar output into the fiber array, thereby reducing the wasted pump power by a factor of ~3 in comparison with the conventional approach and eliminating the associated penalties in cost, complexity, and efficiency. For applications at the 10-100 W power level and those requiring arrays of DCF amplifiers, diode-bar EMSP provides an attractive alternative to systems based on formatted diode bars.

6453-21, Session 6

Pulse compression down to single-cycle pulses in photonic crystal fibers

A. L. Gaeta, Cornell Univ.

We describe our recent work on the use of photonic nanowires for nonlinear optics. Such nanoguides can be used to perform soliton compression of laser pulses down to a single optical cycle.

6453-22, Session 6

Fiber laser pumped ultra-fast optical parametric amplifiers

J. Limpert, Friedrich-Schiller-Univ. Jena (Germany); T. V. Andersen, NKT Research & Innovation A/S (Denmark) and Friedrich-Schiller-Univ. Jena (Germany); C. Aguergaray, E. Cormier, Univ. Bordeaux I (France) and Friedrich-Schiller-Univ. Jena (Germany); J. Rothhardt, O. Schmidt, F. Röser, T. Schreiber, K. Rademaker, A. Tünnermann, Friedrich-Schiller-Univ. Jena (Germany)

Several applications rely on high repetition rate (and therefore high average power) and ultra-intense ultra-short pulse laser systems. If one considers the properties of ytterbium-doped short pulse fiber lasers and ultra-fast optical parametric amplification systems one easily realizes the well matched compatibility of those techniques to achieve these challenging parameters. It is well known that fiber laser systems are average power scalable due to the fiber design itself, parametric amplifiers are inherently immune against thermo-optical problems due to the fulfilled energy conservation during the nonlinear amplification. The generation of ultra-short energetic pulses in rare-earth-doped is restricted by the limited amplification bandwidth (~5 THz in the case of Ytterbium doped fibers) and pulse distortion due to nonlinearity in the fiber core. On the other hand parametric amplification offers an enormous amplification bandwidth (~ 200 THz in non-collinear configuration (NOPA)), furthermore, a gain of 106 or even 108 can be achieved in just few millimeter long

crystals, therefore, the B-integral (accumulated nonlinear phase) is typical negligible. So far parametric amplification suffers from the lack of a high energy high repetition rate pump laser source, whose parameters potentially can be transferred into pulse durations in the sub-10 fs range using the parametric process. High performance short-pulse fiber laser have the potential to fill this gap. In the talk, the progress of this promising approach towards high repetition rate high peak power laser sources will be discussed.

6453-23, Session 6

Dispersion compensation with solid-core photonic bandgap fiber in an Yb-doped mode-locked fiber laser

C. K. Nielsen, Åarhus Univ. (Denmark); K. G. Jespersen, Risø National Lab. (Denmark); T. V. Andersen, S. R. Keiding, Åarhus Univ. (Denmark)

The recent development of photonic bandgap fibers with a solid core enables the construction of all-fiber ultrashort mode-locked fiber lasers. A solid-core photonic bandgap fiber (SC-PBG) can be spliced to standard fibers with relative low loss, but most important, the interface has a negligible Fresnel reflection due to the matching indexes of the cores. We demonstrate the use of SC-PBG fiber for intra cavity dispersion compensation in an ytterbium based mode-locked fiber laser. The limitations on pulse duration due to the relative high third order dispersion of the SC-PBG fiber is discussed.

6453-24, Session 6

High-average-power, low-nonlinearity ytterbium-fiber amplifier using spectral compression

Y. Zaouter, C. Hönninger, Amplitude Systemes (France); E. Cormier, Univ. Bordeaux I (France); E. P. Mottay, Amplitude Systemes (France)

Using a rare-earth-doped fiber-based amplifier we obtain up to 30W average power with an energy per pulse of 10μJ. The technique of self-phase-modulation-induced spectral compression is used to obtain almost transform-limited pulses of ~10-ps duration. The setup consists in a high repetition rate bulk femtosecond oscillator delivering up to 150 nJ at 10MHz, which is negatively chirped in a grating-based compressor. Its repetition rate is then down-counter to 3MHz by a pulse picker. The 10-ps stretched pulses are amplified in a truly single mode rod-type fiber which exhibits a mode-field diameter of about 1500 μm^2. The fiber amplifier is directly diode-pumped at 976 nm and up to 50W are launched into the amplifing media resulting in 30W average output-power at 3 MHz. Furthermore, the spectral width is reduced down to 0.5 nm.

These features are particularly suitable for applications such as micro-machining, waveguide writing, nano-structuring. The spectral width is also optimal for efficient frequency conversion to second and third harmonic.

6453-25, Session 7

Passive coherent combining of fiber oscillators

M. L. Minden, HRL Labs., LLC

Passive combining of fiber oscillators may one day lead to a simple power scaling capability that multiplies the best results obtained by single devices. Along with HRL's unique approach and early experimental demonstrations, I will discuss some of the extensive modeling we are doing to sort through the current controversies in this area, to design for large numbers of fibers, and to create the most stable inphase beam output.

6453-26, Session 7

Characterization and stabilising dynamic phase fluctuations in large mode area fibers

A. M. Scott, D. C. Jones, QinetiQ (United Kingdom)

High power fibre lasers exhibit rapid time dependent phase fluctuations due to the environment and to thermal and other effects associated with the pumping and lasing processes. We characterise these fluctuations in a novel way and demonstrate methods for stabilising the phase. There are also dynamic changes in the laser beam quality parameter, and we discuss the source of these effects.

6453-27, Session 7

Ultimate efficiency of multi-channel spectral beam combiners by means of volume Bragg gratings

A. Sevian, I. V. Ciapurin, G. B. Venus, L. B. Glebov, College of Optics & Photonics/Univ. of Central Florida

Volume Bragg gratings (VBGs) have been recognized as one of the most advanced diffractive optical elements for spectral beam combiners which transform output beams from several distinct laser sources into a single-aperture beam. The VBGs advantage is their extremely narrow spectral selectivity that enables combining of large number of laser beams within the limited spectral range. The VBGs recorded in a photo-thermo-refractive (PTR) glass exhibit a long-term stability of all their parameters at a multi-kilowatt level of CW power. It was demonstrated the 90%+ efficiency for spectral beam combining of high-power laser beams. In order to increase the spectral capacity of such a beam combiner and overall power of spectrally combined beam, we made a simulation of interrelation of combining efficiency with the losses resulting from absorption/scattering in VBG elements and cross-talk losses between neighboring combining channels. This report discusses design peculiarities of specific beam combining schemes and addresses the cross-talk minimization problem based on optimal channel positioning. A mathematical model reveals the critical parameters for practical realization of highly efficient multi-channel spectral beam combining.

6453-28, Session 7

522-W spectrally beam combined fiber laser with near-diffraction limited-beam quality

T. H. Loftus, P. R. Hoffman, A. M. Thomas, M. A. Norsen, R. Royse, E. Honea, Aculight Corp.

We describe a three-channel, spectrally beam combined (SBC), 1-μm fiber laser that clearly illustrates the unique potential for fiber SBC to efficiently generate high power optical beams with near perfect beam quality. The laser features a SBC power combining efficiency of 93%, versatile master-oscillator, power-amplifier (MOPA) fiber channels that produce up to 260 W of narrowband, polarized, and near-diffraction limited output, and currently produces 522 W of power with a dispersed (non-dispersed) beam quality at 522 W of 1.18x (1.22x) diffraction limited and a signal to out-of-band ratio of > 70 dB. To our knowledge, these results represent the best combination of output power and beam quality achieved by SBC to date. Moreover, and in contrast to coherently combined systems (wherein the near-field fill factor degrades the far-field irradiance), the output beam is a nearly perfect, single-mode Gaussian in both the near- and far-fields. Significant additional power scaling with similarly excellent system performance, either by increasing the individual channel powers or adding additional channels, appears feasible. For current demonstrations, the MOPA outputs are individually collimated and then spectrally multiplexed with a multi-layer dielectric diffraction grating. Grating tests at peak irradiances > 1.5 kW/cm2 show negligible wavefront distortion, as confirmed by the excellent combined beam quality. Future efforts will focus on increasing the number of MOPAs and the individual

MOPA output powers. Our latest progress toward achieving > 1 kW SBC combined beams with near-diffraction limited beam quality will also be described.

6453-29, Session 8

Slow, fast, and backwards light in an erbium-doped optical fiber

R. W. Boyd, G. M. Gehring, A. Schweinsberg, Univ. of Rochester

Recent research has shown how peculiar the propagation of light can become. Observed effects include extremely slow propagation (velocities millions of times smaller than the speed of light c in vacuum) and superluminal propagation (velocities greater than c). We recently demonstrated what is perhaps the most exotic of these effects, the occurrence of backwards pulse propagation. This experiment was performed through use of an erbium-doped optical fiber amplifier operated under conditions to produce a negative value of the group velocity.

We found that the peak of the pulse leaving the fiber exits before the peak of the input pulse enters the fiber. We also observed that the peak of an optical pulse propagating through a material with a negative value of the group velocity does in fact move in the backwards direction.

Reference: Observation of Backward Pulse

Propagation Through a Medium with a Negative Group Velocity, G. M. Gehring, A. Schweinsberg, C. Barsi, N. Kostinski, R. W. Boyd, Science 312,985 2006.

6453-30, Session 8

Optical signal processing by fiber-based parametric devices

C. J. McKinstrie, Lucent Technologies/Bell Labs.

Parametric devices based on four-wave mixing in fibers provide many functions that are required by optical communication systems. When operated in the linear regime, para-metric devices provide amplification, frequency conversion and phase conjugation, all with high gain levels and broad bandwidths. They can also be used to monitor and switch signals. When operated in the nonlinear regime, parametric devices regenerate optical signals. In this talk the current status of research on parametric devices will be reviewed briefly, and some promising directions for future research will be indicated.

6453-37, Session 8

Multichannel all-fiber laser system for LADAR applications

M. P. Savage-Leuchs, E. C. Eisenberg, J. Henrie, M. S. Bowers, Aculight Corp.

All-fiber eye safe laser sources can generate high peak and average powers and short (<5 ns) pulses ideally suited for imaging LADAR systems. By operating multiple fiber power amplifiers in parallel, the total pulse energy and therefore the LADAR range can be further scaled by the number of power amplifiers. Such systems are of particular importance for LADAR systems using 2 dimensional detector arrays, as these systems operate with multiple laser beams, whereby only the beam quality of the single laser beams is relevant for the LADAR image quality. In this paper we demonstrate the operation of an all-fiber amplifier system with four parallel fiber power amplifiers seeded by one distributed feedback laser which was operated between 6-18kHz and 5ns pulse duration. The pulse energies achieved in each of the four power amplifiers is within 125μJ±5μJ for a total of 500μJ, whereby all the pump diodes of the four power amplifiers were operated with the same diode current. The observed temporal line shapes are nearly identical and the beam quality of each power amplifier output is M2<1.5. The experiment demonstrates parallel operation of multiple power amplifiers with nearly identical performance.

6453-32, Session 10

Control and compression of extreme spectrally-broadened pulses in highly nonlinear fiber

J. M. Dudley, Univ. de Franche-Comté (France)

Nonlinear pulse compression is of course very well-known, and arises from the initial spectral broadening and temporal compression phase of higher-order soliton evolution in the anomalous dispersion regime of an optical fiber. However, the presence of either noise on the input pulse, or significant higher-order dispersion can induce pulse break-up and instabilities through soliton-fission processes. Recent studies of soliton fission in the context of supercontinuum generation have provided improved insight into the way these processes can be minimized, allowing significant improvement in achievable pulse quality and duration. In this paper we review a selection of theoretical and experimental results, discussing in particular the key steps required to generate few-cycle pulses around 1550 nm from all fiber-format sources.

6453-33, Session 10

Ultrafast fiber lasers for industrial and bio-medical applications

J. R. Clowes, P. Dupriez, A. B. Grudinin, Fianium Ltd. (United Kingdom)

In this paper we present an overview of ultrafast fiber laser technology and existing and emerging applications of picosecond fiber-based systems.

It is nowadays widely accepted that the most effective and efficient way to achieve high peak power and pulse energy is to employ a master-oscillator / power amplifier scheme where a low power fiber master source is followed by a high power fiber amplifier.

We present a review of ultrafast fiber MOPA configurations and methods to achieve high peak power in cladding pumped fiber amplifiers.

In the second part of our talk we describe commercial and experimental ultrafast fiber laser systems including high power supercontinuum fiber lasers and frequency converted UV fiber lasers. Latest developments demonstrate supercontinuum sources with spectra spanning from 440 nm to 2000 and with average power exceeding 8W and quasi-cw UV systems providing in excess of 1W average power at 266nm.

We will present data on spectral density, pulsewidth, reliability, stability and noise characteristics of these sources.

In the last part of our talk we review some of the most exciting applications of ultrafast fiber lasers including micromachining and bio-medical study.

6453-34, Session 10

Numerical study of pulse evolution

T. Schreiber, B. Ortac, J. Limpert, Friedrich-Schiller-Univ. Jena (Germany); A. Tuennermann, Fraunhofer Institut für Angewandte Optik und Feinmechanik (Germany)

We report on a detail numerical study of pulse formation in a saturable absorber mode-locked fiber laser. The simulations are done by solving the nonlinear Schrödinger equation, where each part is solved separately, in contrast to the average solution of the master equation for solid state lasers. It is possible to clearly identify the well-known operation regimes of short pulse fiber lasers: solution, stretched-pulse and self-similar operation. We will discuss a numerical optimization of SESAM parameters, rare-earth-doped fiber parameters, outcoupling ratio, intra-cavity dispersion compensation and cavity setup to obtain stable and self-starting mode-locking with the desired parameters, i.e. largest bandwidth and highest pulse energy.

6453-35, Session 10

Compact 50W ultrashort pulse fiber laser for precision and high-speed material processing

L. Shah, M. E. Fermann, IMRA America, Inc.; J. W. Dawson, C. P. J. Barty, Lawrence Livermore National Lab.

High speed material processing with a 50 W sub-picosecond fiber chirped pulse amplification system generating 50 uJ pulses at a repetition rate of 1 MHz is demonstrated. A compact system configuration is obtained by implementing a fiber stretcher and a 1780 l/mm dielectric diffraction grating compressor. Despite a substantial residual dispersion mismatch between stretcher and compressor, the exploitation of cubicon pulse formation in the fiber power amplifier allows for the generation of sub-picosecond pulses with sufficient quality for high speed machining applications. Moreover, with the dielectric grating compressor no beam distortions up to a (compressed) power of 50 W are observed, ensuring power independent near-diffraction limited beam quality as required for precision micro-machining. Since the output of the system is presently only pump power limited, further power scaling can be expected in the future. We utilize this laser to mill aluminum, alumina, and glass targets with material removal rates >0.2 mm3/s in all three materials. This removal rate is ~1000 times greater than that of conventional ultrashort pulse lasers, and is to our knowledge the highest ablation rate reported using a compact laser system.

6453-36, Session 10

90-W average-power, high-energy femtosecond fiber laser system

F. Röser, D. N. Schimpf, O. Schmidt, B. Ortac, K. Rademaker, J. Limpert, Friedrich-Schiller-Univ. Jena (Germany); A. Tuennermann, Fraunhofer Institut für Angewandte Optik und Feinmechanik (Germany)

In this contribution, we report on a large-mode-area ytterbium-doped photonic crystal fiber based chirped-pulse amplification system generating up to 90 W of average power of 500 fs pulses at 0.9 MHz repetition rate corresponding to 100 μJ of pulse energy and a peak power of 200 MW. One key element of the system is the diffraction grating compressor consisting of multi-layer dielectric reflection gratings which are able to handle this power level. To our knowledge this is the highest average power ever reported for high energy ultrashort-pulse solid-state laser systems.

6453-38, Session 11

Fiber-based mid-IR sources and applications

I. D. Aggarwal, B. L. Shaw, J. S. Sanghera, Naval Research Lab.

Naval Research Laboratory (NRL) is developing chalcogenide glass fibers for applications in the mid and long wave IR wavelength regions from 2-12 μm. The chalcogenide glasses (i.e., glasses based on the elements S, Se, and Te) are transparent in the IR, possess low phonon energies, are chemically durable and can be drawn into fiber. Both conventional solid core/clad and microstructured fibers have been developed. Chalcogenide glass compositions have been developed which allow rare earth doping to enable rare earth doped fiber lasers in the IR. Also, highly nonlinear compositions have also been developed with nonlinearities ~1000x silica which enables nonlinear wavelength conversion from the near IR to the mid and long wave IR. In this paper, we will review rare earth doped chalcogenide fiber for mid and long wave IR lasers and highly nonlinear chalcogenide fiber and photonic crystal fiber for wavelength conversion in the mid and long wave IR.

6453-39, Session 11

Integrated fiber-laser frequency combs with sub-hertz residual linewidths

I. Hartl, IMRA America, Inc.

Fiber based frequency combs have attracted much attention due to their enormous potential in applications requiring compact comb sources capable of long-term, turn-key and low phase noise operation. An overview of recent developments in this field is given. With reverse-proton exchanged PPLN waveguide technology for CEO phase detection a fully optically integrated, in-line, self-referenced Er-fiber frequency-comb based entirely on guided wave propagation was demonstrated. It will be shown that PPLN-waveguide technology can also be used for spectral broadening, enabling fiber-frequency comb sources without the use of highly nonlinear fiber. In those combs spectral broadening and 2f-to-3f CEO-phase detection occurs in a single PPLN waveguide. With the use of highly Er-doped soft-glass fiber, comb spacings of 175MHz could be achieved which is compatible to commercial wavemeter resolution. It will be shown that the comb lines can exhibit sub-hertz relative linewidths over a broad spectral range and therefore fiber-combs can meet the high performance requirements of applications like high precision spectroscopy and optical clocks.

6453-85, Session 11

A C_2H_2 frequency-stabilized erbium-doped fiber laser and its application to coherent communication

M. Yoshida, K. Kasai, J. Hongo, M. Nakazawa, Tohoku Univ. (Japan)

A stable optical frequency in the 1.55 μm region is receiving a lot of attention in the fields of optical communication, metrology, and high-resolution spectroscopy. C_2H_2 (acetylene) molecules have already been utilized for the frequency stabilization of semiconductor lasers and fiber lasers at 1.55 μm. Fiber lasers are very attractive for such fields because of their narrow linewidth. However, one drawback has been that the output beam inevitably accompanied frequency modulation for stabilization. In addition, it has been difficult to stabilize the laser frequencies to molecular absorption lines because the fiber laser has a long cavity, resulting in mode hopping. To overcome these problems, a fiber Bragg grating (FBG) filter with a bandwidth of several GHz and a short laser cavity were adopted.

In this paper, we describe a frequency-stabilized, polarization-maintained erbium fiber ring laser thus achieved. This laser has no frequency modulation at the output beam. A tunable single-mode laser has also been newly developed by simultaneously controlling a tunable FBG with a 1.3 GHz bandwidth and PZT in the cavity. The frequency stability reached as high as 1.3Å~10-11 for an integration time, t, of 1 s. Using this coherent laser as a light source, we have successfully transmitted a 20 Msymbol/s, 128 quadrature amplitude modulation (QAM) signal over 500 km and error free transmission (7 bit/symbol) was achieved.

6453-40, Session 12

Kilowatt-level, narrow-linewidth capable fibers and lasers

D. T. Walton, Corning Inc.

To attain cw fiber lasers operating at kilowatt power levels, stimulated Brillouin scattering (SBS) must be overcome. In this report, we discuss novel fiber designs that have significantly lower SBS than standard amplifying fibers. The designs considerations, fabrication and performance of these fibers will be discussed in detail. Finally, we will demonstrate amplifier performance at the kilowatt level.

6453-41, Session 12

High-power photonic crystal fiber lasers and amplifiers

T. Schreiber, F. Röser, B. Ortac, O. Schmidt, J. Limpert, A. Tünnermann, Friedrich-Schiller-Univ. Jena (Germany)

The remarkable evolutions in fiber design and production technology of photonic crystal fibers made it possible to precisely control light guidance and thereby extend the available range of optical properties. This enabled many new applications not possible with step index fibers. New light sources based on supercontinuum generation, but also rare-earth doped fibers combining the advantages of PCF technology with the laser process have been demonstrated. We will review the process that has been made using rare earth doped photonic crystal fibers with its applications in high power fiber laser systems. Large-mode area single mode photonic crystal fibers with mode field diameters well above 30 μm and length of several 10 cm allowed overcoming the usual restrictions due to nonlinear pulse distortions specifically in ultra-short fiber lasers and amplifiers. State-of-the-art systems in the lab deliver femtosecond pulses with several 10 nJ pulse energy for fiber oscillators and an average power of 100 W with pulse energies well above 100 μJ for fiber amplifier systems. These examples will be described in terms of the fiber designs as well as the performance and limitations of the systems.

6453-42, Session 12

Robust single-mode operation in 50 μm Ytterbium doped leakage channel fibers

L. Dong, X. Peng, W. S. Wong, J. Li, IMRA America, Inc.

It is critical to increase core size for power scaling in fiber lasers. Step index fiber (SIF) and photonic crystal fiber (PCF) are the main candidates. SIF is limited to a core diameter of 35μm. Even though single mode operation in 60 μm SIF has been demonstrated, large number of modes supported in the SIF makes it very difficult to work with. PCF, on the other hand, enables single mode fiber design. This makes launch easier and eliminates issues related to inter-modal coupling. It is, however, very weakly guided. For diameters above 35μm, it has to be kept straight in short rods with few millimeter diameters.

At CLEO 05, we reported a novel leakage channel fiber (LCF), which enables large core designs supporting very few modes while substantially improving bending performance. In a demonstration in a fiber with a MFD of 42.5μm, we have shown robust single mode operation at various bending radii ranging from few tens to 5cm. M2 value of 1.16 was measured. In this work, we will report performance of a 50 μm ytterbium-doped LCF with a similar core design. The fiber OD is 245μm coated with a low index polymer to provide a 0.45 NA pump guide. Pump absorption is ~2.5dB/m at 976nm. CW laser tests with various lengths from 1.8 to 3m are performed with threshold of ~1.5-2.5W (launched power) and slope efficiency 70-90%. Robust single mode operation is maintained, demonstrating practical nature of the design.

6453-43, Session 12

Deterministic nanosecond laser-induced breakdown thresholds in pure and Yb3+-doped fused silica

A. V. Smith, B. T. Do, Sandia National Labs.; M. J. Söderlund, Liekki Oy (Finland)

The objective of this work was to study the optical breakdown leading to catastrophic optical damage in nanosecond pulsed fiber amplifiers. We used a pulsed, single longitudinal mode, TEM00 laser at 1.064 micron, with 8-nsec pulse duration, and focused it to an 8-micron-radius spot in bulk fused silica. The bulk single-shot optical breakdown threshold irradiances in pure fused silica and 1% Yb3+ doped fused silica preform of Liekki Yb1200 fibers were 4.9 x 10^11 and 6.4 x 10^11 Watts/cm^2, respectively. The standard deviation of the damage threshold in pure silica was less than 1%. We corrected these irradiances for self focusing which reduced the area of the focal spot by 13% relative to its low field value.

By using the third harmonic signal generated at the air-fused silica interface, we could put the focal point on the front or back surfaces of the sample with small uncertainty (~10 microns). We measured surface damage threshold irradiances to be in the range of 1.2 x 10^11 to 1.9 x 10^11 Watts/cm^2 for the front surface, and 0.63 x 10^11 to 1.3 x 10^11 Watts/cm^2 for the back surface.

We also studied the bulk damage morphology which was reproducible from pulse to pulse, as well as the temporal structure of the broadband light emitted by the optical breakdown. The broadband light consists of a 16 nsec pulse followed by another pulse of several hundred nsec duration. The spectrum and time profile of the emitted broadband light gave clues to the nature of the material modification.

6453-44, Session 12

Multi-MW peak power, single transverse mode operation of a 100 micron core diameter, Yb-doped photonic crystal rod amplifier

F. Di Teodoro, C. Brooks, Aculight Corp.

We report on the performance of an Yb-doped, 100 micron-core photonic crystal rod (PCR) used as the final amplifier in a gain-staged master oscillator power amplifier source. From the PCR, we obtained 1ns-long pulses of energy in excess of 4.3 mJ, peak/average power ~4.5 MW / 42W, and spectral linewidth ~20GHz. The PCR emitted a beam exhibiting near-Gaussian, single transverse mode profile of M2 ~ 1.3.

6453-45, Session 12

30W Q-SW fiber laser

M. Nakai, K. Shima, M. Saito, T. Kitabayashi, Fujikura Ltd. (Japan)

We have developed a pulse-operated fiber laser with the average output power of 30 W. In this fiber laser, we employed Q-switched Master Oscillator Power Amplifier(MOPA) configuration to get a flexible pulse shape for laser processing. With this configuration we can get various pulse width at the same repetition rate and the same average power. For example, the pulse width is controllable in the range of 50 nsec to 100 nsec at 50 kHz(repetition rate) and 25 W (average power). Though the flexibility is actually a one important feature of this fiber laser, not only the flexibility but high output power will be introduced in the presentation. The peak power of this fiber laser reaches 27 kW at 30 kHz and the average power reaches 30 W at 100 kHz. The peak power is thought to be enough to handle all the metals with our fiber laser and the average power enables high-speed operation. With our end-pumping layout, we have a prospect to achieve an average power of 100 W from a single core. We adopted another advanced function called “reflection suppressed structure”. All these features will be presented.

6453-46, Session 13

Solid-core bandgap fibers

S. Fevrier, Univ. de Limoges (France)

Photonic bandgap fibres have already proved their huge potential for guiding light in air over kilometric lengths. Nowadays, solid-core bandgap fibres draw considerable attention due to their unusual properties. For instance, the bandgap effect may lead to very large mode area operation, management of the chromatic dispersion curve, spectral filtering or bend loss reduction, all features that could enhance fibre laser performances.

Recent results on the design, fabrication and characterization of various types of solid-core bandgap fibers are presented. Prospects of further development of bandgap fiber lasers are discussed.

6453-47, Session 13

Three-dimensional, time-dependent modeling of high-power fiber amplifiers

G. R. Hadley, R. L. Farrow, A. V. Smith, Sandia National Labs.

We have developed a time-dependent 3D numerical model to treat optical pulse propagation through a fiber amplifier. The model neglects group velocity dispersion but includes effects due to bending (mode distortion and loss), spatially-dependent saturable gain, self-focusing, self-phase modulation, and can model fibers with an arbitrary index distribution. This model, when initialized by an accurate population inversion profile, is expected to be an invaluable aid for design, analysis and optimization of overall system performance.

6453-48, Session 13

Design of refractive-index and rare-earth-dopant distributions for large-mode-area fibers used in coiled high-power amplifiers

R. L. Farrow, G. R. Hadley, D. A. V. Kliner, J. P. Koplow, Sandia National Labs.

We have numerically investigated and compared the performance of various designs for the core refractive-index (RI) and rare-earth-dopant distributions of large-mode-area fibers for use in bend-loss-filtered, high-power amplifiers. We first established quantitative targets for the key parameters that determine fiber-amplifier performance, including effective LP01 modal area (Aeff, both straight and coiled), bend sensitivity (for handling and packaging), high-order mode discrimination, mode-field displacement upon coiling, and index contrast (manufacturability). We compared design families based on various power-law and hybrid profiles for the core RI and on confined rare-earth doping. Step-index profiles with unbent-fiber Aeff values > 900 um2 exhibit large decreases in Aeff and displacements upon coiling, in agreement with recent calculations of Fini [Opt. Exp. 14, 69 (2006)] and Hadley et al. [Proc. of SPIE, Vol. 6102, 61021S (2006)]. Triangular profiles can substantially mitigate these effects, but they suffer from excessive bend sensitivity. Square-law (parabolic) index profiles eliminate modal distortion but are hampered by bend sensitivity (although to a lesser degree than triangular profiles) and exhibit the largest mode displacements. We find that hybrid (combined power-law) profiles provide some decoupling of these phenomena and allow all design goals to be achieved simultaneously. We will present optimized fiber designs based on this analysis.

6453-49, Session 13

Fiber designs for exceeding the bulk-media self-focusing threshold

A. D. Yablon, J. C. Jasapara, OFS Fitel, LLC

Self-focusing is thought to be a fundamental constraint on the maximum power achievable in short pulsed optical fiber lasers or amplifiers. Peak powers approaching the conventionally defined critical power for self-focusing have recently been documented. One proposed approach for transcending the self-focusing limit is to employ a hollow-core photonic bandgap (PBG) microstructured optical fiber that guides most of the optical signal in an airhole or void. However, the overlap between gain producing dopants and the optical signal is expected to be inherently poor whereas fabricating and interconnecting such fibers pose additional difficulties. Using numerical simulations we show that certain large-mode-area (LMA) non-microstructured fiber designs can guide a stable fundamental mode at more than 10 times the conventionally defined critical power for self-focusing. These fiber designs can be fabricated using conventional MCVD technology. The fiber designs suppress the onset of self-focusing by stabilizing an optical spatial soliton in silica glass, which is a non-saturable Kerr material. The fiber designs are analyzed by a numerical solution of the (2+1)-dimensional scalar non-linear Schrodinger (NLS) equation as well as by a scalar finite-difference beam-propagation-method (FD-BPM). This class of fiber designs can extend the performance of extremely high-peak-power (>4 MW) short-pulse (<1 ns) optical fiber lasers and amplifiers.

6453-50, Session 13

Photodarkening measurements in large mode area fibers

J. J. Koponen, M. J. Söderlund, H. J. Hoffman, Liekki Oy (Finland); D. A. V. Kliner, J. P. Koplow, Sandia National Labs.

Yb-doped fibers are widely used in applications requiring high average output powers and high power pulse amplification. Photodarkening is one limiting factor in these fibers. In this paper, characterization of photodarkening in LMA fibers is presented building upon our previous work which indicated that meaningful comparison of photodarkening properties from different fibers can be made as long as care is taken to equalize the excited state Yb concentration between samples as much as possible. For example we found that it is sufficient to use the same inversion level for different samples with similar dopant concentrations. We have also shown that the measurement technique can be used effectively even for LMA fibers by employing cladding pumping rather than the more standard core pumping. The work reported here goes a step further by addressing the issues of stabilization of photodarkening over time, the effectiveness and trade-offs introduced by using temperature based annealing and the impact of certain dopants and glass compositions on the photodarkening process.

6453-51, Session 13

Current developments in high-power, monolithic, polarization maintaining fiber amplifiers for coherent beam combining applications

D. P. Machewirth, Q. Wang, B. N. Samson, K. Tankala, M. O'Connor, M. Alam, Nufern

This paper summarizes current developments in PM optical amplifiers at Nufern. Amplifier systems based on 20 μm and 25 μm core fibers are investigated. Using a ~3 kHz linewidth laser source and a Nufern 10W narrow linewidth fiber amplifier to seed these PM amplifiers (PER > 20 dB), SBS threshold output powers for these systems will be presented. Additional characterization of advanced amplifier components, such as the latest in pump diode and pump/signal combining technology, will be discussed to explore PM fiber amplifier systems capable of >1 kW output power.

6453-52, Session 14

All-fiber mid-infrared supercontinuum source to 4 μm with 1.3 watts time-averaged power in ZBLAN fluoride fibers

C. Xia, M. Kumar, M. Cheng, Univ. of Michigan; M. N. Islam, Univ. of Michigan and Omni Sciences Inc.; A. Galvanauskas, F. L. Terry, Jr., Univ. of Michigan; M. J. Freeman, Omni Sciences Inc.; M. Poulain, Univ. de Rennes I (France); G. Mazé, Le Verre Fluore (France)

We demonstrate mid-infrared supercontinuum (SC) generation in ZBLAN (ZrF4-BaF2-LaF3-AlF3-NaF...) fluoride fibers extending from ~0.8 μm to beyond 4 μm with 1.3 W time-averaged power, the highest power reported to date to our knowledge. The all-fiber SC light source operates at room temperature by using commercially available off-the-shelf telecommunication components and is in the single spatial mode for the entire spectrum. Unlike many other SC experiments, we use amplified nanosecond laser diode pulses instead of femtosecond mode-locked lasers. SC is generated in 3 m standard single-mode fiber (SMF) followed by 13

m ZBLAN fiber. The nanosecond pulses, which are amplified by an erbium/ytterbium doped cladding-pumped fiber amplifier, are broken up into femtosecond pulses in the SMF fiber and the spectrum is then broadened through fiber nonlinearities in the ZBLAN fiber. The time-averaged power is scaled by varying the pulse repetition rate. For examples, the average power of the SC is ~23 mW at 5 kHz, while at 300 kHz, 1.3 W average power is obtained. We observe the ZBLAN fiber can handle more than 2.5 W average power. Therefore, the SC average power can be potentially scaled up to ~2.5 W by adopting better thermal management. We will also report results on an all-fiber-integrated ZBLAN-based mid-infrared SC light source which can provide more than 1 W average output power in the 1~4.5 μm regime.

6453-53, Session 14

High-power, high-brightness green laser based on a frequency doubled picosecond fiber laser

P. Dupriez, J. K. Sahu, Y. Jeong, A. Malinowski, D. J. Richardson, J. Nilsson, Univ. of Southampton (United Kingdom)

Over recent years, there has been a tremendous and rapid progress in power scaling Yb-doped fiber-based picosecond sources due to their high efficiency, excellent beam quality and immunity to thermo-optical effects. These remarkable properties are not only very attractive for many scientific and industrial applications but also for frequency doubling to generate green. Besides good beam quality, a high degree of polarization and a narrow linewidth, further increase in conversion efficiency requires high peak power and increased crystal length. High peak power can be obtained by employing a fiber master-oscillator power amplifier design (MOPA) where seed pulses with adequate duty cycle are amplified to high average powers. However in this arrangement minimizing nonlinear effects arising in the fiber amplifiers becomes a challenge. The amplification of picosecond pulses causes linewidth broadening and the spectral bandwidth of the crystal is reduced by a preferred longer length. This trade-off can result in lower frequency doubling efficiency.

In this paper, as well as the benefits and limitations of fiber lasers applied to nonlinear frequency conversion, we will review the various design considerations for the development of a high average power picosecond green laser based on single-pass frequency doubling of a fiber MOPA system. We will describe a picosecond Yb doped fiber MOPA with continuously variable duty cycle that can be finely adjusted to the nonlinear crystal length. This led to the demonstration of a nearly diffraction limited output beam of 80-W of average power at 530 nm which will be presented. We believe diffraction limited green lasers with >100 W output power can be realized based on the proposed laser architecture.

6453-54, Session 14

Forward and backward-seeded CW Raman-fiber amplifiers based on multimode fibers

N. B. Terry, K. Engel, T. G. Alley, Air Force Institute of Technology; T. H. Russell, Air Force Research Lab.; W. B. Roh, Air Force Institute of Technology

We report on the performance of seeded CW Raman fiber amplifiers based on multimode graded index fiber. The “beam-cleanup” improvement in beam quality of the Stokes beam over that of input pump beam (previously observed in unseeded Raman fiber amplifiers in multimode graded index fiber) is shown here to be limited by the beam quality of the input seed beam for seeded amplifier configurations. The amplifiers are characterized in terms of their capacity for beam-cleanup, their ability to amplify the seed and in terms of their output spectra. The advantages and disadvantages of a backward-pumped geometry versus a forward-pumped geometry are discussed. Depending on the geometry, amplified power can be readily distributed to a cascade of Stokes frequencies (unseeded forward-pumped geometry) or can be mostly contained in the seed frequency (seeded backward-pumped geometry).

6453-55, Session 14

Single-frequency photonic crystal fiber amplifier with 148-W output power

M. Hildebrandt, Laser Zentrum Hannover e.V. (Germany)

We report on a high power Ytterbium doped photonic crystal fiber amplifier with a single-frequency Nd:YAG non-planar ring oscillator seed source. In order to realize high power operation below the threshold for stimulated Brillouin scattering a short large-mode area fiber was used. The system delivers an output power of up to 148 W with a slope efficiency of 75% with respect to the launched pump power. At full output power the amplified spontaneous emission was suppressed by more than 40 dB. The fiber was coiled to get single transverse-mode operation with $M(c)^2$ values around 1.4 measured by standard method. To investigate the real overlap of the photonic crystal fiber transversal-mode with the Gaussian fundamental-mode sensitive beam quality measurements with a Fabry-Perot ring-cavity premode cleaner will be presented.

6453-57, Session 15

An all-fiber approach for in-phase supermode phase-locked operation of multicore fiber lasers

L. Li, A. Schülzgen, V. L. Temyanko, H. Li, J. V. Moloney, N. N. Peyghambarian, The Univ. of Arizona

Active multicore fiber (MCF) brings a promising solution to power-scalable compact fiber laser device. As thermal issue is less concerned, more output power can be extracted per unit fiber length. Nevertheless, effectively obtaining high-brightness output beams, e.g., the in-phase supermodes with Gaussian-like far-field intensity distributions from MCFs with 2-D isometric core-array through phase-locking operation, constitutes a challenge. Conventionally, free-space optics, i.e., air gaps and bulk optics, is utilized to provide discrimination against high order supermodes so that the in-phase mode oscillates exclusively. However, for compact photonics system applications, free-space optics approach is not favored because of its substantial device size, aligning complexity and susceptibility to external and thermal disturbances. Ideally, the phase locking operation should take place in confined waveguides.

In this paper, we report on compact multicore fiber lasers that utilize an all-fiber approach to phase lock and select the in-phase supermode. The fundamental in-phase mode is selectively excited within a completely monolithic fiber device, simply by fusion splicing passive coreless optical fibers with controlled lengths at both ends of a piece of MCF. The experimental demonstration has been done with in-house-made MCFs of 19 and 37 doped cores in 2-D isometric array. The whole MCF laser device is in principle a single fiber chain that is only ~10 cm in length, aligning-free in operation, and robust against environmental disturbance.

6453-58, Session 15

Spectral beam combining of fiber lasers with increased channel density

O. G. Andrusyak, I. V. Ciapurin, College of Optics & Photonics/Univ. of Central Florida; V. I. Smirnov, OptiGrate; G. B. Venus, L. B. Glebov, College of Optics & Photonics/Univ. of Central Florida

Incoherent combination of laser radiation from multiple sources into a single near-diffraction-limited beam results in energy brightness increase. Incoherent spectral beam combining (SBC) by means of volume Bragg gratings (VBGs) has been shown to be a simple and robust technique for generating high-power laser radiation. High-efficiency VBG recording in photo-thermo-refractive (PTR) glass has been recently developed. A set of original features of PTR glass enables VBGs which withstand high-power laser radiation, making them ideal elements for high-power SBC.

We present experimental results of successful 5-channel SBC with reflecting VBGs in PTR glass with extremely low channel separation (< 0.5

nm around 1064 nm). Absolute system efficiency in excess of 90% at low power is demonstrated and propagation properties of individual and combined beams are studied. Experimental results of high-power SBC of five 150-W state-of-the-art fiber lasers with near-diffraction-limited single-frequency outputs are discussed.

We show how power scaling allows adding channels to the system with little effect on total system efficiency and output beam quality. Multi-kW near-diffraction-limited beams can be obtained in the near future via SBC with volume Bragg gratings in PTR glass.

6453-59, Session 15

Spectral beam combining of Yb-doped fiber lasers

S. Klingebiel, R. Kinney, F. Röser, B. Ortac, J. Limpert, Friedrich-Schiller-Univ. Jena (Germany); A. Tuennermann, Fraunhofer Institut für Angewandte Optik und Feinmechanik (Germany)

Spectral beam combining (SBC) is a promising way for future power scaling of fiber lasers. The cw-output power of a single fiber is limited due to nonlinear effects or damage of the fiber. We report on a spectral combination of three fiber lasers without reduction of the beam quality. Thus, the combined beam has a single-transverse mode beam quality (M^2 < 1.2), just like each single beam. Each laser is built in a Master-Oscillator Power-Amplifier setup with a tunable cw all-PM-fiber oscillator as the seed source and an Yb-doped polarizing photonic crystal fiber as main amplifier. The linearly polarized output leads to a very high combination efficiency of more than 90% using a dielectric transmission grating. The latest results of high power combination experiments will be discussed.

6453-60, Session 16

Highly nonlinear single-mode chalcogenide fibers for signal processing

L. Fu, V. G. Ta'eed, M. Rochette, The Univ. of Sydney (Australia); A. Fuerbach, Macquarie Univ. (Australia); I. C. Littler, M. Pelusi, M. R. Lamont, H. C. Nguyen, K. Finsterbusch, D. J. Moss, E. C. Mägi, B. J. Eggleton, The Univ. of Sydney (Australia)

Chalcogenide glass based optical waveguides offer many attractive properties in all-optical signal processing because of the large Kerr nonlinearity (up to 500 Å~ silica glass), the associated intrinsic response time of less than 100 fs and low two-photon absorption (TPA). These properties together with the convenience of a fiber format allow us to achieve all-optical signal processing at low peak power and in a very compact form. In this talk, a number of non-linear processing tasks will be demonstrated including; all-optical regeneration, wavelength conversion and femto-second pedestal-free, pulse compression. In all-optical regeneration, we generate a near step-like power transfer function using only 2.8 m of fiber. Wavelength conversion is demonstrated over a range of 10 nm using 1 m of fiber with 7 ps pulses, peak power of 2.1 W, and 1.4 dB additional penalty. Finally, we will show efficient compression of low-power 6 ps pulses to 420 fs around 1550 nm in a compact all-fiber scheme.

These applications show chalcogenide glass fibers are very promising candidate materials for nonlinear all-optic signal processing.

6453-62, Session 16

Methods of supercontinuum generation for effective down-conversion in photonic crystal fibers

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In recent years photonic crystal fibers (PCF) have dramatically improved supercontinuum generation (SCG) performance and lowered the demanded power of the pump lasers. Especially, PCF light sources have been demonstrated with broad, smooth and stable double-peaked supercontinuum. This is generated from femtosecond pulses by optical frequency up- and down-conversion as dispersive waves are generated on both sides of a narrow anomalous pumping region. But, despite of high interest within applications such as optical coherence tomography (OCT), effective conversion, when the targeted center wavelength is far from the pump, has not been fully investigated nor optimized.

Here, we report on experimental and numerical investigation of the SCG in the 1300 nm region, crucial to OCT, dominated either by soliton self frequency shift alone or together with dispersive waves. A Ti:Sapphire laser, providing femtosecond pulses at 800 nm, is used to generate the continuum by pumping a nonlinear PCF in the anomalous dispersion region. Of interest are nonlinear PCFs with the second zero dispersion wavelength above (1450 nm) or below (1160 nm) the targeted wavelength. For the two fibers investigated, the experimental ratio of conversion from input power to the wavelengths range of interest is 35% and 25%, respectively. The characteristics of the generated spectra are controlled by input power and fiber length, but stability and energy conversion are strongly connected to the different nonlinear processes taking place in the PCFs. Experimental observations such as central wavelengths and bandwidth compares well with numerical simulations.

6453-63, Session 16

Limiting effects of four-wave-mixing in high-power pulsed-fiber amplifiers

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We present an experimental and theoretical analysis of four-wave-mixing in nanosecond pulsed fiber amplifiers, which leads to a saturation of the amplified pulse energy and to distortions of the spectral and temporal profiles. These behaviours are well described by a simple model considering both Raman and four-wave-mixing contributions

6453-64, Session 16

Nonlinear frequency conversion with mode-locked erbium-fiber lasers

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We present an overview of nonlinear optical frequency conversion techniques that we have developed and optimized for use with mode-locked Erbium fiber lasers. Starting with 70 fs, 3 nJ pulses at 1560 nm, we are able to access the entire wavelength band from 500 nm to 2000 nm without any gaps. Over this broad range of wavelengths, we adapt pulse parameters such as temporal duration and spectral width to the specific application requirements.

As one example, the excitation of various fluorophores in confocal microscopy calls for a widely tunable but nonetheless narrow-band laser source in the visible spectral range. We solve this task in a two-step process starting with supercontinuum generation in the near infrared. The non-solitonic radiation peak is shifted to a desired wavelength between 1020 nm and 1400 nm. In the next step, we exploit a mixture of intrapulse sum frequency generation and second harmonic generation in a periodically poled nonlinear crystal for further frequency conversion. This interplay of effects results in the generation of pulses continuously tunable between 510 nm and 700 nm with spectral widths ranging between 1 and 2 nm (FWHM), despite starting from a broad distribution in the near infrared (50 -100 nm, FWHM) [1]. The output power in the visible range amounts to 5 -10 mW.

Further options for nonlinear frequency conversion of the Erbium laser include direct frequency doubling to 780 nm, yielding pulse parameters similar to classical Ti:sapphire oscillators (pulse duration 100 - 200 fs, output power 70 - 120 mW). In turn, these pulses may be used to generate white light continua between 500 nm and 1000 nm, making use of photonic crystal fibers specifically designed for this pump wavelength.

[1] K. Moutzouris et al., Opt. Lett. 31, 1148 (2006)

6453-61, Poster Session

Coherence measurements of supercontinuum source based on a fiber laser and highly nonlinear dispersion shifted fiber

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We report a coherence measurements of supercontinuum (SC) source generated in highly nonlinear dispersion shifted fiber (HN-DSF) using a delayed pulsed method. An all-fiber SC is generated by putting the amplified fiber laser pulse at the wavelength of 1.557 mm into the HN-DSF whose zero dispersion wavelength is 1.537 mm. As the pump pulse, we used a passively mode-locked Er-doped fiber laser (PML-EDFL). It generates ~ 1 ps pulses at a repetition rate of 11 MHz with an average output power of 0.5 mW. These pulses are amplified in a short Er-doped fiber amplifier (EDFA).

The amplified laser pulses are put into the HN-DSF whose nonlinear coefficient is about 10.5 /W/km at the input wavelength. The polarization state of the generated SC spectra is well defined such that it can be properly controlled by the polarization controller. The coherence as a function of wavelength across the SC is measured over a wide range of input pulse parameters using a Michelson interferometer consisting of all-fiber components. The strong dependence of the spectral coherence on the input pulse width, chirp, energy and HN-DSF length is observed experimentally. And optimal conditions of pulse parameters for obtaining wide SC with high coherence are investigated in detail. We believed that our proposed all-fiber laser based SC source with high coherence has many important applications in recently developed frequency-domain measurement techniques such as optical coherence tomography (OCT), optical frequency domain imaging (OFDI), optical frequency domain reflectometry (OFDR) and their instrumentation.

6453-65, Poster Session

Mode-locking characteristics of hybrid soliton pulse source

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In recent years, several examples of short optical pulse sources using active mode-locking have been proposed. This method provides low timing jitter picosecond pulses, locked to an external electrical reference frequency, for high-speed optical communications systems. Fibers grating external cavity lasers have been experimentally demonstrated in the mode-locking regime at 2.5 GHz and 10 GHz. Hybrid soliton pulse source (HSPS) is one such device, developed as a pulse source for soliton transmission system. A practical soliton transmission system may be required to operate at the 2.488 GHz with a pulsewidth of around 50 ps giving a time-bandwidth product range of 0.3 to 0.5. An interesting feature of these devices is the extremely wide operating frequency range, which can be enhanced by using chirped gratings, as reported. Measured results showed that transform-limited pulses are generated over a frequency range of 850 MHz using linearly chirped Gaussian apodized fiber Bragg grating (FBG). However, in this paper, theoretical model of the mode-locked HSPS with linearly chirped Gaussian apodized FBG is described.

Results indicate that transform-limited pulses are generated over a wide tuning range of 900 MHz for linearly chirped Gaussian apodized FBG and this grating is a good candidate to be used in soliton pulse propagation systems. All results have found to be fit well compared with the experimental results in the literature.

6453-66, Poster Session

Q-switched fiber laser using a novel rotary mirror

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Traditionally, Q-switches for lasers have been acousto-optic (AO) switches, electro-optic (EO) switches, and rotating polygons. Recently, there have also been reports of lasers Q-switched using MEMS devices. Each of these technologies has significant drawbacks, e.g. high-voltage operation, alignment difficulties.

In this study, we report a simple Q-switch consisting of a rotating planar-mirror where the reflectivity of portions of the surface are high and the reflectivity of the remaining portions are low. This novel Q-switch is demonstrated using a fiber laser.

The laser cavity is formed by the rotating planar-mirror acting as one mirror and a fiber Bragg grating (FBG) acting as the other mirror. As the mirror is rotated, the cavity has a high-Q when the high-reflectivity portion forms the laser cavity and has a low-Q when the low-reflectivity portion rotates into position.

In this study, the rotating planar-mirror consists of a gold-coated, 3.75" diameter disc taken from a standard, magnetic hard-drive. The surface was first gold-coated to improve the reflectivity and was subsequently covered with a carbon-coated plastic-film to form the absorbing, low-reflectivity regions. Four slits, approximately 1 mm wide and spaced 90° apart, were removed from the absorbing plastic at the perimeter of the disc to optically access the high-reflectivity gold-surface.

Using two meters of single-mode, 5 μm core, Yb-doped fiber, a 40% FBG at 1060 nm, and a single-mode diode-pump at 976 nm, a fiber laser with a threshold power and slope efficiency of approximately 25 mW and 33% was achieved, respectively, with the rotary mirror held stationary at the high-reflectivity region to form part of the laser cavity. With the mirror rotating at a fixed speed of 7200 rpm, pulses with a 150 ns FWHM at a repetition rate of 480 Hz were observed. At an optical pump-power of 80 mW, the average power from the Q-switched fiber laser was 3.5 mW resulting in a calculated, peak pulse-power of 48.6W.

6453-67, Poster Session

Preparation of large-mode-area laser fibers with microstructured cores

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Important progress in the development of rare earth doped high power fiber lasers was possible by large-mode-area fibers with increased core diameters and reduced core apertures as low as 0.05. In this way, the excellent beam quality is maintained, but the power density can be reduced below critical values despite of very high output powers beyond 1 kW. Sophisticated concepts had to be developed in order to maintain the low NA in the case of high doping, e.g. the codoping by index-decreasing components as boron or fluorine.

Here we report on the progress in the preparation of microstructured laser fibers, the core area of which is composed of parts with high doping and parts with refractive index lower than the silica pump cladding. In contrast to the direct co-doping, in this way the atomic environment of the active atoms can be tailored and optimized independently on the mean refractive index of the core. The preparation was carried out by stacking different rods in a multistep process, leading to cores with up to more than hundred single elements. Both for ytterbium and erbium/ytterbium doped fibers, good optical properties concerning basic attenuation and rare earth fluorescence could be reached by introducing additional purification steps. The pump power absorption and the coupling of the active elements in order to get a single-moded laser output were investigated. Different fiber structures were characterized concerning pump power stability of the outer cladding (polymer, air-clad) and mechanical strength.

6453-68, Poster Session

Fiber Raman laser in visible wavelength region

Y. Feng, D. Bonaccini Calia, W. K. P. Hackenberg, European Southern Observatory (Germany)

Fiber Raman lasers have been intensively studied in recent years in the near infrared wavelength region because of applications in telecommunication. However, fiber Raman lasers in the visible wavelength region have hardly been explored yet. Compact, moderate-power, and visible fiber laser source are actually very interesting for applications in medicine and scientific research.

Our motivation of the study is to investigate the potential of fiber Raman laser or amplifier in developing laser source at 589nm for laser guide star adaptive optics, which require the laser to have a narrow linewidth (<3GHz). We have made a simulation study on a 0.5 GHz linewidth 589 nm laser by Raman shift from a commercially available solid state green laser, done in a single mode fiber. The efficiency of such narrow band fiber Raman laser is limited by the onset of stimulated Brillouin scattering. Our simulations show that several hundreds of milliwatts may be obtained with a 10 W pump laser at 532 nm, depending on the discrimination ratio of the Raman and SBS oscillation in the resonator. An appropriate laser configuration should only resonate the Raman Stoke but leak the Brillouin light. With a master oscillator power amplifier scheme this could be an alternative approach for the laser system required for laser guide star adaptive optics.

We will also discuss the technical challenges for this type of lasers and corresponding proposals. Experimental demonstration of fiber Raman laser pumped by a solid state green laser is planed in coming months.

6453-69, Poster Session

Soliton resonance in dispersion oscillating fiber

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It is known that the single mode fibers with varying along length dispersion have a lot of applications in optical signal processing. For example the dispersion decreasing fibers (DDF) have been used for high-quality soliton pulse compression and stable against pump noise continuum generation. In this work we propose a novel method to carry out the selection of ps and subps optical pulses by its amplitude and width in dispersion oscillating fiber. The behavior of solitons described by the nonlinear Schrodinger equation with periodic perturbation is known well when the period of perturbation is essentially less than the soliton period (guiding-center soliton case).

On the other hand, when the period of perturbation is close to the soliton period, the resonance effects take place. In particular one is able to increase the pulse repetition rate by means of fission of second-order solitons in the fiber with periodically modulated dispersion. This effect has been studied numerically and experimentally. Good agreement between theory and experiment was obtained.

6453-70, Poster Session

Multiple wavelengths generation with 22-GHz-spacing incorporating hybrid Brillouin-Erbium dual-cavity fiber laser

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Multiwavelength fiber lasers are one of attractive solutions to support dense wavelength division-multiplexed systems. A group of laser lines can be generated from a seed signal utilizing hybrid Brillouin-Erbium gain in the same laser cavity. Brillouin-Erbium fiber lasers have attracted lots of research attention owing to its efficiency of generating a sequence of Brillouin Stokes lines simultaneously with about 11-GHz-spacing. However, the narrow channel spacing cannot match with the commercially available filters. Therefore, the spacing between neighboring Stokes lines must be further separated. In this paper, the spacing of the multiwavelength lines is doubled to about 22 GHz incorporating a dual-cavity laser. In the research work, the dual-cavity laser consists of two identical ring cavities that share the same single-mode fiber (SMF) and erbium-doped fiber. A Brillouin Stokes line is initiated in the first ring (clockwise direction) through pre-amplified Brillouin pump at one end of the SMF then, become the Brillouin pump at the opposite end of the same SMF to generate the next Brillouin Stokes line in the second ring (anti clockwise direction). In our research work, the odd and even order Brillouin Stokes lines oscillate in isolated ring cavity. The proposed dual-cavity fiber laser structure exhibits a low threshold power of 3 mW to get the first Brillouin Stokes line and is able to produce up to 26 stable output lines (2 x 13 lines) with 22-GHz-spacing. For each output arm, the average isolation between odd and even Stokes lines is higher than 15 dB.

6453-71, Poster Session

mJ pulse-energy fiber lasers based on Yb-doped photonic crystal fibers

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Ytterbium-doped double-clad photonic crystal fibres are ideal candidates for diffraction limited pulse amplification to energies of several mJ. The combination of large mode field diameter and high numerical aperture allows short high pump absorption and high thresholds for detrimental non-linear effects. We present results from ns-pulsed Q-switched laser and MOPA systems with pulse energies exceeding 1mJ and peak powers of 5 to 10kW realised using photonic crystal fibres with an MFD of 22μm. The results are scalable with core area to much higher pulse energies when applying PCFs with larger MFD. Truly single mode PCFs with MFD up to 70μm have been realised indicating the scalability to pulse energies exceeding 10mJ.

6453-72, Poster Session

Passively mode-locked short-cavity 10-GHz Er:Yb-codoped phosphate-fiber laser using carbon nanotubes

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Passively mode-locked fiber lasers are practically important due to their simplicity and their ability to generate transform-limited pulses in the picosecond regimes. A passively mode-locked fiber laser employs a mode-locker, usually a saturable absorber. A drawback of the conventional passively mode-locked fiber lasers is that the pulse repetition frequency is relatively low, at best a few tens of MHz, because of long cavity length. In order to raise the repetition frequency up to a few GHz, the cavity length has to be shortened below a few centimeters. Fiber lasers with such a short cavity require a high gain fiber and a small saturable absorber with low loss. Recently, the authors have proposed and demonstrated a small and low-loss saturable absorber device incorporating carbon nanotubes (CNT). Using CNT, we have realized a very stable 2cm-long, 5GHz mode-locked Er:Yb-codoped silica-fiber laser, but the output power was limited to ~0.2mW due to insufficient gain in the Er:Yb-codoped silica-fiber. Here we used heavily Er:Yb-codoped phosphate fiber to form a 1cm-long cavity with 100% and 50% fiber mirrors, and succeeded in generating stable pulse trains fundamentally mode-locked at the repetition frequency as high as 10GHz at 1550nm. The Er:Yb-codoped phosphate fiber has Er concentration of 1.1*10^26 ions/m^3, and Yb concentration of 8.6*10^26 ions/m^3. The output power from the end of 50% fiber mirror was as high as 30mW at the pump power of 300mW at 980nm. The pulsewidth inferred from the autocorrelation trace was ~4ps, and the repetition frequency was found to be 9.69GHz.

6453-73, Poster Session

Integration aspects of a flexible, pulsed high-power single-transverse mode fiber laser system in MOPA configuration

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Pulsed fiber laser systems allow the generation of pulses in a wide range of pulse lengths and repetition rates with constant beam quality. Based on the experience with an existing three stage high power fiber amplifier that was developed in MOPA configuration, system integration aspects of flexible high power single transverse mode Yb-doped fiber lasers will be presented.

The requirements of pulsed high power fiber lasers for industrial applications will be examined and system parameters will be derived.

Components required for a power amplifier system will be investigated. In order to maintain a high beam quality single mode, single clad fibers were used in the first two amplification stages. Since the absorption equation does not apply at the required pump power levels, experiments were conducted to optimize the length of the amplification fibers according to the application. The results will be presented.

As the power limits of the single mode fibers were reached, large mode area fiber was employed for the final stage. The requirements of components for a monolithic setup between the second and the third stage were examined. Technologies such as tapering and coiling for maintaining single mode beam quality were investigated.

Material processing experiments using the MOPA fiber laser have been conducted. They showed that depending on the parameter/material combination a certain degree of output isolation is required to operate the system. The measurement results of the material processing experiments and the examined inter-stage components will be presented.

Also, the integration of the system will be discussed. Hardware components that are crucial to maintain stable and safe operating conditions were examined. Integrating the hardware components lead to various control concepts that will be described.

6453-74, Poster Session

Long-wavelength operation of double-clad Tm:silica-fiber lasers

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Lasers operating at wavelengths that pass through the atmosphere are required for many applications, including lidar, ladar, and pollution detection. One window of particular interest is between 2.05 to 2.3 μm. For many applications requiring high average powers, fiber lasers may be the preferred radiation source. A Tm:silica fiber laser may be a candidate for operating in this window, but reported solutions using double clad fibers only achieved wavelengths up to 2090nm even though the ASE spectrum of the lasing band extends beyond 2200nm.

The wavelength band of operation of a Tm:silica fiber laser depends on cavity losses, dopant concentration, and fiber length. By carefully selecting these parameters, the operating wavelength may be adjusted. A laser based on a double clad Tm:silica fiber laser coupled to a bulk grating for wavelength selection was constructed. By changing the output coupler reflectivity the maximum obtainable wavelength shifted from 2040nm to 2140nm, and another mirror resulted in 2188nm lasing operation.

6453-76, Poster Session

Microsecond-pulsed ytterbium-fiber laser system with a broad tuning range and a small spectral linewidth

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We present a tunable high power ytterbium fiber laser system which is suitable for a variety of applications, e.g. in nonlinear frequency conversion, spectroscopy or in medicine technique. The realized laser system consists of a master oscillator power amplifier arrangement with a fiber integrated pulse shaper. The continuous-wave core-pumped fiber oscillator with a grating in Littman configuration as tuning element defines the spectral properties of the system, like tuning range and spectral linewidth. A fiber integrated modulator is used for pulse generation and shaping. The losses due to this modulator are compensated for in a core-pumped amplifier. The final amplifier stage applying a double clad fiber generates peak powers at a multi Watt level. At a repetition rate of 20 kHz and a pulse duration of 3 μs an average output power of 1.8 Watt is achieved corresponding to a peak power of nearly 50 W. The system is tunable from 1040 nm to 1070 nm with a linewidth of 10 MHz. Experimental results on tuning performance, pulse shaping and stability as well as noise behaviour will be presented.

6453-77, Poster Session

Two-stage single-pump Er-doped fiber amplifier with 55-dB amplification ns-long pulses

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We present a design of a simple two-stage EDFA with amplification higher than 50 dB pumped by a single 980-nm laser. The first stage in the reflective configuration uses a 20-m Er-doped fiber. The reflection of the signal is provided by a FBG with the reflectivity of 100% and FWHM of 0.4 nm. The reflected signal is transferred by an optical circulator to the 9-m long second stage. For both stages we used the 1000-ppm Er-doped fiber. The pump is launched first to the second stage in the forward direction and than the rest of the pump from the end of the second stage is launched to the first stage as well in the forward direction. We choose the amplification of the first stage close to lasing threshold while the amplification of the second stage was restricted by ASE at the end of the first stage. For optimization of the EDFA we have measured the fiber parameters and found 0.11 m-1 background attenuations both for signal and pump caused presumably by exited state absorption. The amplification grows very rapidly with the increasing of the pump power at low pump power and becomes flat. At 35-mW pump power the amplification reaches 50-dB and then grows to 55 dB at 100 mW of the pump power. For measurements we do not use the spectral filter between first and second stages. Simulations show that the filter does not change significantly the maximum amplification however decreases required pump power.

6453-78, Poster Session

Experimental investigation of a figure-eight fiber laser with a symmetrical NOLM and highly twisted fiber in the loop

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In figure-eight lasers (F8L) the modelocking is achieved through a nonlinear fiber amplifier loop mirror (NALM) or an asymmetrical nonlinear opti-

cal loop mirror (NOLM). In a previous work, we demonstrated that a symmetrical NOLM with a highly twisted fiber and a Quarter-Wave (QW) retarder in the loop is useful for application as a passive modelocking of fiber lasers. In this work we experimentally demonstrate the operation of a F8L based on the symmetrical NOLM with a twisted low-birefringence fiber in the loop. The modelocking operation is achieved by nonlinear polarization rotation. We found that the counter-propagating beams accumulate a differential nonlinear phase shift when they have different polarizations. The best situation is when we have linear polarization for one of the beams and circular polarization for the next one. With the QW position it is possible to change the transmission behavior from a maximum to a minimum of low input power. We can get the modelocking at any position of the QW. When the QW position is for minimal transmission we need more pump power than when the position is for maximal transmission to get the modelocking operation. For minimal transmission we used a 95 mW pump power to get the modelocking. The pulse repetition frequency was 0.8 MHz. The modelocked laser ran in stable operation for hours. The adjustment procedure was straightforward. The laser shows stable operation and exhibits high pulse energy. We achieved stable generation of subpicosecond pulses with milliwatts of average output power.

6453-79, Poster Session

10-W ASE-free single-mode high-power double-cladding erbium-ytterbium amplifier

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We designed a high output power double cladding erbium-ytterbium fibre amplifier that showed no amplified spontaneous emission (ASE) at 1.0 μm using a quasi single mode fiber. The reduction of the amplified stimulated emission (ASE) at 1.0 μm was found to be the combination of fibre design and temperature effect in the core. A 10W output double cladding Er-Yb amplifier with a core/cladding fibre diameter of 10/125 μm was realized with a seed signal of 1.4 W at 1563 nm and with counter-propagating pump power of 35 W at 976 nm without any significant ASE generation at 1.0 μm. The fibre also exhibits singlemode behaviour with M2 <1.1 and a high slope efficiency of 30%. By incorporating into our model the core temperature increase coming from the quantum defect of the Er/Yb system, we can predict a decrease in the emission cross-section of the ytterbium ions yielding to an increase of the 1 μm ASE threshold from 14 W to 35 W pump power, which allowed us to reach a 10 W output power at 1563 nm instead of 5 W normally predicted by the theory. The fibre was also designed to minimize ASE at 1.0 μm by heavily doping the fibre and using the appropriate ratio between ytterbium and erbium ions.

These results show potential power scaling of the output power or double cladding erbium ytterbium amplifier using quasi singlemode core erbium ytterbium fibre avoiding the need of large core dimension that degrades the beam quality.

6453-81, Poster Session

High-peak-power pulse amplification using Yb-doped double-clad fiber

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Laser diode pumped Yb-doped fiber MOPA (Master Oscillator Power Amplifier) system has been researched. MOPA system consists of short pulse (~ns) oscillator and fiber amplifier. Oscillator is actively Q-switched microchip laser at 50 kHz and has a pulse width of 2.8ns. Amplifier is Yb-doped polarization maintaining fiber having a large mode area. As a result of amplification experiments, the average power of 10W and the light-light conversion efficiency of 59% were obtained. The amplified pulses have a high peak power and induce a nonlinear effect, i.e. self-phase modulation (SPM), in fiber. The spectral broadening by SPM was observed. In the succeeding SHG (Second Harmonic Generation) experiments, KTP crystal and LBO crystal were used. The conversion efficiency of 21% and 40% were obtained in KTP and LBO respectively. In order to explain the difference, the spectral broadening due to SPM was analyzed on the theory of frequency chirp.

6453-82, Poster Session

Multiwavelength fiber-ring laser with switchable fiber Bragg gratings

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Various techniques have been suggested to build a fiber ring laser using a fiber Bragg gratings (FBG) as a lasing wavelength selection filter. For most of FBG filter, a circulator has been used as a key component to convert the reflection characteristic of FBG to the transmission spectrum, but it has been hard to tune the spectral reflectance or transmittance of FBG intrinsically. In this research, a multi-wavelength fiber ring laser is proposed based on a novel switchable bandpass filter to show tunable multiple lasing spectra with high extinction. The proposed switchable bandpass filter consists of multiple FBG's incorporating Sagnac loop interferometer configuration. Transmission spectra of bandpass filter can be greatly varied for more than 20 dB as changing the phase of polarization controller in the Sagnac loop. We experimentally demonstrate the lasing wavelength is easily selected by the switchable FBG's at multiple spectral positions.

6453-83, Poster Session

High-power multi-FO-lasers hosted on a THS

M. Checchetti, Microptronics Srl (Italy)

The forced air Turbo Heat Sink / THS is an effective cooler for electronic systems.

AlN, a ceramics, sports low TCE and high thermal conductivity, like Al. The deep, curved air-cooling channels are milled before firing; later, the mounting plane and more linear groves are ground.

The mounting plane with multilayer tracks solders directly the Laser Diodes / LD; the hybrid electronics includes IO, drivers, controls, Opto and thermal sensors. The groves, part of the semi-kinematics positioners, seat and locate accurately the coupling optics and eventually the hot part of each lasing FO. A window closes the hermetic chamber; with outer FOs, the window integrates a lens array.

Side Pumping. Many well spaced LDs mate with more, shared beam forming lenses, typ. cylindrical; each beam is optimally focused etc on the inner lasing FO core after crossing the D-flat.

For Telecom, a central unit with many spare FOs boost reliability, is open to expansion, can host more functions, and is much better than many boards full of butterflies with NO explicit cooling means. Bragg mirrors mounted on integral thermal bridges can shift / select each wavelength.

In the general case, air or gas cools the FO coils. With outer FOs, it can form an universal engine.

End Pumping. The substantially free vertical space can be uses to collimate and bend more beams to center each exposed FO end, potentially more refined. A geometric coupling is ? insensitive.

In both cases, few shared, miniature, uniaxial, low cost elements are mounted collectively.

6453-84, Poster Session

Gamma radiation effects in Yb-doped optical fiber

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Determination of the radiation response of doped-fiber laser materials, systems and components to relevant ionizing radiation fluxes is central to the prediction of long-term fiber-based laser performance/survivability in adverse and/or space-based environments. It is well known that optical elements that are placed into orbit around the Earth experience harsh radiation environments that originate from trapped-particle belts, cosmic rays and solar events. Of particular interest to optical materials is the continuous flux of gamma photons that the materials encounter. Such radiation exposure commonly leads to the formation of color centers in a broad range of optical materials. Such color center formation gives rise to changes in optical transmission, loss and luminescent band structure, and, thus, impacts long-term optical device performance.

In this paper we will present the results of our investigation of gamma-radiation-induced photodarkening on the optical transmittance of a number of Yb-doped optical fibers. We will discuss the evolution of the optical response of the fiber across the 1.0 to 1.6 micron wavelength window with increasing gamma exposure. Results indicate that these fibers exhibit reasonable radiation resistance to gamma exposures typical of a 5-year, low-earth orbit environment. Maximum transmittance losses of less than 10% were observed for total gamma exposures of 2-5 krad (Si).

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6454-01, Session 1

Solid sampling with 193-nm excimer laser ablation

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Reliable and sensitive elemental analysis of solid samples is a crucial task in areas of geology (e.g. microanalysis of fluid inclusions), material sciences, industrial quality control as well as in environmental, forensic and biological studies.

To date the most versatile detection method is mass-spectroscopic multi-element analysis. In order to obtain reproducible results, this requires transferring the solid sample into the gas-phase while preserving the sample's stoichiometric composition.

Laser Ablation in combination with inductively coupled plasma-mass spectrometry (LA-ICP-MS) is a proven powerful technique to meet the requirements for reliable solid sample analysis. The sample is laser ablated in an air-tight cell and the aerosol particles are carried by Helium or Argon inert gas to a micro-wave induced plasma where its constituents are atomized and ionized prior to mass analysis.

A newly developed 193 nm excimer based laser ablation workstation for controlled sample ablation with utmost precision and mechanical stability will be described. The high photon energy and excellent beam characteristics of the integrated 193-nm excimer laser virtually eliminate elemental fractionation and matrix effects and permits clean ablation of even transmissive solid materials such as carbonates, fluorites and diamond.

High performance optics for beam homogenizing and demagnification with variable aperture allow solid sampling throughout the entire material spectrum. Ablation quality obtained with 193nm for various geological samples will be discussed and compared to results achieved with longer ablation laser wavelengths.

6454-02, Session 1

High-average-power CO2 laser MOPA system for Sn target LPP EUV light source

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Laser produced plasma EUV source is the candidate for high quality, high volume machine (HVM) EUV light source for the next generation microlithography. High conversion efficiency (CE) from the laser energy to EUV in-band energy is the primarily important issue for the concept to be realized for HVM. Cost effective laser driver is also the key requirement for the realization of the concept as a viable scheme.

We have achieved CE of 2.8% with solid wire Tin target by a TEA-CO2 laser MOPA system with pulse width, pulse energy and pulse repetition rate as 10~15 ns, 30 mJ and 10 Hz, respectively. A CO2 laser system with a short pulse length less than 15 ns, a nominal average power of a few kW, and a repetition rate of 100 kHz, based on RF-excited, axial flow CO2 laser amplifiers is under development. Output power of 3 kW has been achieved with a pulse length of 15 ns at 130 kHz repletion rate in a small signal amplification condition with P(20) single line. The CO2 laser system is reported on short pulse amplification performance using RF-excited axial flow lasers as amplifiers. And the CO2 laser output power scaling is shown towards 10 kW, 10 ns, 100 mJ from a MOPA system.

This work was supported by the New Energy and Industrial Technology Development Organization (NEDO), Japan

6454-03, Session 1

Distributions of temperature and thermal stress in soda-lime glass irradiated by CO2 laser

X. Wang, J. Jiao, X. Wang, Huazhong Univ. of Science and Technology (China)

CO2 laser is an ideal tool to machine glass for its high absorption to the CO2 laser, but the fracture of the glass made it rather difficulty to machine with CO2 laser. It is important to understand the temperature and thermal stress distribution in glass under CO2 laser irradiation. In order to investigating the difference of thermal stress in soda-lime glass heated by laser beam between preheating and no-preheating, considering radiation and conduction, a mathematical model of temperature distribution was established. The relationship between thermal stress and temperature distribution was analyzed. The temperature and thermal stress distribution was obtained through numerical simulation with Ansys. The calculating result shown that, the thermal stress in preheated glass was smaller than no-preheated glass heated by laser beam. To compare with the numerical simulation, the temperature distribution of the soda-lime glass on the surface of the heated region under CO2 laser irradiation was measured with the thermo vision infrared system. Thermocouple device was used to correct the thermo vision infrared system. The measured temperature distribution agrees well with the numerical simulation results obtained form the Ansys software.

6454-04, Session 1

Some experimental studies on the UV-preionized TEA CO2 laser propulsion

L. Hong, D. Zuo, Z. Cheng, B. Zhai, X. Wang, Huazhong Univ. of Science and Technology (China)

This paper presents some results on the air-breathing propulsion experiments with a parabolic light craft and a self-made UV-preionized TEA CO2 laser with 115J maximum pulse energy. In wire-guided vertical flight experiment, impulse-coupling coefficient 390 N/MW is obtained at the pulse energy 60J. The influence of the shape of the lightcraft and the laser pulse profile on the coupling coefficient was discussed. The air disturbance is obtained by probing the intensity variations with He-Ne laser. The influence of the focal length of the parabolic lightcraft on the air-disturbance was found. Two shock waves were detected for longer focal length, but only one shock wave was detected for short focal length, air-disturbance could be detected after 5 ms of the laser pulse when single pulse with 32J energy interacted with short focus lightcraft. The spectrum of the plasma was detected using monochromator, and the time evolvement process of line spectrum of the plasma was analyzed.

6454-05, Session 1

Laser hardening process simulation for mechanical parts

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In this work a numerical simulation of the laser hardening process is presented.

The laser beam can be set to assume every spatial and temporal distribution and so the shape and dimensions of the spot. The part to be hardened is modelled as a 3D grid hit from a moving laser spot and the elements of the grid can model the laser/material interaction with the physi-

cal properties varying with temperature and phase changing.

The simulator evaluates the temperature distribution by solving the heat conduction with the Finite Difference Method. The temperature/time distribution obtained permits to evaluate the microstructure in every point of the part. The transformations are simulated by the use of a phenomenological model based on an extension of the Avrami kinetic law to multiple phases. The presented model starts from the usual isothermal transformation diagram and determine the coefficients for a set of coupled differential equations that, numerically integrated in time, gives the fraction off all the phases. It is so possible to pre-determine the HAZ extension and the micro-hardness of the material at different depth.

The main limit of the method, the "square" topology of the grid unsuitable for hardening complex geometry parts, is by-passed by the use of the Constrained Free Form Deformation technique. In the paper a new approach is proposed that foresees to apply a spatial transformation to "flatten" the original part surface. The same transformation is applied to the laser beam while the material parameters of every element are varied to compensate the local volumetric shrinkage. This configuration is solved with the usual Finite Difference Method and the solution is then applied to the original part.

Experimental tests performed on different steels will be presented for a validation of the method.

6454-06, Session 1

Measurement of cutting performance of high-power laser on concrete

K. Tei, S. Yamaguchi, K. Nanri, T. Fujioka, Tokai Univ. (Japan)

We demonstrated concrete cutting with various modes using a 5kW-class laser. The demonstrated slab thickness was 100mm. One of modes provides us the dross-free technique. This technique is on the basis of a multi-scan method for cutting and can be extended to thick concrete slabs more than 1m without laser power increasing. This paper reports the cutting performance, which is mainly about cutting speed on various types of concrete. The laser power to be changed during experiments ranges over 20 kW.

6454-07, Session 2

Repetitively pulsed and cw sealed-off slab CO laser with cryogenic cooling

A. A. Ionin, L. V. Seleznev, P.N. Lebedev Physical Institute (Russia); A. Shelestovich, Moscow Engineering Physics Institute (Russia); D. V. Sinitsyn, P.N. Lebedev Physical Institute (Russia)

Experiments on fundamental band CO lasing in sealed-off cryogenically cooled slab system with RF discharge excitation were carried out. CW and periodically pulsed modes of RF discharge excitation were studied. Average output power achieved 12 W. Lasing efficiency exceeded 10%. The output laser spectrum was observed within wavelengths range 5.08-5.34 microns. Stable lasing was obtained for tens minutes.

6454-08, Session 2

Electra: durable repetitively pulsed 700 J, 100-ns electron-beam pumped KrF laser

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Electra is a repetitively pulsed, electron beam pumped Krypton Fluoride (KrF) laser at the Naval Research Laboratory that is developing the technologies that can meet the Inertial Fusion Energy (IFE) requirements for durability, efficiency, and cost. The technologies developed on Electra should be directly scalable to a full size fusion power plant beam line.

Electra in oscillator mode has demonstrated single shot and rep-rate laser energies from 300 to over 700 J with 100 ns pulsewidth at 248 nm. The laser has operated continuously for more than 2.5 hours without failure at both1 Hz and 2.5 Hz. The intensity and energy per shot is constant in over thousand shot runs at rep-rates of 1 Hz, 2.5 Hz and 5 Hz. The KrF intrinsic efficiency is predicted to be 12% based on oscillator measurements and modeling with the NRL Orestes Code. Orestes includes all the major physical processes and accurately predicts the Electra measurements In addition Orestes predictions are in agreement with initial results of 23 J for the Electra Pre-Amplifier. Orestes has been used to design large KrF laser systems for inertial fusion energy drivers.

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6454-09, Session 2

The conception for creation of industrial CO laser for dismantlement of reactors and hardening of rails

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The industrial lasers for dismantlement of obsolete nuclear reactors, laser-hardening of the surfaces of rails and etc. don't exist now. Reason consists in the high cost of necessary lasers. The cost is several million USD.

The conception for creation of industrial CO laser for dismantlement of reactors and hardening of rails is proposed. The estimated cost of a proposed laser is several hundred thousand USD.

So low cost comes out from the absence in the closed working cycle: a body of closed contour, special pumping system, cryogenic refrigerators, sectionalized electrode, active ballast resistances, electron gun, fiber-optic delivery.

The proposed CO laser has a closed working cycle and a high-frequency (RF) capacity discharge to excite a supersonic gas flow cooled to cryogenic temperatures due to expansion in nozzle.

The RF discharge in supersonic flow allows working with high pressure before the nozzle and average pressure after diffuser. Therefore a body of closed contour isn't need. There are only pipelines and a head of laser may install in any place, for example on manipulator. The laser can work without fiber-optic delivery.

The necessary prerequisites for creating the proposed CO laser:

- the unique properties of CO molecule make its all-pass transducer of electric energy to laser radiation;
- the CO laser cutting impressive demonstration at Nuclear Power Corporation in Japan;
- the low-current RF discharge similar to a nonself-maintained discharge with an external ionization source;
- getting of stability, uniformity, RF discharge in a supersonic flow;
- getting of laser radiation on a small-scale experimental installation in non-stop run with RF discharge in supersonic flow;
- creation of mathematical model of CO laser scaling with RF discharge;
- the estimated low cost of proposed CO lasers is connected to simplicity of laser installation, opportunity of using the serial standard elements (compressor, RF generator, manipulator);
- possibility to install head of laser on manipulator and to work without fiber-optic delivery;
- the available standard components in working laser system at early stages of design makes possible to reduce substantially expenditures on its performance.

6454-10, Session 2

High-intensity optical sources of femtosecond pulses on the base of hybrid laser systems with wide-aperture gas laser amplifiers

A. A. Ionin, A. Konyashchenko, P.N. Lebedev Physical Institute (Russia); B. M. Kovalchuk, Institute of High Current Electronics (Russia); O. N. Krokhin, P.N. Lebedev Physical Institute (Russia); V. F. Losev, Institute of High Current Electronics (Russia); G. Mesyats, A. G. Molchanov, L. D. Mikheev, Y. Novoselov, A. N. Starodub, P.N. Lebedev Physical Institute (Russia); V. F. Tarasenko, Institute of High Current Electronics (Russia); S. I. Yakovlenko, General Physics Institute (Russia); V. D. Zvorykin, P.N. Lebedev Physical Institute (Russia)

The multi-stage hybrid laser system producing ultra-short pulses of radiation with peak power ~E14 - E15 W being now under developing at the Lebedev Physical Institute of Russian Academy of Sciences is discussed. The distinction of the laser system is direct amplification of ultra-short pulses produced by solid state laser system, first going through a prism stretcher with negative dispersion, in gas active medium without using rather expensive compressors of laser pulses. Two hybrid schemes are being developed now based on the amplification of femtosecond pulses of the third harmonic of Ti:Sapphire laser at the wavelength 248 nm in the active medium of KrF laser amplifier, and on the amplification of the second harmonic of Ti:Sa laser at the wavelength 480 nm in the active medium of photochemical XeF(C-A)-laser excited by VUV radiation of an e-beam pumped Xe2 lamp. The final stage of the laser system is supposed to be an e-beam pumped facility with a laser chamber of 60 cm in diameter and 200 cm long in case of KrF laser, and with another laser chamber of 30-40 cm in diameter put into the former one in case of XeF(C-A) laser. The parameters of such e-beam facility are close to those of previously developed at the Institute of High-Current Electronics of Siberian Branch of RAS: electron energy ~600 keV, specific input power ~ 300-500 kW/cm3, e-beam pulse duration ~ 100-200 ns. A possibility of using Kr2F as an active medium with saturation energy 0.2 J/cm2 for amplification of ultra-short laser pulses is also under consideration. Theoretically demonstrated that the energy of a laser pulse at the exit of the final stage of the laser system could come up to ~ 15 J with pulse duration ~50 fs in case of KrF laser, and ~75 J with pulse duration of 25 fs in case of XeF laser. Two Ti:Sa laser systems producing 50 fs pulses with energy ~0.5 mJ at the wavelength 248 nm and ~5 mJ at the wavelength 480 nm have been already developed and are being now installed at the Lebedev Institute.

6454-11, Session 3

Tracking system by phase conjugation for laser energy transmission

C. A. Schäfer, O. Matoba, N. Kaya, Kobe Univ. (Japan)

The concept of an optical retrodirective tracking system by phase conjugation is proposed for the purpose of supplying a moving vehicle constantly with energy by a laser beam. This application is thought to be in space.

The system includes a divergent signal beam coming from the target propagating in the direction of the power station. The signal beam gets amplified and phase conjugated in order to return to the target. There, the beam hits a solar cell area which is placed around the signal laser beam to deliver the electric power.

In this setup, the signal beam is lead to an array of channels, in which it gets pre-amplified, phase conjugated and amplified again before leaving the channel to the direction of the target. Therefore, each channel contains a 2-way amplifier and a four wave mixing phase conjugated setup. The pump beams' source is only one master oscillator distributed over the whole array, so that the phase conjugated beams are spatially coherent. In order to control the conjugated beam pattern at the target, a phased array is realized by taking each channel as a light source. The phase control is implemented by shifting the phase of one pump beam in the four wave mixing process. This can be realized by using one Spatial Light Modulator for multiple channels.

First results of the interference pattern of multiple phase conjugated beams and their phase control are presented.

6454-12, Session 3

The effect of a prepulse technique in the stimulated Brillouin scattering and its applications

D. H. Beak, K. Park, H. J. Kong, Korea Advanced Institute of Science and Technology (South Korea)

We have introduced the additional prepulse with main pulse to generate the stimulated Brillouin scattering (SBS) and investigated the effect of this technique. In general, temporal pulse shape deformation takes place when the pulse is reflected from the medium breeding SBS. This deformation of the SBS wave can cause optical breakdown in the optical components and consequently it leads to low reflectivity and low fidelity of the phase conjugated wave in the SBS medium. It has been shown that there is an optimum prepulse time delay and minimum energy for preserving the SBS waveform. This method is so simple that it can be applied to other systems and utilized in many applications easily, such as high-power laser and optical isolator applications employing several SBS cells.

6454-13, Session 3

Development of the high-energy/power laser system with high-repetition rate using the beam combination technique

H. J. Kong, J. W. Yoon, J. S. Shin, Korea Advanced Institute of Science and Technology (South Korea)

The beam combination technique using the stimulated Brillouin scattering phase conjugate mirrors (SBS-PCMs) is known as the one of the most promising technology to realize high energy/ high power/ high repetition rate, especially for the laser fusion drivers. The beam combination technique using SBS-PCM can compensate any optical distortions occurred in the amplifier chain because it gives the phase conjugated wave for the good beam quality. In this paper we will show the essential fundamental technology for the realization of the beam combination system for this purpose using the new SBS phase control technique proposed by the one of the authors, H.J.Kong. These new technique is the most simple among the phase locking techniques developed historically, and furthermore it is possible not only to lock but also to control the phases of the SBS waves very accurately.

6454-14, Session 3

Long-term stabilization of the phase control technique of the stimulated Brillouin scattering wave for the beam combination technique

J. W. Yoon, J. S. Shin, H. J. Kong, Korea Advanced Institute of Science and Technology (South Korea)

For the laser fusion energy (LFE) generation, the laser driver should deliver a high energy over several MJ and a high repetition rate over 10 Hz. To obtain such a laser driver with the high energy and the high repetition rate, it is highly required to reduce the thermal load of the laser system efficiently. Several methods have been developed for this goal, such as the beam combination, diode-pumped laser, the electron beam pumped gas laser and the large sized ceramic Nd:YAG. Among these techniques the beam combination technique using stimulated Brillouin scattering (SBS) phase conjugate mirrors (PCMs) proposed by one of the authors, H.J.Kong is the most promising one. Using the beam combination technique, we can scale up output energy unlimitedly by increasing the num-

ber of separate amplifiers to be combined. However, the phase controlling of the SBS waves is essentially required for the beam combination system, since the SBS-PCM generates the random phase intrinsically. In this paper, we will show the recent experimental results about the long-term stabilization of the phase controlling and the beam combination laser for developing the IFE driver.

6454-15, Session 3

Prepulse technique for preserving the pulse shape of the stimulated Brillouin scattering

H. J. Kong, D. H. Beak, K. Park, Korea Advanced Institute of Science and Technology (South Korea)

We have found that it is possible to preserve the temporal waveform of the reflected wave generated from stimulated Brillouin scattering (SBS) by using a pre-pulse technique. In this work, the fundamental research has been carried out to preserve the deformed pulse shape reflected from SBS medium. It is well known that the reflected SBS wave has a steep rising edge. If one employs SBS cells in series, the rising edge of the pulse shape becomes steeper every time it reflects at every SBS cell. This deformation of the SBS wave can cause the undesirable effects when we employ several SBS cells in series, such as an optical breakdown in the optical components and the lower reflectivity and lower fidelity of the phase conjugated wave in the SBS medium. A pre-pulse energy of 5 mJ and a time delay of 5 ns have been measured to be the optimum values under this experimental conditions. This pre-pulse method is useful in developing a multistage system employing several SBS cells in series for high-power laser applications.

6454-16, Session 3

High-power phase conjugate mirror for CW radiation

D. A. Rockwell, R. S. Baltimore, Raytheon Space and Airborne Systems

Loop phase conjugate mirror was demonstrated to reflect up to 170 W with phase conjugation for CW input beam power 200 W at 1.03 microns. High fidelity level was tested by restoring up to 70% of the beam power to 1.6xDL beam after double passing heavily aberrating chain of amplifiers.

6454-17, Session 4

A singlet oxygen generator on a chip for MEMS-based COIL

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Microelectromechanical systems (MEMS) offer a promising approach for creating compact, efficient chemical oxygen iodine lasers. A recent modeling study [Wilhite et al., IEEE J. Quant. Elec. 40, 1041-55 (2004)] showed that scaling, along with the improved mixing and heat transfer that it enables, potentially makes possible the replacement of macroscale COIL components (e.g. SOG, mixing nozzle, and pressure recovery system) with smaller, more efficient arrays of microscale components. In this paper we report the demonstration and characterization of a chip-scale, MEMS-based singlet oxygen generator, or microSOG. The microSOG is a batch-fabricated silicon chip that is micromachined to form reactant inlets and distribution system, an array of microstructured packed bed reaction channels to ensure good mixing between the BHP and the chlorine, a gas-liquid separator that removes liquid from the output stream by capillary effects, integrated heat exchangers to remove the excess heat of reaction, and product outlets. The microSOG has generated singlet delta oxygen, and singlet delta concentrations were measured in a quartz test cell downstream of the chip using absolutely-calibrated near-infrared emission measurements made by an InGaAs array spectrometer. A kinetics analysis was used to determine the concentration at the chip outlet from the concentration at the measurement point. Singlet delta yield at the outlet was determined to be about 69% at 100 Torr plenum pressure with a 25 sccm flow of chlorine and a 3:1 helium:chlorine dilution ratio. The corresponding output flow carries about 1.2 W of power at the chip's outlet. The microSOG chip operated successfully at hydroxide ion to chlorine ratios well below ten, indicating highly efficient mixing.

6454-18, Session 4

Kinetics of oxygen discharges and I(2P1/2) excitation for EOIL

W. T. Rawlins, S. Lee, D. B. Oakes, S. J. Davis, Physical Sciences Inc.

Generation of singlet oxygen metastables, O2(a1Delta), in an electric discharge plasma offers the potential for development of compact electric oxygen-iodine laser (EOIL) systems using a closed-cycle, all-gas-phase medium. Use of an appropriate discharge E/N, coupled with the dilution of O2 with Ar and/or He, gives energetic electron energy distributions in the discharge. This in turn leads to increased O2(a) production rates, resulting in high O2(a) yields in the range 20-40%. However, additional discharge-produced species are also present in the discharge effluent flow and contribute to the reactions with injected I2. These species include O, O3, and possibly metastable states of excited O and O2. For example, previous investigations have identified the dual role of atomic oxygen to promote I2 dissociation and quench I(2P1/2). However, even when atomic oxygen concentrations are reduced, the gain is still limited by kinetic losses. We will discuss a series of reacting flow measurements using a comprehensive suite of optical emission and absorption diagnostics to monitor the absolute concentrations of O2(a), O2(b), O(3P), I2, I(2P3/2), I(2P1/2), small-signal gain, and temperature. We have also recently developed and implemented a highly sensitive, quantitative diagnostic for O3. These multispecies measurements help to constrain the kinetics model of the system, and quantify the chemical loss mechanisms for I(2P1/2).

6454-19, Session 4

ElectricOIL experiments and modeling

D. L. Carroll, J. T. Verdeyen, D. M. King, A. D. Palla, J. K. Laystrom, G. F. Benavides, CU Aerospace LLC; J. W. Zimmerman, B. S. Woodard, T. Lim, W. C. Solomon, Univ. of Illinois at Urbana-Champaign

The development of the hybrid electric discharge Oxygen-Iodine laser (ElectricOIL) has proven to be a fascinating (and at times frustrating) challenge due to the complex interactions between chemical kinetics, electrodynamics, fluid mechanics, and laser physics that are inherent in gas discharge lasers. In the ElectricOIL system, the desired O2(aD) is produced using a low-to-medium pressure electric discharge. The discharge production of atomic oxygen, ozone, and other excited species adds higher levels of complexity to the post-discharge kinetics which are not encountered in a classic purely chemical O2(aD) generation system. Experimental studies over the past six years using electric discharges have successfully demonstrated O2(aD) yields greater than 20%, gain, and cw laser power. Several modeling studies have also been performed for ElectricOIL and similar systems. As the development of this type of iodine laser continues, the roles of oxygen atoms and NO/NO2 are found to be very significant in both the discharge region and downstream of the discharge region. In this paper we present an updated look at experimental data and modeling of the ElectricOIL system.

6454-20, Session 4

The role of I_2B in the dissocition of iodine by $O^2(^1\Delta)$

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Visible luminescence from I2(B) is observed when iodine is added to a gas flow containing O2(1?). The excitation mechanism has not been ascertained completely. The energy of this state is considerably higher than that of the singlet oxygen molecule and excitation requires at least two consecutive collisions of I2 with O2(1?) molecules. Another possible pathway to I2(B) formation is three-body recombination of excited and ground state iodine atoms.

In this study the kinetics of I2(B) was examined in flow tube experiments that utilize detection by emission spectroscopy. O2(1?) was produced in a chemical jet type singlet oxygen generator. Iodine atoms were produced in two ways: by dissociation of iodine molecules in the flow of singlet oxygen and by preliminary dissociation of CH3I in a glow discharge.

We have demonstrated that role of I2(B) in the I2 dissociation mechanism is negligible. Addition of CO2 gas that is a good quencher of excited O2(1?) molecules has shown that the population of I2(B) state does not rely on excitation by O2(1?) molecules. We considered the possibility that electronically excited states of I2 are involved in the I2(B) pumping process via the sequence O2(a,?) + I2(X) ? O2(X) + I2(A?, A) and O2(a) + I2(A?, A)? O2(X) + I2(B). In our experiments vibrationally excited singlet oxygen O2(a,?) and electronically excited molecular iodine I2(A) was detected in the chemical oxygen iodine laser active medium using the near IR emission spectroscopy method.

6454-21, Session 4

Observation of fast quenching of $O_2(a^1\Delta)$ in O/O_2/O_3 mixtures

V. N. Azyazov, M. H. Kabir, M. C. Heaven, Emory Univ.

Rapid quenching of O2(aD) has been observed in O(3P)/O2/O3 mixtures. Oxygen atoms and singlet oxygen molecules were produced by the 248 nm laser photolysis of ozone. The kinetics of O2(aD) quenching were followed by observing the 1268 nm fluorescence from the O2(aΔ-X3) transition. O atom concentrations, monitored via the O+NO chemiluminescent reaction, correlated with the instantaneous O2(a) decay rates. Three-body deactivation via the process O2(a)+O2+Oμ2O2+O can account for the rapid quenching that was observed, but the rate constant obtained under the assumption that this is the dominant quenching channel was unreasonably large (10-31 cm6 s-1). The mechanisms of O2(aD) quenching in this system are under investigation and the results will be discussed. Understanding of this system will be essential for the future design of discharge singlet oxygen generators that can provide viable yields at high pressures (>50 Torr).

6454-22, Session 4

Characterization of the AFRL EOIL teststand

D. A. Hostutler, Air Force Research Lab.

No abstract available

6454-24, Session 4

A laser-diode array-pumped Cesium-vapor laser

B. Zhdanov, T. Ehrenreich, R. J. Knize, U.S. Air Force Academy

An efficient Cesium vapor laser pumped with a continuous wave narrowband Laser Diode Array (LDA) was demonstrated. To obtain a high efficiency, it is necessary to narrow the linewidth of the LDA pump radiation to match the Cs atom absorption line. At a buffer gas pressure around 500 torr the Cs absorption linewidth is about 10 GHz, which is much less than typical linewidth of commercially available LDAs (about 1 THz). An external cavity with holographic grating was used to narrow a commercially available LDA linewidth to a value below 10 GHz. The developed pump source was used for pumping a Cs vapor laser which operated at 894 nm in single longitudinal and fundamental transverse modes.

The half confocal Cs laser cavity, with a flat output coupler and a 20 cm radius concave input mirror, was a 16 cm long. The input mirror had 99% reflectivity at 894 nm (lasing wavelength) and 90% transmission at 852 nm (pump). The output coupler had 50% reflectivity at 894 nm and 90% reflectivity at 852 nm. The 2 mm long Cs vapor cell was assembled inside the oven and positioned close to the input mirror. It was filled with Cesium and 500 Torr of Ethane and had AR-coated optical quality windows. The spatially multimode pump beam was focused into the cell by an aspheric lens with focal length 35 mm. Preliminary experiments yielded 400 mW output power and about 20% slope efficiency. Improvements in these numbers will be presented.

The developed laser can be scaled to high powers and used for civilian and military directed energy applications.

6454-25, Session 4

Theoretical simulation of diode-pumped alkali vapor laser

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Diode-pumped alkali vapor laser (DPAL) is a new class of laser, which combines some advantages such as high power and efficient diode-pumping, good thermal management and optical properties in gas media and high quantum efficiency (99%) for D transition of the alkali metal atoms. It is expected to realize high efficiency and high-average-power laser with good beam quality (near-diffraction-limited). DPAL offers CW laser radiation at near-infrared wavelengths: cesium 895 nm, rubidium 795 nm, and potassium 770 nm and can find a lot of applications in power beaming, drilling oil and gas wells and laser material processing.

Based on the theoretical model of DPAL introduced by Beach [1], the dependences of cesium laser output power on the pump power and line width have been simulated. Unlike Beach's simulation (where only low pump power up to 0.8 W were calculated), our simulation for higher pump power region (1 - 100 W) has been done. The results showed that (1) laser power is not linear proper to the pump power, but reach saturation at higher pump power region. (2) Maximum laser power decreased and power saturation retarded with increasing of the pump line width. A reasonable explanation has been given. In the meantime, the influence of vapor and gas pressure, volume and temperature of laser medium on the laser output characteristics were studied.

[1] R. J. Beach, W. F. Krupke, V. K. Kanz, et.al., "End-pumped continuous-wave alkali vapor lasers: experiment, model, and power scaling", J. Opt. Soc. Am. B, Vol.21, No. 12, 2151 (2004)

6454-26, Session 5

Technical challenges for the future of high-energy lasers

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The Solid-State, Heat-Capacity Laser (SSHCL)* program at Lawrence Livermore National Laboratory is a multi-generation laser development effort scalable to the megawatt power levels with current performance approaching 100 kilowatts. This program is one of many designed to harness the power of lasers for use as directed energy weapons. There are many hurdles common to all of these programs that must be overcome to make the technology viable. There will be a in-depth discussion of the general issues facing state-of-the-art high energy lasers and paths to their resolution. Despite the relative simplicity of the SSHCL design, many challenges have been uncovered in the implementation of this particular sys-

tem. An overview of these and their resolution are discussed. The overall system design of the SSHCL, technological strengths and weaknesses, and most recent experimental results will be presented.

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6454-28, Poster Session

Gas-dispersed active medium for high-energy HF/DF laser systems based on a photon-branched chain reaction

R. R. Letfullin, Rose-Hulman Institute of Technology; T. F. George, Univ. of Missouri/St. Louis

A promising avenue in the development of pulsed chemical HF/DF lasers and amplifiers is the utilization of a photon-branched chain reaction (PBCR) initiated in a two-phase active medium, i.e., a medium containing a working gas and ultradispersed passivated metal particles. These particles are evaporated under the action of IR laser radiation, which results in the appearance of free atoms, their diffusion into the gas, and the development of the photon-branching process. The key obstacle here is formation a relatively-large volume (in excess of 1000 cm3) of the stable active medium and filling this volume homogeneously for a short time with a sub-micron monodispersed metal aerosol, which has specified properties. In this report, we present the results of an extensive study of a gas-dispersed component of a HF laser active medium, including novel techniques for the formation of a two-phase active medium with specified properties, aerosol optics, non-resonant initiation of a PBCR into gas-dispersed active medium by IR laser radiation, degradation of the dispersed component, and beam stability of a chemically-active aerosol. The results of this investigation should help lead the way to creating powerful, reliable and inexpensive self-contained pulsed sources of coherent radiation with high energy, high laser beam quality, and the possibility of scaling up the output energy.

6454-29, Poster Session

DPSS lasers hosted on a THS

M. Checchetti, Microptronics Srl (Italy)

The forced air Turbo Heat Sink / THS is an effective cooler for electronic systems.

AlN, a ceramics, sports low TCE and high thermal conductivity, like Al. The deep, curved air-cooling channels are milled before firing; later, the mounting plane and more linear groves are ground.

The mounting plane with multilayer tracks solders directly the Laser Diodes / LD; the hybrid electronics includes IO, drivers, controls, Opto and thermal sensors. The groves, part of the semi-kinematics positioners, seat and locate accurately the coupling optics and eventually the hot part of each lasing FO. A window closes the hermetic chamber; with outer FOs, the window integrates a lens array.

Side Pumping. Many well spaced LDs mate with more, shared beam forming lenses, typ. cylindrical; each beam is optimally focused etc on the inner lasing FO core after crossing the D-flat.

- For Telecom, a central unit with many spare FOs boost reliability, is open to expansion, can host more functions, and is much better than many boards full of butterflies with NO explicit cooling means. Bragg mirrors mounted on integral thermal bridges can shift / select each wavelength.

- In the general case, air or gas cools the FO coils. With outer FOs, it can form an universal engine.

End Pumping. The substantially free vertical space can be uses to collimate and bend more beams to center each exposed FO end, potentially more refined. A geometric coupling is ? insensitive.

In both cases, few shared, miniature, uniaxial, low cost elements are mounted collectively.

6454-30, Poster Session

Laser milling simulation system for moulds manufacturing

G. Tani, Univ. degli Studi di Bologna (Italy); L. Orazi, Univ. degli Studi di Modena e Reggio Emilia (Italy); A. Fortunato, G. Cuccolini, Univ. degli Studi di Bologna (Italy)

This work refers to the development of a numerical simulator for the Laser Milling process. The purpose is to obtain a useful system for industrial application able to predict the machining results when different materials are processed, different surface conditions are encountered and spatial and temporal distributions of the pulsed beam are set. A three dimensional grid solved by using the Finite Difference Method was implemented. The elements of the grid were modelled to manage the laser/material interaction, to keep into account the variation of the physical properties with the temperature and the phase changing and to evaluate the influence of the plasma plume above the recessing surface. The temperature of the solid phase is evaluated by solving the Fourier equation. The recession velocity is evaluated according the Hertz-Knudsen equation assuming that the explosive effects are negligible. The plasma plume is considered as a volume with a homogeneous temperature, pressure and ion distribution; at every integration time-step the plume receive the new evaporating material coming from the correspondent element and the energy coming from the direct and reflected beams. On the other hand the plume irradiates towards the elements and the open space.

The latter energy balance equation permits to evaluate the new temperature, ion distribution and pressure under the assumption that the gas expansion, from the surface target, produces a sonic front. These simplifications avoid the solution of Navier-Stokes equation and the simulation time is drastically reduced.

The simulation setup permits to vary every parameter of the scanning beam and the graphical output gives the geometry of the ablated part.

The numerical results were compared to the experiments conducted using a Nd:YAG diode pumped source on different materials like Aluminium alloys and steels.

6454-31, Poster Session

Experimental research of the RF discharge in pure oxygen and oxygen mixture with He, Ar, Xe

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Producing singlet delta oxygen in electric discharge is the current trends in pumping chemical oxygen-iodine lasers (COIL); RF discharge in oxygen and its mixture has many advantages compared with the DC discharge. In this paper a RF discharge device was presented. The discharge was running at frequency of 47MHz, the discharge cross-section is 5mm´5mm, the electrode material is anodic oxidation aluminium, the discharge can run at high pressure (20 Torr for pure Oxygen and 50 Torr for oxygen mixture with He, Ar etc.). The voltage between the electrodes was measured by a RF high voltage probe, the electron mean energy was measured by double probe method. The spectrum was recorded using the spectrometer USB2000 (Ocean Optics Co.). The intensity of the 777.19nm was recorded for various gas mixture, it can explain the dissociation of the O2 in the discharge area. The spectrum results show that in pure O2 discharge there exists a pressure at which the intensity of 777.19nm is minimum, in our experimental condition this value is about 10 Torr. In the O2 mixture with He, Ar, the intensity of 777.19nm increased with the increase of pressure, while in the O2-Xe mixture, the intensity of 777.19nm decreased with the increase of pressure at fixed O2 pressure, which means the Xe can reduce the O2 dissociation. This phenomenon can be explained by reduced electron energy in O2-Xe mixture, and the measured electron energy in the discharge area by double probe method has confirmed this.

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6455-01, Session 1

Design and characterization of a rugged and compact setup for widely tunable harmonic generation in the ultraviolet

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Design and experimental characterization of a nonlinear optical converter module for the generation of widely tunable UV radiation is presented. The module combines units for second, third and fourth harmonic generation of tunable Ti:Sapphire lasers. A modified conversion scheme based on a new combination of nonlinear crystals reduces the complexity and sensitivity of our former published UV setup - resulting in a significant increase of performance and long-term stability of the system. The comparison of the former and the improved UV setup contains theoretical modeling data as well as the results of the experimental characterization of both setups. The experimental studies of the converter module are carried out with a widely tunable Ti:Sapphire laser with nanosecond pulses and a repetition rate of 1 kHz. The laser provides a continuous tuning range of 690 nm to 1010 nm with pulse energies up to 2.0μmJ and a spectral line width of less than 10 GHz resulting in an output power of the converter module of 1000 mW, 400 mW and 200 mW respectively for the second, third and fourth harmonic generation. The new converter module is a decisive step in the development of a hands-off solid-state laser system with a continuous tuning range from the UV to the NIR - 200 nm to 1000 nm.

6455-02, Session 1

Generation of >300 mW diffraction-limited light at 405 nm by second-harmonic generation of an external cavity tapered diode laser

O. B. Jensen, J. Holm, Risø National Lab. (Denmark); B. Sumpf, G. Erbert, Ferdinand-Braun-Institut für Höchstfrequenztechnik (Germany); P. E. Andersen, P. M. Petersen, Risø National Lab. (Denmark)

Blue light in the wavelength region around 400 nm is needed for a range of applications within biomedicine, especially in fluorescence diagnostics. In general, both high power and the ability of efficient fiber coupling are required. High power (>100 mW) is achievable from GaN diode lasers but so far due to the broad area structure of these high power diode lasers the beam quality is poor and fiber coupling is not very efficient. For some spectroscopic applications narrow bandwidth, or even single-frequency operation, is a further requirement. Currently, this demand cannot be met by high power GaN diode lasers.

In this work, we demonstrate efficient second-harmonic generation (SHG) of diode lasers in order to achieve the desired output at around 400 nm with close-to-diffraction-limited beam quality. A tapered amplifier at 810 nm is set up in an external cavity and used as pump source for a second external cavity. The external cavity tapered diode laser system consists of a 4 mm single quantum well tapered amplifier with 1 mm long ridge section and a taper angle of 6° and a blazed diffraction grating mounted in the Littrow configuration. The tapered laser system pumps an external bow-tie cavity using 10 mm periodically-poled KTP. At a pump level of 1 W at 809 nm, we demonstrate more than 300 mW at 405 nm in single-frequency. The frequency-doubled system has a footprint of 40 by 40 cm2 and fully portable.

6455-03, Session 1

Novel low-loss ring resonator for second-harmonic generation of 808 nm into 404 nm using periodically poled KTP in a compact 3 element setup

J. Holm, Risø National Lab. (Denmark) and Lunds Tekniska Högskola (Sweden); O. B. Jensen, Risø National Lab. (Denmark); B. Sumpf, G. Erbert, Ferdinand-Braun-Institut für Höchstfrequenztechnik (Germany); S. Andersson-Engels, Lunds Tekniska Högskola (Sweden); P. E. Andersen, P. M. Petersen, Risø National Lab. (Denmark)

Blue light in the wavelength region around 400 nm is needed for a range of applications within biomedicine, especially in fluorescence diagnostics, where the light is delivered through optical fibers. In order to achieve the high power needed and minimize coupling losses the beam quality is important. We have constructed a new compact ring resonator design consisting of only three optical elements, of which one is a nonlinear crystal and the other two are spherical mirrors of equal radius of curvature. In order for the three components to form a closed ring, the crystal is anti-Brewster cut. We investigate two different materials for second harmonic generation of 808nm radiation to 404nm. The crystals employed are BIBO for a low loss setup and periodically poled KTP. In the BIBO setup the resonator path-length is controlled by translating the crystal, whereas the standard mirror-translation is used with the pp-KTP setup. The internal losses of the BIBO setup are below 0.1% including crystal absorption making this a very high finesse resonator suitable for high power applications. The pump sources for the two setups are a commercial single-mode non-tunable 808nm diode for the BIBO setup, and a tapered amplifier with grating feedback for the pp-KTP. The tapered laser is 4mm long with a 4-degree taper angle and 1mm ridge section, capable of delivering more than 1.3W of 808nm power and can be tuned to crystal resonance. The BIBO setup is pumped with 120mW from which 3.5 mW of blue power has been generated. The pp-KTP setup is estimated to deliver more than 200mW.

6455-04, Session 1

Multiwatt CW 589-nm Na D2-line frequency doubled Raman fiber laser system for LGS-assisted AO

L. R. Taylor, Y. Feng, W. K. P. Hackenberg, D. Bonaccini Calia, European Southern Observatory (Germany)

We are developing a novel all-solid-state frequency-doubled fibre laser system for the purposes of laser guidestar (LGS) assisted adaptive optics (AO). The required output is of the order of P589 ~ 10W in air, in a diffraction-limited beam with bandwidth < 2GHz.

Using a narrowband Raman-shifted 1178nm fibre as fundamental, we generate what we believe to be the highest power, single-pass CW 589nm SHG result reported to date. Greater than P589 > 5W have already been achieved. We see that significant radial and longitudinal non-uniform thermal gradients limit the high-intensity conversion rates in most commercially available periodically poled nonlinear optical samples, but that power scalability at constant efficiency is possible under certain conditions. Pump power limitations force a further optimization of the typical operating conditions.

Consequently, we develop a detailed analysis of the arising thermal effects within the sample, determine the thermal and visible power generation profiles under various operating conditions, and optimize the available parameter set. We indicate that the careful engineering of an applied external thermal gradient along the sample can enhance and stabilize the high-end conversion rates, and increase the achievable visible output power.

6455-05, Session 2

Frequency doubling of ps Ti:sapphire laser with PPMgLN waveguide for spin polarization of 3He

K. Kyutoku, S. Maeda, H. Kumagai, A. Kobayashi, Osaka City Univ. (Japan)

Magnetic resonance imaging based on the polarized noble gas has been attracted attentions in the field of medicine due to the development and application of powerful semiconductor lasers pumping for the D1 transition of the Rb system in recent years. Although high nuclear polarization is accomplished due to the spin exchange (SE) between optically pumped alkali atoms and ground states of noble gas, the SE-cross section in He-Rb collisions is small, which causes the long SE time constant through ground-state 3He atom. On the other hand, the metastability exchange through the metastable states has larger cross section between the ground-state 3He and the polarized metastable 3He (3He*) by optical pumping, which allows spin transfer rate to be much larger. 3He* has two optical pumping transitions, which are the 23S1→23P0 (1083nm) and the 23S1→33P0 (389nm), respectively. We have developed the laser source for optical pumping of 3He* with the 23S1→33P0. The 389-nm laser light is obtained by frequency doubling of the fundamental of the picosecond Ti:sapphire laser (pulsewidth: 13ps, linewidth: 60GHz, repetition rate: 200MHz), which make it possible to observe transient phenomena .We adopted the quasi phase-matched periodically poled MgO-doped LiNbO3 (PPMgLN) waveguide whose conversion efficiency is expected to be high.

6455-06, Session 2

Integrated ultraviolet and tunable mid-infrared laser source for analyses of proteins

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In biological research fields, functional analyses of proteins are becoming more important. A mass spectrometry with a matrix-assisted laser desorption/ionization (MALDI) is one of the most widely used method to analyze proteins. Ultraviolet (UV) lasers have commonly been used to ionize analytes in MALDI. However, it is difficult to analyze insoluble proteins which have important roles in researches on disease mechanisms or in developments of drugs, with UV lasers. Recently, a significant improvement in a MALDI analysis of insoluble proteins using a combination of an UV nitrogen laser and a tunable mid-infrared (MIR) free electron laser (FEL) was reported [1].

Since the FEL is a very large and expensive equipment, we have developed a tabletop laser source which can generate both UV and tunable MIR lasers with a nonlinear frequency conversion. A tunable MIR laser (5.5-10 micron) was obtained by a difference frequency generation (DFG) with a Nd:YAG laser (1064 nm) and a tunable Cr:forsterite laser (1180-1350 nm) using two AgGaS2 (Type II) crystals. This MIR laser can generate laser pulses having an energy of up to 1.4 mJ, a pulse width of 5 ns, and a repetition rate of 10 Hz. On the other hand, an UV laser was obtained by a third harmonic generation of a Nd:YAG laser splitted from that used for the DFG. A time interval between the UV and MIR laser pulses can be precisely controlled with a variable optical delay.

[1] Y. Naito et al., Nucl. Instr. and Meth. A 528 (2004) 609.

6455-07, Session 2

Active narrowband multiple fundamental and second-harmonic wavelength filters in aperiodically poled lithium niobates

Y. Chen, C. Lin, J. Chang, National Central Univ. (Taiwan)

We report active narrowband multiple fundamental and second-harmonic wavelength filters at telecomm C-band in aperiodically poled lithium niobates (APLN). In this work, two interesting features of ·olc-type wavelength filters based on electro-optic (EO) APLN potential for DWDM application have been proposed and calculated with the stimulated annealing (SA) method.

When a 5cm long APLN filter was pumped by a broadband and equalized telecomm C-band source and applied with an electric field of 298 V/mm along the crystal y axis, ~100% transmission of 8 International Telecommunication Union (ITU) standard wavelengths from 1542.93 to 1559.79 nm with frequency spacing of 300GHz was simultaneously achieved. The full width at half maximum (FWHM) of each signal was ~0.45nm. The highest level of the noise sidebands was around 20%.

We further integrated a 1cm long EO APLN with a 1cm long second-harmonic generation (SHG) APLN in a monolithic LiNbO3 crystal pre-designated for four ITU wavelengths and their SHGs, respectively. When such a crystal was placed between two parallel polarizers aligned in transmitting TE fundamental waves and again pumped by a broadband and equalized C-band source, we obtained four narrowed ITU SHG signals with highly reduced sidelobes in comparison with the fundamental spectrum traced immediately after the first EO APLN section. The peak narrowing and spectrum cleaning in SHG signals resulted from the cascade nonlinear processes.

Devices proposed in this paper can be readily implemented in nonlinear optical waveguides such as Ti:LiNbO3 waveguides.

6455-09, Session 3

Terahertz wave generation in orientation-patterned GaAs using resonantly enhanced schemes

K. L. Vodopyanov, Stanford Univ.

Zincblende semiconductors (GaAs, GaP) show great potential for quasi-phase-matched (QPM) THz generation because of their small (20 times less than in lithium niobate) absorption coefficient at terahertz frequencies, small mismatch between the optical group and THz phase velocities, high thermal conductivity, and decent electro-optical coefficient. Terahertz-wave generation was demonstrated recently in QPM GaAs, using optical rectification of femtosecond pulses. Here we report on a new efficient widely tunable (0.5-3.5 THz) source of THz radiation based on orientation-patterned GaAs (OP-GaAs) crystal and picosecond optical pump pulses. The source is based on difference frequency generation inside the cavity of the synchronously pumped OPO and takes advantage of resonantly enhanced both the signal and the idler waves. THz average power as high as 1 mW was achieved in a compact setup.

6455-10, Session 3

Nonlinear wavelength conversion into the mid-infrared within engineered glass-bonded QPM GaAs crystals

P. D. Mason, P. J. Webber, B. J. Perrett, S. C. Woods, D. A. Orchard, QinetiQ Ltd. (United Kingdom)

Non-linear optical wavelength conversion of near-infrared lasers within optical parametric oscillators (OPOs) offers a route to powerful tunable sources in the mid-infrared (mid-IR). Engineered quasi-phasematched (QPM) non-linear optical materials based on gallium arsenide (GaAs) offer an alternative to conventional birefringently phasematched single-crys-

tal materials such as ZnGeP2, which are currently used in mid-IR OPOs. QPM GaAs crystals have been assembled from commercially available, high-optical quality 100-micron thickness gallium arsenide (GaAs) wafers using a novel glass-bonding (GB) process. The glass-bonding technique uses thin-layers (several microns thick) of a low softening temperature infrared transmitting chalcogenide glass (refractive index matched to GaAs), which are deposited on to appropriate thickness (i.e. 3rd order coherence length) GaAs wafers. These glass-coated wafers are then fused together under heat and pressure to form a monolithic structure. Using this wafer bonding process, 100-layer GBGaAs crystals have been manufactured with large useable apertures (4 mm diameter) and low optical loss (3% absorption at 2 μm). By varying the thickness of the deposited glass layers, the dispersion in the glass can be used to compensate for variations in GaAs wafer thickness and to fine tune the phasematching wavelengths of the crystal. GBGaAs crystals have been designed and built for wavelength conversion from 2 μm into the mid-IR. We report the performance of these crystals used as optical parametric amplifiers (OPAs) and within seeded-OPOs, when pumped by a 2.094 μm source, and compare experimental results to performance predictions obtained from a numerical model.

6455-11, Session 3

Optimization of noncollinear optical parametric amplification

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The development of ultrashort sources opens new fields of research in science. The large bandwidth of the high gain in optical parametric amplification (OPA) enables the generation of high peak-power short pulses (<10 fs). In particular, non-collinear geometry for the signal and pump beam have been used for the ultra-broadband parametric amplification. In such a configuration the group velocity of the faster traveling idler wave is projected at an angle onto the direction of the slower traveling signal wave, therefore, the temporal overlap is improved and a broad phase-matching bandwidth is achieved.

From simulations regarding type-1 phase-matching of the non-collinear OPA using the Sellmeier coefficients of BBO follows that the k-vector mismatch |Δk| can be fairly good approximated by the component along the signal direction, Δ k parallel . Furthermore, a plane-wave model may be used if there is sufficient temporal overlap of the pump with respect to the signal during the three-wave process. However, temporal walk-off due to dispersion could be also included. Since the angles of the non-collinear geometry are usually quite small, and in addition, the spots of the beam overlap along propagation through the crystal, diffraction and spatial walk-off may be also neglected.

By means of such simulations it is feasible to obtain the gain spectrum for the signal. In addition, the resulting pulse duration can be estimated. Thus, we will present numerical simulation to optimize the obtainable amplification bandwidth and therefore pulse peak power from a non-collinear parametric amplifier. Experiments to confirm the numerical predictions will be discussed.

6455-12, Session 3

Optical parametric generation of high-energy femtosecond pulses in the 1-3 μm spectral range using BiB3O6

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We report efficient optical parametric generation in BiB3O6 pumped by amplified 80-fs pulses near 800 nm, at a repetition rate of 1 kHz. Type-II (oe-o) interaction in the X-Z plane was utilized for better control of the spectral bandwidth, especially near degeneracy. Samples of 3 and 5 mm thickness were studied in a double pass configuration. The first pass was seeded by continuum and the second pass was seeded by the signal pulse. The performance was compared to that of a standard AR-coated crystal of BBO (type-II, 5 mm thickness) used in the same configuration. The conversion efficiency obtained with the BiB3O6 crystals was higher, although these samples were uncoated. A total energy output (signal + idler) of about 80 μJ was obtained in the plateau region of the tunability curve with the 3-mm thick BiB3O6 crystal for a total pump energy of 375 μJ for all stages. The tunability extended roughly from 1 to 3 μm with much higher output near these limits in comparison to BBO. The basic advantage of BiB3O6 against BBO is the higher effective nonlinearity which allows shorter samples to be used. As a result of this, shorter pulse durations were obtained with the 3-mm thick BiB3O6: e.g. cross correlation measurements of the idler pulse near 3000 nm gave a FWHM of the order of 120 fs. No damage was observed in the BiB3O6 crystals in this regime.

6455-13, Session 3

Compact sub-mW mid-infrared DFG laser source using direct-bonded QPM-LN ridge waveguide and laser diodes

O. Tadanaga, Y. Nishida, T. Yanagawa, K. Magari, T. Umeki, M. Asobe, H. Suzuki, NTT Photonics Labs. (Japan)

We report the first sub-mW mid-infrared (IR) laser source based on difference frequency generation (DFG) in a quasi-phase matched (QPM) LiNbO3 (LN) waveguide directly pumped with two laser diodes (LDs). We did not employ a fiber amplifier or a high power solid-state laser. The signal was obtained from a 1.55-μm band DFB-LD, and the pump from a fiber Bragg grating stabilized LD. We used 1.064 and 0.976-μm pump LDs for 3.4 and 2.6-μm generation, respectively. To construct the mid-IR laser sources, we employed wavelength conversion modules with fiber pigtails. We used the V-groove connection technique to splice a direct-bonded QPM-LN ridge waveguide to an input fiber. The modules had high external conversion efficiencies of 10 and 16 %/W for 3.4 and 2.6 μm, respectively. The two LDs and the wavelength converter were assembled with a polarization maintaining fiber, and then packaged in a box (100 x 180 x 100 mm).

We measured the output power of the mid-IR laser light sources as a function of the DFB-LD injection current. We obtained high outputs of up to 0.20 and 0.33 mW for the 3.4 and 2.6-μm laser sources, respectively. The narrow linewidths of the 3.4 and 2.6-μm laser light sources enabled us to detect the respective absorption lines of CH4 and H2O clearly.

These compact sub-mW mid-IR laser sources based on DFG are promising for application to high-sensitivity, real-time, and in-situ measuring systems for various gases such as hydrocarbons, CO2, and H2O.

6455-14, Session 3

8.6-watt single-frequency CW OPO

A. J. Henderson, R. Stafford, Aculight Corp.

A continuous wave singly resonant optical parametric oscillator (CW SRO) has been developed which produces a total of 8.6 Watts of single frequency output at two wavelengths. 5.1 Watts of signal output at 1.65 microns and 3.5 Watts of idler output at 3.0 microns was measured, using a 15 Watt, single frequency fiber laser pump source. Power stability of 3% peak to peak was measured over a period of 24 hours, and six hours of operation without longitudinal mode hops was recorded. The beam quality of both outputs was near-diffraction-limited, with an M2 parameter < 1.1.

We have also observed for the first time, the transition from single frequency to broadband oscillation of a CW SRO at pumping levels greater than three times threshold. At the highest pumping levels, Raman conversion of the signal frequency was observed. Based on these measurements we have been able to define an optimum operating point for CW SROs ensuring maximum conversion efficiency and single frequency oscillation.

6455-15, Session 4

Nonlinear optics for high-order frequency conversion: applied attosecond science

X. Zhang, A. Lytle, O. Cohen, D. Gaudiosi, T. Popmintchev, H. C. Kapteyn, M. M. Murnane, Univ. of Colorado/Boulder

The high-order harmonic process is the first and best example of a complex process where attosecond time-scale dynamics can be coherently manipulated, thus representing the fastest technology yet devised by man. Useful examples of this manipulation include methods for phase matching the high-order harmonic process, for manipulating the spectral characteristics of the radiation, and for generating attosecond pulses. In this talk, I will discuss a variety of results from our group, including recent work that uses counter-propagating pulsetrains to manipulate the phase of the recolliding electron and thus increase the efficiency of the generation process. I will also discuss the unique characteristics of HHG that present both challenges and opportunities in exploiting it as a nonlinear-optical process.

6455-16, Session 4

Coherent detection of multicycle THz pulses generated in periodically inverted GaAs

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Narrowband multi-cycle THz pulses have been generated in the pre-engineered domain structure of periodically-poled lithium niobate (PPLN) crystals. The mechanism for THz generation is quasi-phase-matching (QPM) optical rectification. Recently, THz generation of high conversion efficiency in a new material, QPM GaAs, were demonstrated using mid-IR femtosecond pulses. GaAs has several advantages for QPM THz wave generation, as compared to PPLN. First, it is highly transparent at THz frequencies (absorption coefficient below 1.5 THz < 1cm-1). Second, the mismatch between the optical group velocity and THz phase velocity is much smaller: the corresponding group (ng) and refractive (n) indices are ng =3.431 at 2 um and n=3.61 at 1 THz. In this work, we report on generation of THz wave packets in three different types of QPM GaAs, combined with their coherent detection using two-color THz time-domain spectroscopy. The QPM GaAs structures are optically-contacted GaAs, diffusion-bonded GaAs, and all-epitaxially-grown orientation-patterned GaAs. The QPM optical rectification in GaAs is a nonresonant mechanism, as opposed to widely used photoconductive antenna technique in GaAs, where THz radiation is produced via ultrafast charge transport caused by photoexcitation with femtosecond laser pulses of the near-IR range. In order to avoid linear and two-photon absorption in GaAs, we use 2-um femtosecond pulses to generate THz pulses. We measure the THz waveforms via electro-optic sampling in ZnTe using 0.8-um probe pulses. The corresponding power spectra are also measured by a THz Michelson interferometer. Frequency tunability in the range 0.8-3 THz is achieved with several structure periods.

6455-17, Session 4

Fiber continuum-seeded ultrafast parametric amplification

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We discuss the fiber based generation of broadband signal for ultrafast parametric amplifiers. The benefit from such a approach is the low broadening threshold, high beam quality and stability of the continuum, which is in contrast to conventional continua generation in a bulk sapphire or glass plate. In this paper we demonstrate parametric amplification and later recompression to ultra short pulse spectra created in a photonic crystal fiber (PCF) by careful engineering of the signal. When coupling a pulse into a PCF the pulse moves into a Nth order soliton. During its propagation this soliton is spectrally broadened by SPM and its blue part overlaps with the resonant linear wavelengths (non-solitonic Radiation - NSR) which emerge as anti-stokes radiation. As consequence, by paying attention to the power injected in the PCF, it is possible to excite one single first order soliton associated with its non-solitonic radiation. In that case, as they experience different group velocities and therefore separate in time after a certain propagation length in the fiber, amplifying the NSR part of the spectrum is now straightforward.

Considering now the propagation of the resonant waves we see that it follows the group delay of the fiber. In the region where the NSR is located, far from the ZDW, the group delay is almost linear. As a consequence, the NSR exhibit a linear temporal chirp which makes the NSR very attractive for ultra short pulse OPCPA. Indeed, as it can be amplified in a NOPA without changing its temporal profile, this spectrum whose phase follows a monotonic relation can be easily recompressed with a simple prism sequence opening the range of recompressed few femtoseconds pulses. In a first experiment, we realized the parametric amplification and subsequent recompression to <50 fs pulses with a center wavelength of ~850 nm. The signal is generated in a photonic crystal fiber with a zero dispersion wavelength of 975 nm with an initial pulse duration of 400 fs at 1030 nm from a short pulse fiber laser system at 1 MHz repetition rate.

6455-18, Session 4

Nonlinear control of ultrafast lasers with intense coherent THz pulses

G. L. Carr, Y. Shen, C. Kao, Brookhaven National Lab.

The electro-optic effect in ZnTe is commonly used for coherent detection of few-cycle THz pulses. The instantaneous THz E-field induces a refractive index change that is sensed as a phase shift in a co-propagated laser pulse. Because most THz sources are weak, the phase shift is sufficiently small that its time-dependence can be ignored. This is not the case for coherent THz pulses produced by relativistic electron sources, where THz pulse energies can reach 100 microjoules and E-fields exceed 100 kV/cm. For such fields, the time-dependent phase modulation gives rise to significant spectral shifting and chirping of the co-propagated laser pulse. We demonstrate this and other effects (such as THz induced lensing) using THz pulses from a ~100 MeV electron linac combined with 800 nm, 150 fs Ti:sapphire laser pulses in 110 oriented ZnTe. Together, these effects illustrate how intense THz pulses can control ultrafast light pulses.

6455-19, Session 4

Arbitrary THz pulse shaping in fanned-out periodically poled lithium niobate

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We demonstrate a novel THz-pulse shaping technique, which guarantees ultimate flexibility for arbitrary THz-pulse generation. The THz-pulse shaper consists of a fanned-out periodically-poled lithium niobate (FO-PPLN) crystal-the domain width of the FO-PPLN crystal varies continuously across the lateral direction-, a spatial mask, and a spherical mirror. Optical pulses are line-focused on the FO-PPLN crystal to generate spatially separated multi-frequency components of THz-pulses. The spatial mask is placed in front of the FO-PPLN crystal in order to manipulate the spatial pattern of the incident optical beam, thus to control the amplitudes of the spatially dispersed THz frequency components. Spectral resolution of this method is determined by FO-PPLN bandwidth and mask resolution: estimated practical resolution is ~0.01 THz for 1 THz bandwidth. After the spherical mirror assembles the various frequencies into a single collimated beam, a shaped THz-pulse can be obtained, with the pulse shape determined by the Fourier transform of the pattern transferred by the mask. As a proof-of-principle experiment, we measured THz wave-

forms using metal masks. The experiment was performed using 800-nm, 100-fs pulses from a 1-kHz Ti:sapphire regenerative amplifier. We used a 5-mm long FO-PPLN sample (width = 10 mm, height = 0.5 mm) continuously tunable from 0.6 to 1.5 THz. We tested the metal masks of three different spatial patterns: low-pass filter, high-pass filter, and double slit. The experimental results show that the THz waveforms are determined by the spatial patterns of the masks.

6455-20, Session 4

Extending the flat gain bandwidth of combined Raman-parametric fiber amplifiers using highly nonlinear fiber

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Highly nonlinear fiber (HNLF) has been used previously as the interaction medium for both Raman amplifiers (RAs) and optical parametric amplifiers (OPAs). Combining these processes in HNLF has also received attention, mainly for the purpose of using the Raman gain in order to enhance the parametric process in either a Raman mediated OPA (RM-OPA) or a Raman assisted OPA (RA-OPA). These previous studies have focused on the gain enhancement effects and the coupling between these two nonlinear processes within a bandwidth where both of the processes exhibit strong gain. We experimentally investigate an alternative way to combine RAs and OPAs using HNLF that enables us to extend the flat gain bandwidth of Raman amplifiers beyond the limits that are set as a consequence of the Raman gain coupling between multiple Raman pump lasers. This involves separating the Raman and parametric pumps by about 160 nm and adjusting the relative pump powers in order to achieve a gain of over 20 dB with an extension (beyond that of RA) of at least 30 nm and with a gain ripple below 5 dB. In order to understand the limits of this type of combined RA-OPA, we experimentally compare two configurations of this amplifier. The first we call the Unison configuration in which the RA and OPA use the same HNLF and the other we call the Tandem configuration in which the RA and OPA use separate HNLFs. Measured Noise figure and Bit error rate results are presented for both of these configurations.

6455-21, Session 5

Cascaded-stage parametric amplification

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We performed a numerical simulation of optical parametric amplification using a two-stage optical amplifier, i.e. two nonlinear crystals. The improved output efficiency from the second stage is compared with a single stage amplifier. We describe the down-conversion process of generating longer wavelengths by the usual three coupled amplitude equations. These are solved including transverse coordinates and walkoff by a Fourier transform split step method. The beam propagation parameter M2 value was also calculated.

The crystals selected for the system were the chalcopyrite, ZnGeP2, due to their large nonlinearity of 75pm/V and high transparency in the chosen wavelength region of 5-9 μm wavelengths. The input beams called pump and signal for this system are obtained as pump and signal outputs from Nd:YAG pumped source that is tunable in the range from 1.76-2.61 μm. The pump absorption, the walkoff angles of the signal and generated idler e-waves were also taken into consideration. The efficiency (idler energy divided by pump energy) is 6.37% at 9.12 μm when pump absorption is included in the calculation. The signal and idler outputs from first crystal are used as a pump and signal, respectively, for second crystal, which boosts the efficiency of the 9.12 μm beam energy to 18.6%. We show that the increase in efficiencies are not wavelength specific but rather can be utilized for any wavelength across the transparency of the material. Calculations are performed for the range of output wavelength from 5.404μm-9.12μm and there are comparable increases across the entire spectrum. We find that the output efficiency from the second stage is nearly tripled over the output efficiency from a single crystal stage.

6455-22, Session 5

Four-dimensional treatment of frequency conversion and the effect of smoothing by spectral dispersion

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Orion is a new laser facility under construction at AWE for studying high energy density physics, and is a replacement for the 25-year old HELEN laser. It will combine 10 long pulse beams operating in the nanosecond regime with 2 short pulse beams operating in the sub-picosecond regime to access novel experimental conditions.

The design of Orion has been underwritten by modeling various aspects of the beamlines. For the long pulse beams this has included modelling the frequency conversion process from the first to the third harmonic. The need to take account of the effect of the phase modulation applied for Smoothing (of the output focal spot) by Spectral Dispersion (SSD) has led to the development of a four-dimensional (x,y,z,t) frequency conversion code. The code uses a split-step approach, considering diffraction, walk-off, coupled waves, the effect of wavefront error on phase-matching, self-phase modulation, and group velocity dispersion.

The results of this frequency conversion modelling will be reported, showing the anticipated reduction in the conversion efficiency due to the SSD process and conventional wavefront error. Also reported are the small variations in conversion efficiency as the direction of the angular dispersion is oriented differently with respect to the conversion crystal axes. Finally, a model which demonstrates the smoothing of the focal spot as a function of time using a prototype kinoform phase plate will be given.

6455-24, Session 5

Analysis of a third-order optical parametric oscillator in TiO2

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A novel third-order optical parametric oscillator (OPO) based on four-wave mixing process in bulk TiO2 is theoretically characterized.

The OPO is assumed to be synchronously pumped by pulses of either a 100fs duration at 800nm or 100ps at 1.06μm. For the former case, its signal is tunable from 0.4 to 0.8μm by changing the crystal orientation; for the latter case, it's tunable from 0.6 to 1.06μm roughly. The threshold conditions are also calculated considering the effect of group velocity mismatch (GVM) between the pump pulse and the signal (or idler) pulse. The threshold is dependent on signal wavelength since GVM increases as signal wavelength decreases. Using a 2mm-length crystal and assuming optimum focusing, the threshold for singly resonant condition is 710mW at 700nm for the former case and 93.6W for all the signal wavelengths for the latter case. The threshold condition is also calculated assuming different pumping pulse widths. The result shows the ideal pulse width is around 3ps, for which the threshold power is 2.13W for all the signal wavelengths.

6455-25, Session 5

Singly resonant optical parametric oscillators with pump-modulation transfer for frequency modulated spectroscopy in the mid-infrared

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Frequency modulation (FM) techniques such as wavelength-modulation spectroscopy (WMS) and frequency-modulation spectroscopy (FMS) are well known methods for improving signal-to-noise ratios in laser spectroscopy. Such techniques have proven particularly effective with diode lasers due to the ease with which they can be frequency modulated via their injection current. By contrast, the use of these techniques with other

types of laser requires the added complexity of external modulation devices, making the approach much less attractive. Singly-resonant optical parametric oscillators (SROs) have been shown to be flexible, powerful and widely-tuneable sources for various spectroscopic applications in the mid-infrared (MIR). However, in common with the majority of other non diode-laser sources, the utilisation of FM techniques with SROs suffers the inconvenience of requiring an external modulator. As a consequence, FM techniques have been rarely applied with such devices.

Recent demonstrations have shown that the combination of an SRO with a widely-tuneable ytterbium fibre based pump source allows wide-range and rapid tuning of the MIR idler output of the SRO by pump tuning alone. Using this approach, the SRO itself acts simply as a wavelength converter, transferring the spectral and tuning properties of the pump to the MIR idler frequency while the resonant signal frequency remains fixed.

In this submission, we discuss the extension of this approach to frequency-modulation techniques. A ytterbium-fibre-amplified diode laser is used to pump an SRO. In addition to tuning the MIR output of the SRO by tuning the diode laser, frequency modulation of the diode laser, achieved by modulating its injection current, is transferred to the MIR output of the OPO. By this means, a range of FM based spectroscopic techniques, including WMS and FMS, are demonstrated in the MIR. We believe this novel approach offers the possibility of using FM techniques with powerful, widely tuneable MIR sources while retaining the simplicity of modulation offered by diode lasers.

6455-26, Session 5

Simultaneous SHG of orthogonally polarized fundamentals in single QPM crystals

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Fabrication of quasi-phase-matching (QPM) gratings suitable for cascading of two second-order parametric nonlinear processes in a single lithium niobate crystal is being undertaken using a new technique - electric field poling assisted by laser micro-machined topographical electrodes. To date, single period poled gratings with 45, 45.7, and 46 μm periods have been fabricated in order to demonstrate second harmonic generation of 1064 nm laser light with 1st order type-I and 7th order type-0 QPM, simultaneously. Our experimental temperature tuning curves show a partial overlap of the type-I and type-0 processes, and indicate that a sample with 45.8 μm will give exact coincidence of the two processes at a temperature around 160°C. The two frequency doubling processes share a common Z polarized second-harmonic wave which allows exchange of energy between the two orthogonally polarized fundamental waves and several second order cascading interactions can be realized. We will also demonstrate simultaneous phase-matching of 1st and 5th order processes in 32 μm period crystals (~240°C), as well as 1st and 3rd order processes in a phase reversed grating. The use of the higher QPM orders (3rd, 5th or 7th) for the type-0 second harmonic generation process leads to comparable efficiencies of the two processes, as the respective nonlinear coefficients dzzz ~ 6Å~dyyz in lithium niobate crystals. Possible applications include; polarization switching, parametric amplification and pulse regeneration, induced change of polarization state, and polarization insensitive second harmonic generation.

6455-30, Session 5

Iterative resonator model describing the Stokes and anti-Stokes emission of a continuous-wave silicon-based Raman laser

N. Vermeulen, C. Debaes, H. Thienpont, Vrije Univ. Brussel (Belgium)

The recent development of a silicon-based Raman laser has substantially increased the interest in the field of Raman lasers. Up to now, most efforts in modeling continuous-wave silicon-based Raman lasers have been dedicated to describing the steady-state Stokes emission. However, neither the modeling of the lasers' transient characteristics nor that of supplementary anti-Stokes emission has been addressed so far. Moreover, in the majority of cases, one uses optical-power-based models, which are inadequate when it comes down to incorporating the interference effects that occur in some silicon-based Raman laser configurations.

In this paper, we present a novel field-amplitude-based model that resolves the shortcomings of the above mentioned modeling approaches and therefore enables us to take the modeling of silicon-based Raman lasers an important step further. Our so-called 'iterative resonator model' evaluates for every half roundtrip time the longitudinal distribution of the intra-cavity pump, Stokes and anti-Stokes fields propagating in forward and backward directions. Hereby, the most important loss mechanisms in a silicon-based Raman laser when operating in the telecom window around 1.5 micrometer, i.e. linear losses, two-photon-absorption and free-carrier-absorption, are also taken into account. On one hand, we demonstrate that our model correctly implements interference effects that may occur in some silicon-based Raman laser configurations. On the other hand, we present the first numerical simulation results for a silicon-based Raman laser emitting both Stokes and anti-Stokes photons. Finally, we explain how the iterative resonator model also allows generating data on the transient characteristics of a continuous-wave silicon-based Raman laser.

6455-23, Session 6

Modeling mid-infrared continuous-wave silicon-based Raman lasers

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A very promising wavelength region for pumping silicon-based Raman lasers is the wavelength range above 2.2 micrometer, where the pump photon energy is smaller than half the bandgap energy. Indeed, for such low photon energies, two-photon-absorption is ruled out and only less efficient absorption processes involving three photons or more can occur. Moreover, the free-carrier-absorption associated with the weak three-photon-absorption mechanism is negligible, and the linear losses in silicon become minimal at pump wavelengths beyond 2.2 micrometer. Additionally, when carefully selected pump wavelengths are used, the silicon-based Raman laser might be able to cover spectral regions in the mid-infrared that have not been addressed so far, and this could open up a myriad of potential applications in spectroscopy, medicine, etc.

In this paper, we present the first modeling results for a continuous-wave silicon-based Raman laser pumped at wavelengths larger than 2.2 micrometer. We obtained these data using an iterative resonator model that incorporates linear and three-photon-absorption losses. We compare these graphs with the simulation results for a silicon-based Raman laser with a pump wavelength situated in the telecom window around 1.5 micrometer. The latter data are generated by the use of an iterative resonator model that includes linear losses, two-photon-absorption and free-carrier-absorption. Besides comparing the Stokes emission of these lasers, we furthermore discuss the differences in the anti-Stokes emission and explain how the generation of anti-Stokes photons is influenced by the respective loss mechanisms.

6455-27, Session 6

Improved NLO crystals for mid-IR laser applications

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In the past two decades mid-IR nonlinear optical crystals have grown from scientific curiosities to practical robust materials generating efficient, multi-watt output in the 3-12 micron spectral range. Nonetheless, improved NLO crystals are critical for further advancing mid-IR laser development. In particular, mid-IR materials are needed which: 1) efficiently convert cw pump sources; 2) can be pumped with 1-micron (Nd and Yb)

lasers; and 3) offer improved performance in the 8-12 micron range and beyond. For such applications a high nonlinear coefficient is desirable, but this is less important than more practical properties such as low absorption loss, high laser damage threshold, low thermal lensing, and noncritical phase matching (NCPM). To meet these demands, the search for improved mid-infrared NLO crystals is proceeding on three fronts. First, work continues to reduce losses in the best existing materials such as ZnGeP2, AgGaSe2, and CdGeAs2. Secondly, new compounds (such as the Li-(In,Ga)-(S,Se,Te)2 chalcopyrite analogs) and mixed crystals (AgGa1-xInxSe2 and Ag1-xGa1-xGexS2) are being evaluated. Thirdly, and most promising, is the work on all-epitaxial processing of quasi-phase-matched GaAs and other binary semiconductor analogs such as ZnSe, GaP, and GaN. Recent progress on all these fronts will be reported, along with corresponding advances in mid-infrared laser performance.

6455-28, Session 6

Raman gain measurements and photo-induced transmission effects in germanium and arsenic-based chalcogenide glass

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The absolute Raman gain spectra of millimeter thick germanium and arsenic based chalcogenide glasses have been measured with a novel direct nonlinear optics measurement technique. Pump light originates from a picosecond Nd:YAG operating at 1064 nm and an OPG/OPA is used as the probe light. The new technique is calibrated on a 3 mm thick piece of fused silica and the measured absolute peak Raman gain coefficient agrees with previosly published values. A peak Raman gain coefficient around 170 times greater than the peak of fused silica for 24As-38S-38Se was measured, the highest increase over fused silica measured to date in glass using this technique. The germanium based chalcogenide glasses yielded Raman gain coefficients around 60-80 times greater than the peak of fused silica. The Raman gain data is also compared to recently published values of n2 in the same glasses which were also reported using a 1064 nm picosecond pump beam. A completely reversible photodarkening effect which responds to picosecond pulses has been discovered. This effect shows no “memory” on a shot-to-shot basis using picosecond pulses and a 10 Hz repition rate, and it is completely reproducible anywhere in the sample. This photodarkening effect may present a limitation on the use of these glasses in high power applications, such as amplifiers or fiber lasers. Finally, surface optical damage thresholds at 1064 nm in the picosecond regime are found to be as high as 9 GW/cm^2, which is as high or higher as some previously reported tellurite (defined as TeO2-based glasses) which possess lower nonlinearities.

6455-29, Session 6

Stimulated Raman scattering in new organic and inorganic crystalline materials

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The demand for laser systems generating new wavelengths in the UV, visible and near Infrared spectral region has caused a growing interest in stimulated Raman scattering (SRS) in crystalline materials as an effective means to convert the emission of commercially available laser systems. The size of this discrete frequency shift is material specific due to the energy of the participating optical phonon. Therefore it is necessary to investigate a large number of Raman-active materials with promising nonlinear properties. In the recent years attention has been increasingly concentrated on organic materials. Energies of the Raman-active phonons of around 3000 cm-1 due to the strong nonlinear polarizability in such materials have been observed. Results of our SRS investigations of the organic crystals α-Ca(HCOO)2 (calcium formate), LiNH2C6H4SO3·H2O (lithium sulfanilate monohydrate) and [N(CH2CH2NH2)3]·3HBr (tren trihydrobromide) are presented. Currently a promising development in solid-state laser physics is the use of highly transparent ceramics. We have demonstrated efficient SRS in three ceramics based on cubic rare earth sesquioxides RE2O3 (RE = Sc, Y and Lu) with Raman shifts in the range of 378 cm-1 to 419 cm-1. Cascading $\chi(3) \rightarrow \chi(2) \rightarrow \chi(3)$ lasing effects, self-SHG, self-SFM and cascading Stokes and anti-Stokes generation between phonons of different energies has been observed in Li2SO4·H2O (lithium sulphate monohydrate), CsLiMoO4 (cesium lithium molybdate) and $CsLiMoO4 \cdot {}^{1}/_{3}H2O$.

6455-31, Session 6

Third-order nonlinear optical properties of tellurite glasses in femtosecond regime

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Optical glasses based on TeO2 are promising materials for photonics and optoelectronics applications. They are transparent in the visible, near and middle infrared regions. In comparison with silica glasses, they present larger refraction index (~2.0) and smaller phonon energies (~700 cm^(-1)), in the same tier as germanate glasses. In relation to fluoride glasses, which also have various photonic applications, they offer the advantage of better chemical durability. Although it is believed that TeO2 based glasses should present large nonlinear refractive indexes, the nonlinear optical properties of such materials were not yet completely investigated. In this work, we report on the measurements of the nonlinear refraction and absorption at 810 nm in the femtosecond regime for five different tellurite glass compositions. Using the I-scan technique, positive nonlinear refractive indexes of ~10^(-15) cm^2/W were measured. Nonlinear absorption coefficients were estimated to be smaller than 1 cm/GW for all studied samples. The figure of merit W for all-optical switching was also evaluated for these glasses and our results indicate that tellurite glasses are very good candidates to the development of optical devices for ultrafast photonic applications.

6455-32, Session 7

Optimization of nonlinear optical frequency conversion

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Given a highly energetic pump laser, it is usually desirable to obtain the highest amount of power at a different wavelength (or wavelengths), using one or more nonlinear optical crystals. In addition, good spatial characteristics of the generated radiation are desirable in order to provide high irradiance when the light is refocused. Linear absorption of the pump or generated light can give rise to a temperature gradient in the crystal. This temperature variation can cause a refractive index change which may not only distort the beams, but also cause a phase mismatch which can reduce the conversion efficiency and degrade the spatial beam quality. Pump beam depletion can also hamper conversion and degrade the beam quality. Moreover, laser induced damage of the crystal imposes the upper limit of the pump irradiance that can be used.

A detailed study of the focusing conditions in nonlinear optical interactions to obtain the maximum irradiance at a focal plane will be presented, along with experimental results on optimization of second harmonic generation of nanosecond and picosecond duration infrared lasers in high gain nonlinear optical crystals.

6455-34, Session 7

Red to green upconversion in erbium-doped BaTiO3 nanocrystals

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Recent studies have demonstrated the large frequency upconversion efficiency of rare-earth (RE) doped nanocrystals that can be controlled by selecting appropriate hosts having low cutoff phonons as well as changing particle sizes and RE ions concentration. Barium titanate (BaTiO3) nanocrystal is one of the RE hosts that have been studied for luminescence. The present work extends previous investigations with this material. Here a red-to-green upconversion process, in erbium (Er3+) doped BaTiO3 nanocrystals, is studied in details. A nanopowder (with grains having average dimensions of 60 nm) doped with Er3+ (0.5 mol %) was studied. The experiments were performed using a tunable dye laser (CW, 638 to 660 nm) to excite green fluorescence corresponding to the transitions from levels 2H11/2 and 4S3/2 to the ground state of the Er3+. Excitation experiments, performed varying the laser wavelength, have shown the existence of three fluorescence maxima, when the laser is operating at 640, 652 and 658 nm. The fluorescence spectral behavior and its intensity dependence with the pump intensity were investigated. We observed that the luminescence was strongly saturated when the pump laser is centered at 652 and 658 nm. The upconversion process was modeled as a two-step one-photon absorption phenomenon, using a system of rate equations for the density of levels population. The theoretical results presented a good agreement with the experimental data.

6455-35, Session 7

Reduction of the optical damage in lithium niobate crystals by thermo-electric oxidization

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Lithium niobate crystals (LiNbO3) enable nonlinear optical frequency conversion. As an impurity iron is to some extend always present in LiNbO3. It occurs in two valence states, Fe2+ and Fe3+. Exposure with visible light excites electrons from Fe2+ to the conduction band. Inhomogeneous illumination yields a charge transport in the conduction band because of the bulk photovoltaic effect, diffusion, and drift. The electrons are finally trapped by Fe3+ sites, preferentially in the darker areas. Space charge fields build up and modulate the refractive index through the electro-optic effect. In nonlinear-optical experiments these refractive index changes are unwanted (“optical damage”) because they disturb the phase matching conditions and the beam profile. We introduce a method that reduces optical damage by nearly perfect oxidization of iron in LiNbO3, i.e., almost all Fe2+ ions are oxidized to Fe3+. The nominally undoped samples are heated to 700 °C for 6 hours in air. During the entire process an electrical field of about 100 V/cm is applied with a current density limitation of 0.01 mA/mm2. The optical damage in treated crystals is suppressed by one order of magnitude, presumably because due to the strong oxidization there are no electrons left, that can be excited. Frequency doubling experiments show a strong enhancement of the reachable output power.
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6455-36, Session 7

Novel high-sensitivity thermal managed eclipse Z-scan technique

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For the appropriate development of applicable photonic materials, particularly glasses with high third order nonlinear optical susceptibility appropriate characterization methods which can provide flexibility and yield direct information on the nonlinearities and its origin are highly desirable. The well established conventional Z-scan method exploits the light-matter interaction so that an incident beam propagating inside a nonlinear medium induces a self-change in the phase that gives rise to a wave front distortion of the beam. Several variations of the methods have been developed, as the eclipse Z-scan that can provide up to two orders of magnitude higher sensitivity than the original Z-scan set-up. We report a new variation of the Z-scan method to characterize the third-order optical nonlinearity of photonic materials. By exploiting the combination of the eclipse Z-scan with thermal nonlinearity management, we demonstrate an improvement in sensitivity and flexibility of the method to simultaneously characterize the electronic and thermal nonlinearity of optical materials. The method is demonstrated by measuring the nonlinear refractive index in CS2 , SiO2 and H2O as standard materials, and also of a biomaterial, the amino acid Tryptophan in water solution, using the same experimental set up based on a femtosecond Ti-saphire laser operating at 76MHz repetition rate.

6455-37, Session 7

Magnetization-induced second- and third-harmonic generation in magnetophotonic crystals

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In this paper the results of our recent studies of the magnetization-induced nonlinear optical second-order and third-order effects in one-dimensional and three-dimensional magnetophotonic crystals are surveyed. Three-dimensional magnetophotonic crystals are fabricated on the base of artificial opals infiltrated by yttrium iron-garnet (YIG). The samples of one-dimensional magnetophotonic crystals and microcavities are prepared by RF-magnetron sputtering. Magneto-photonic microcavities are comprised of Bi-substituted yttrium-iron-garnet (Bi:YIG) half-wavelength spacers, sandwiched between two dielectric multiplayer-distributed Bragg reflectors. Each BR consists of five pairs of alternating quarter-wavelength-thick silicon oxide layers. One-dimensional magnetophotonic crystals are comprised of pairs of quarter-wavelength Bi:YIG and SiO2 layers.

Nonlinear magneto-optical Kerr effect in magnetization-induced second- and third-harmonic generation is observed in YIG-containing magnetophotonic crystals and microcavities in the spectral range of the band edge of magnetophotonic crystals or microcavity mode of magnetophotonic microcavity.

The SHG intensity reveals the enhancement by a factor of 100 near the photonic band edge. The enhancement of SHG is attributed to the fulfillment of the phase matching conditions for second-harmonic generation effect.

Three-dimensional magnetophotonic crystals on the base of artificial opals infiltrated by yttrium iron-garnet are fabricated and their structural, optical and nonlinear magneto-optical properties are studied. The second-harmonic generation technique is used for the first time to study the magnetization-induced nonlinear-optical properties of the composed opal-based photonic crystals.

6455-38, Poster Session

Comparison between stimulated Raman and Brillouin scattering processes in magnetized doped III-V semiconductors

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There has been considerable interest of researchers in stimulated scattering processes as these have manifest technological applications and provide understanding of light matter interactions in quantum electronics. In the present work, using the hydrodynamic model [1] of semiconductor plasmas and following the coupled mode approach an analytical investigation of the stimulated Raman (SRS) and Brillouin (SBS) scatterings of the Stokes mode is undertaken in doped III-V semiconductors subjected to a large magnetostatic field. These phenomena have been studied considering that the second-order forces responsible for them are different, viz., the finite differential polarizability gives rise to SRS,

while the material properties like piezoelectricity and electrostrictive strain produces SBS in the medium [2]. The qualitative behavior of gain coefficients is found to be in agreement with the experimental and other theoretical observations. The proper selection of doping concentration and an externally applied magnetic field substantially enhances the gain coefficients of SBS and SRS processes. The ratio between the two gain constants indicates that for the same pump field SBS exhibits higher gain than SRS by two orders of magnitudes. Numerical estimates have been made for n-type doped InSb crystal at 77K duly irradiated by 10.6 μm CO2 laser.

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6455-39, Poster Session

Parametric oscillation in BiB3O6 pumped at 1.0642 um

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Widely tunable parametric oscillation has been obtained in the temperature-tuned, Z-cut, 90 phase-matched BiB3O6 Pumped by a Nd:YAG laser. Tuning range was 1.625~3.083um at the crystal temperature of 20~190C. These data were used to reconstruct the high-accuracy Sellmeier and Thermo-optic dispersion formulas in the 0.474~3.083um that give an excellent reproduction of the phase-matching conditions thus far reported in the literature.

6455-40, Poster Session

Noncritical phase-matched difference-frequency generation in AgGa1-xInxS2

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We have demonstrated the 90 phase-matched type-I difference-frequency generation (DFG) in AgGa1-xInxS2 with x = 0.15 by mixing the dual-wavelength pulses emitted from an electronically tuned Ti:sapphire laser. Infrared radiation continuously tunable over the range of 4.8-6.98um was generated by independently varying the two wavelengths in the spectral range of 705-932nm. In addition, 4.04um radiation was generated by mixing a Nd:YAG laser with the Ti:Sapphire laser in the same crystal. Sellmeier equations that reproduce well the experimentally obtained data for these processes are presented.

6455-41, Poster Session

New experimental results for SHG and DFG in AgGaGeS4

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This paper reports the experimental results on the phase-matching properties of AgGaGeS4 for second-harmonic generation (SHG) at 0.8um that was achieved by using the idler output of the BBO/OPO and difference-frequency generation (DFG) at 2 and 5-12um that were achieved by using the dual-wavelength emitting Ti:Sapphire laser and the Nd:YAG laser. Two AgGaGeS4 samples showed different phase-matching conditions which were probably caused by different crystal compositions. The Sellmeier equations for these two crystals were constructed using the literature value of the refractive indices and compared with the experimental data. A satisfactory agreement between the model calculation and the experiments is obtained.

6455-43, Poster Session

Hybrid intra-extra cavity OPO using monolithic crystal for improvement in OPO efficiency

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In general OPOs for conversion of Nd:YAG Laser wavelength (1064 nm) to an eye-safe wavelength (1572 nm) use a KTP crystal in either extra cavity or intra cavity configuration. In both of these configurations input energy to Nd:YAG laser is well above the lasing threshold of Nd:YAG laser. We have designed and developed a laser system, which uses a monolithic KTP crystal external to the output mirror of Nd:YAG laser The monolithic crystal has a High Reflective (HR) coating for 1064 nm at its output face. The Nd:YAG laser has a resonator configuration, which is highly insensitive to misalignments. Due to this a complex set of 1064 nm oscillations take place between (1) HR mirror and Partial Reflective (PR) mirror of Nd:YAG laser. (2) HR mirror of Nd:YAG laser and HR mirror of KTP crystal. (3) PR mirror of Nd:YAG laser and HR mirror of KTP crystal.

Hence this configuration becomes a mix of intra and extra cavity OPO, which gives a advantage of increased efficiency. It is observed that the eye-safe output is obtained even if Nd:YAG laser is operated much below the lasing threshold. This also reduces the heat load problems to an extent. This configuration also leads to variable OPO output pulse width that can be obtained by angle tuning. An eye-safe laser built using hybrid OPO configuration is described and results presented.

6455-44, Poster Session

Supercontinuum generation enhanced by conventional Raman amplification at pumping by nanosecond pulses from a directly modulated DFB laser

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We investigated spectral broadening in a standard fiber using a nanosecond directly modulated DFB laser amplified by EDFA for pumping and measured the process of the development of the spectrum in 9.13-km length fiber. Initial transient part of a pulse shows supercontinuum generation whereas the plateau results in conventional Raman amplification of this supercontinuum.

6455-45, Poster Session

Resonant doubler with a 2-THz automatic quasi-smooth scan range for widely tunable CW single-frequency lasers

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Technique of efficient frequency doubling of CW single-frequency laser radiation in an external resonant high-Q optical cavity is extensively used for generation of radiation in UV and visible spectrum ranges. Usually, the range of smooth laser frequency scanning supported by the existing resonant frequency doublers in automatic mode lies between few and dozens of GHz.

In the present work, demonstrated for the first time is automatic quasi-smooth scanning of an resonant doubler cavity synchronously with the frequency of a CW auto-scanned Ti:Sapphire laser within a 1-THz frequency range (2 THz for second harmonic), which is limited only by the spectral acceptance bandwidth of non-linear crystal. Significant (more than by an order of magnitude) widening of the synchronous scanning

range was achieved owing to the suggested method of automatic re-locking of the external cavity. The number of automatic cycles when the input frequency is re-locked to different transmission peaks of the doubler cavity can be arbitrarily large, and the domain of automatic quasi-smooth frequency scanning that is composed of multiple smooth scanning ranges (~ few GHz wide). The doubler was tested with bow-tie-shaped ring cavity configuration and LBO/BIBO crystals. Doubling efficiency was in the range of 25-42% at input power of 0.7-2.1 W. Scanning features of the doubler are discussed with different regimes of automatic re-locking.

6455-46, Poster Session

Mid-infrared ZnGeP2 optical parametric oscillator directly pumped by a q-switched Cr,Tm,Ho:YAG laser

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Mid-infrared radiation around 6.5 mm has been demonstrated to efficiently remove soft tissue with minimal collateral damage, using ps pulses from a Free Electron laser. As a more cost-efficient and compact alternative for further medical application tests, we generate mid-infrared pulsed light tunable over this range using an optical parametric oscillator (OPO) directly pumped by a 2 mm, Q-switched laser. The pump source is a Cr,Tm,Ho:YAG laser with a Rubydium Titanyl Phospate (RTP) Pockels cell as a Q-switch. Operation in a single transverse (TEM00) mode is obtained by placing an aperture at approximately the beam waist of the stable resonator. The Holmium laser produces pulses shorter than 100 ns and energies of up to 40 mJ.

The singly resonant OPO (SRO) uses a linear cavity consisting of two plane mirrors for best overlap between the pump, signal and idler beams. The OPO is based on ZnGeP2 (ZGP) as the non-linear material. The ZGP crystal size is 5.5x5.5x20mm3, cut at an angle of 52.5o for type-I birefringent phase matching. The SRO has a threshold of 3 mJ, an idler pulse energy of 3.1 mJ, and is tunable from 5.6 to 6.6 mm. This wide tuning range together with high pulse energies in the important wavelength range around 6 mm make the SRO highly suitable for application tests, e.g. for cutting of soft tissue during surgery or corneal corrections.

6455-47, Poster Session

Amplitude and frequency characteristics of a multiphonon light scattering in tellurium dioxide single crystal

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The results of our studies related to a multi-phonon light scattering or, what is the same, a multi-order Bragg light diffraction by acoustic phonons, in optically anisotropic bulk crystals are presented. Together with this, we consider an opportunity of applying such a nonlinear mechanism to the creation of effective spatial optical modulators with an improved frequency or/and angular resolution. The main peculiarity inherent in these regimes of light scattering is connected with the problem of providing rather acceptable linearity of the input-output characteristic in similar modulators. For this purpose, first, we have developed perfectly adequate mathematical models of the nonlinear phenomena under analysis. Such models give us exact and closed analytical solutions allowing sufficiently vivid physical interpretation of redistributing the energy between orders of scattering. Secondly, the basic input-output acousto-optical characteristics of spatial modulators have been estimated from the viewpoint of their optimization. Then, we have considered the optical schemes providing a two- and three-phonon light scattering in the visible range by slow shear acoustic phonons in anisotropic tellurium dioxide single-crystals oriented along [110]-axis. Finally, a set of trial experiments with a TeO2-cell in nonlinear regime has been carried out. In particular, we have measured the output intensity-frequency distributions governing the bandwidth of modulators, the amplitude characteristics being responsible for both the linearity and the efficiency of operation, and the frequency (or angular) resolution determining the advantage of such modulators in the number of resolvable spots. Potential applications are oriented to implementing spatially multichannel large-aperture modulators for modern needs in the radio-astronomy.

6455-48, Poster Session

Optical parametric generation at extremely low pump irradiance in a long periodically poled lithium niobate

S. Acco, P. Blau, S. Pearl, Soreq Nuclear Research Ctr. (Israel); A. Arie, Tel-Aviv Univ. (Israel)

Optical parametric generator (OPG) is a very attractive optical down-conversion configuration since it is a single pass process and no cavity mirrors alignment is required. Thus the system configuration is much more simple, compact and robust.

Traditionally, OPG process was demonstrated using a pump source with a pulse length of the order of picoseconds or less. This is because GW/cm2 order of magnitude pump irradiance was required to excite an OPG process, and such irradiance in nanosecond long pulses damages the non-linear crystal.

The introduction of periodically poled crystals with high non-linear coefficients has lowered significantly the threshold for parametric processes. Improvements in quality and length of these non-linear crystals enable to excite OPG processes at less than 100 MW/cm2 irradiance, using nanoseconds long pulses from Q-switched lasers.

We present an OPG frequency conversion from 1.064 μm wavelength pump to 1.45 μm wavelength signal, with a record low threshold below 10 MW/cm2 using a 80 mm long Periodically Poled Lithium Niobate nonlinear crystal. More than 20% signal conversion efficiency and more than 1 W signal power were obtained at 25 nanosecond pulse length, 10 kHz repetition rate pumping without damaging the crystal.

Theoretical approaches for modeling the OPG in this operating regime will be discussed.

6455-49, Poster Session

CW Z-scan measurements in ionic liquids

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A large number of photonic applications have been developed based on the nonlinear optical properties of materials. Different kinds of media have been studied and engineered aiming their use in photonics devices. Among the myriad of studied compounds, organic materials are of great importance due to their large optical nonlinearities and fast responses. However, a large number of organic materials have their optical properties currently uninvestigated, as ionic liquids for instance. Ionic liquids are organic salts that are liquids at room temperature and present a strong ionic nature. They have a relatively wide electrochemically stable window, good electrical conductivity, high ionic mobility, negligible vapor pressure, and excellent chemical and thermal stability. These materials are important for a large number of applications in chemistry and industry, such as catalysis, batteries and stabilizer for colloids containing nanoparticles. An important characteristic of these materials is that some of them possess liquid crystal properties, which indicate that these compounds may present large nonlinear optical responses. In this work, we report on the first investigation of the nonlinear optical properties of two kinds of ionic liquids: 1-n-butyl-3-methylimidazolium tetrafluoroborate (BMI-BF4) and 1-n-butyl-3-methylimidazolium hexafluorophosphate (BMI-PF6), using the Z-scan technique. Nonlinear refraction and absorption measurements were performed for two different laser wavelengths, 514

and 810 nm, in the CW regime. The results showed that these specimens have large negative nonlinear refractive indexes, of ~ 10^(-9) to 10^(-8) cm^2/W, but of thermal origin. The of the studied samples were also calculated. Nonlinear absorption was not observed for these compounds.

6455-50, Poster Session

Domain inversion in lithium niobate patterned by interference lithography

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We report on the fabrication of 1-D and 2-D periodically poled lithium niobate samples with periods from 7 to 2 um patterned by interference lithography. Interference lithography technique can be used to obtain short period and various types of periodical photoreisit structures via controlling the conditions of exposure and development process. Then, the surface periodical structures are transformed into the lithium niobate by electric field poling. The periodical domain can clearly be observed by scanning electron microscope (SEM) after chemical etching.

6455-51, Poster Session

Fast-acting nonlinear optical limiters and switchers, based on fullerenes and fullerene-like nanostructures

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Mechanisms of nonlinear optical limiting by fullerenes and fullerene-like nanostructures in solutions, suspensions, polymer and microporous matrices were theoretically and experimentally investigated in wide spectral range 0.3-1.1 μm as well as in wide range of pulse durations (from several picoseconds to tens of nanoseconds).

An essential contribution of photoinduced scattering to nonlinear optical limiting was demonstrated in fullerene solutions and in suspensions of fullerene-like nanostructures. It is shown than suspensions based on fullerene-like nanostructures are the most perspective for devices design with nonlinear optical protection from laser radiation (speed less than 1 ns, dynamic range 103-104, limiting threshold 5?10-6 J/cm2, spectral range 0.3-1.1 μm, color-comfortable vision through it, i.e. the absence of limiter color.) Devices with nonlinear optical limiters are demonstrated.

The computer simulation of femtosecond range optical switchers, based on fullerene containing media was performed. Fabri-Perot interferometers, containing film of fullerene film, produced by vacuum deposition and film of fullerene-polymer solid solution were investigated. Fullerene polarization nonlinearity leads to light-induced refractive index change. The probability of interferometer reflection and transmission control by low intensity signal is demonstrated.

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6456-01, Session 1

Thermal and strain characteristics of high-power 940-nm bars mounted with AuSn solders on CuW submounts

J. L. Hostetler, G. W. Charache, R. Roff, T. Li, C. Miester, F. Dorsch, TRUMPF Photonics

As diode pumped solid state lasers gain more market share, the performance, stability and lifetime of the diode pump source faces unprecedented scrutiny. Lifetimes of diode pumps lasting the duration of the total system lifetime are sought with no intervention or maintenance from the end user. The two major power and lifetime limiting issues are soft solder creep and micro-channel degradation. This report focuses on examining the first of these issues and outlines the advantages and drawbacks of utilizing harder solders such as Gold/Tin with Copper Tungsten sub-mounts as compared to the traditional Indium mounting. In this investigation, high power 940 nm laser bars operating in the 100 to 200 W power range were mounted using AuSn/CuW and In soldering schemes. The differences in performance, thermal resistance and strain characteristics are investigated through the examination of emitter wavelengths, nearfield measurements, electrical behavior, interferometry and smile. The measurements are correlated with finite element modeling to predict the 3-dimensional thermal distributions within the laser bars.

6456-02, Session 1

Heat transfer and thermal lensing in large-mode high-power laser diodes

K. L. Chan, K. P. Pipe, Univ. of Michigan; J. J. Plant, R. B. Swint, P. W. Judoawlkis, MIT Lincoln Lab.

In semiconductor lasers, key parameters such as threshold current, efficiency, wavelength, and lifetime are closely related to temperature. These dependencies are especially important for high-power lasers, in which device heating is the main cause of decreased performance and failure. Heat sources such as non-radiative recombination in the active region typically cause the temperature to be highly peaked within the device, potentially leading to large refractive index variation with bias. Here we apply high-resolution CCD-based thermoreflectance to generate 2D maps of the facet temperatures of a high power semiconductor laser with 500 nm spatial resolution. The device under study is a 1 cm-long InGaAsP/InP slab-coupled optical waveguide laser (SCOWL) that emits watt-class power in a large (>5x5um) single mode lasing at 1.55um. We examine different regions of the device for heat sources such as non-radiative recombination, Joule heating, contact heating and optical absorption. We also study the dissipation of these heat sources due to substrate conduction and convection through the top metal contact. Due to the highly non-uniform temperature distribution measured within the device, we predict a large variation in the refractive index as the bias increases. Using the experimentally measured 2D temperature profiles as the input to a FEM based optical mode solver, we predict variation of the optical mode size and shape (up to 18% shrinkage at 4A input current) due to thermal lensing; this improvement in mode circularity can greatly increase coupling efficiency to circular-mode fibers. The predicted mode behavior agrees well with experimentally measured beam profiles, demonstrating the general usefulness of high-resolution 2D thermal imaging for studying mode dynamics and temperature-related phenomena in photonic devices.

6456-03, Session 1

Robust hard-solder packaging of conduction cooled laser diode bars

D. A. Schleuning, C. D. Nabors, G. L. Ng, J. C. McNulty, H. Zhou, Coherent, Inc.

We present the reliability of high-power laser diodes utilizing hard solder (AuSn) on conduction cooled CTE-matched submounts. We present results of hard-pulse operation at 8xx and 9xx wavelengths demonstrating an order of magnitude improvement over traditional packaging. We discuss FEA modeling and time dependent chirp measurements combined with experimental life-test data to quantify true hard-pulse operation. We also present analytic, FEA, and measured stress profiles across laser bars comparing soft and hard solder packaging.

6456-04, Session 1

Reliability and failure-mode investigation of high-power multimode InGaAs strained quantum well single emitters

Y. Sin, M. Mason, N. Presser, B. Foran, J. Scarpulla, S. C. Moss, The Aerospace Corp.

In recent years record performance characteristics from multi-mode InGaAs strained quantum well single emitters at 920-980nm have been reported including a maximum CW optical output power of ~20W and a power conversion efficiency of ~75%. These excellent performance characteristics are only possible through combined optimization of laser structure design, chip fabrication processes, and packaging. Whereas broad area multi-mode single emitters likely have sufficient reliability for industrial uses, reliability of these lasers still remains a concern for communications applications including deployment in potential space satellite systems where high reliability is required. Most previous reports on these lasers have been focused on their performance characteristics with very limited reports on failure mode analysis although understanding the physics of failure is crucial in developing a proper lifetime model for these lasers. We thus report on the reliability and failure mode analysis of high power multi-mode single emitters.

The lasers studied were broad area strained InGaAs single quantum well lasers at 940-980nm with typical aperture widths of around 100um and maximum cavity lengths of around 4mm. C-mounted AR-HR coated laser diode chips were in junction down configuration to reduce thermal resistance. At an injection current of 7A typical CW output powers were over 6W at 25C with a wall plug efficiency of ~60%. First, various lasing characteristics were measured including spatial and thermal characteristics that are critical to understanding performance and reliability of these devices. ACC burn-in tests with different stress conditions were performed on these devices until their failure. We will report accelerated lifetest results with accumulated test hours of over 5000hours. We will also report results of an EBIC (Electron Beam Induced Current) technique employed to investigate failure modes of degraded lasers that showed various degradation modes including sudden failure and gradual degradation. Finally, we will report results of cross-sectional TEM employed to investigate defects and dislocations in the degraded lasers.

6456-05, Session 1

Degradation behavior and thermal properties of red (650 nm) high-power diode single emitters and laser bars

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The degradation behavior of broad-area laser diodes and bars emitting at 650 nm under constant power operation is investigated. In addition to the increase in operation current the temperature of the laser facets (using Raman spectroscopy) and of the bulk of the diodes (using thermal imaging) was monitored. The formation of defects was studied using photocurrent spectroscopy while cathodoluminescence provided insight into the position of extended non-radiative defects at different stages of degradation.

Although the facet does not show any visible alteration even for failed devices, its immediate vicinity appears to be the starting point of the observed gradual degradation effects. At the same time the local facet temperature is increased.

The observed aging behavior is compared to the known degradation scenarios for devices emitting at 808 nm. In both cases there is a clear correlation between packaging-induced strain and observed degradation effects as demonstrated by the results obtained for bars. For the 650 nm devices a correlation between optical load and facet temperature exists, which proves that here facet heating is indeed caused by re-absorption processes. Furthermore, the degradation process is not accompanied by the creation of dark bands along <100> directions as observed earlier for 808 nm devices (with InAlGaAs QW). The observed gradual degradation of the 650 nm devices is primarily accompanied by the formation of deep-level point defects, followed by the creation of macroscopic areas of reduced luminescence intensity.

6456-06, Session 1

High-reliable, high-power AlGaAs/GaAs 808-nm diode laser bars

R. Hülsewede, H. Schulze, J. Sebastian, P. Hennig, M. Schroeder, J. Meusel, JENOPTIK Laserdiode GmbH (Germany)

There are strong demands in the market to increase power and reliability for 808 nm diode laser bars. To increase the number of applications the price per watt for mounted bars has to be reduced. One way is increasing the power, wall plug efficiency, reliability and brilliance of the bars itself.

JENOPTIK Diode Lab GmbH developed high performance 808 nm diode laser bars using the AlGaAs/GaAs material system with special emphasis to the long time stability.

Optimization of the epitaxial structure and -growth and improvements of the lateral structure results in a very high slope efficiency of >1.2 W/A at a low threshold current.

Including small serial resistance power conversion efficiencies up to 65 % for our 50 %, 30 % and 20 % filling factor 10 mm diode laser bars were measured.

With the JENOPTIK Diode Lab cleaving and coating technique the maximum output power (COMD-level) is 205 W in CW operation and 300 W in QCW operation (200 μs, 2 % duty cycle) for bars with 50 % filling factor.

These bars mounted on micro channel cooler showing a very high reliability of >10.000 h at an output power operation of up to 80 Watt.

6456-07, Session 2

Goals and status of the German national research initiative BRIOLAS (brilliant diode lasers)

F. G. Bachmann II, Rofin-Sinar Laser GmbH (Germany)

Optical Technologies have been recognised as pacemakers for modern technology, economy and society. Consequently, the German Federal Ministry of Education and Research (BMBF) has launched a funding program “Optical Technologies in the 21st century” in 2002, which covers a wide range of generation, control and application of photons. One of the initiatives implemented in this program meets the requirements of diode laser market, i.e. increase of brilliance and reliability of high power diode lasers. That’s why the initiative is named BRIOLAS - Brilliant Diode Lasers. Beginning 2004 ten projects are performed which cover a wide range of diode laser related questions: Basic studies for improvement of power, beam quality and lifetime of diode lasers form the central core of the initiative, but also diode laser applications for solid state laser pumping, for direct materials processing and even laser and system technology for medical applications and display technology are investigated. The presentation will provide an insight into the targets and the current status of the individual projects.

6456-08, Session 2

Recent advances in actively cooled high-power laser diode bars

N. P. Ostrom, S. D. Roh, D. M. Grasso, Nuvonyx Inc.

In order to meet the ever increasing demands of many high power laser diode customers, Nuvonyx has worked to improve a number of key metrics of the diode laser package. The most often challenged specifications are power per bar, efficiency, and reliability in both hard pulse and constant current mode. In response to these requests, Nuvonyx has worked to offer commercial component devices in excess of 100 and 150 watts per bar package in multiple colors. The packages are routinely combined to form single stacks that generate greater than 3.5 kilowatts each and two-dimensional arrays which produce in excess of 10 kilowatts. These parts all demonstrate predicted lifetimes in excess of 10,000 hours. The microchannel cooled heatsink has also been improved by closer matching the coefficient of thermal expansion of the cooler to the laser diode bar, which allows for harder solders such as gold-tin to be employed. All of this work has helped to meet the specifications of the most demanding laser diode customers.

6456-09, Session 3

Ongoing development of high-efficiency and high-reliability laser diodes at Spectra-Physics

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Laser diodes are critical components of high-power laser systems including diode-pumped solid-state (DPSS) lasers, fiber lasers, and optical amplifiers. Fundamental improvements to laser performance, especially power conversion efficiency (PCE), can have far-ranging implications, including lower cost and improved reliability and portability. Ultimately, these improvements could enable field-deployable laser systems operating in excess of 100 kW. Here we present recent advances at Spectra-Physics in next-generation, high-efficiency, high-reliability laser diodes (single-emitter devices and bars) in the wavelength range of 780-980 nm.

Ongoing optimization of epitaxial designs, MOCVD growth processes, and device engineering has yielded significant improvement in both PCE and reliable power, without compromising manufacturability in a high-volume production environment. The improvements are primarily driven by reductions in operating voltage and increases in differential quantum efficiency. For 9xx, 8-element laser bars with 100μm-wide emitters have

been operated at CW mode in excess of 148 W, corresponding to linear power densities at the facet above 185 mW/μm. With 2-mm-long devices operating 940 nm, PCE's of 71% and 69% have been achieved with single-emitter devices and bars, respectively. The low-loss structure has enabled the production of highly reliable single-emitter devices (100 μm stripe) that operate on conventional heat sinks at 8W CW with a PCE above 65%. Ongoing life-testing, in combination with stepped stress tests, indicate rates of random failure and wearout well below those of earlier device designs. The improvement achieved with 8xx materials will also be reported.

6456-10, Session 3

High-brightness semiconductor lasers

P. T. Rudy, J. E. Ungar, M. L. Osowski, R. M. Lammert, S. W. Oh, Quintessence Photonics Corp.

QPC has recently demonstrated high power semiconductor laser bars and single emitters at 808 nm, 976 nm, 1470 nm, 1532 nm, and 1550 nm that include an internal grating which provides feedback to narrow the linewidth, reduces the wavelength-temperature sensitivity, and ensures that the device operates at the desired wavelength. Performance and reliability data will be presented for high power single mode devices and well as multimode single emitters, barsd, and 2D arrays.

6456-11, Session 3

High-power single emitter 12xx-nm quantum dot lasers with 12W peak power and 36% power conversion efficiency suitable for medical and sensing applications

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Diode lasers supply high power densities at wavelengths from 635-nm to 2000-nm, with different applications enabled by providing this power at different wavelengths. As the range of available wavelengths broadens, many novel medical and atmospheric applications are enabled. Traditional quantum well lasers provide high performance in the range 635-nm to 1100-nm range for GaAs-based devices and 1280-nm to 2000-nm for InP, leaving a notable gap in the 1100 to 1280-nm range. There are many important absorption lines in this range corresponding to carbon-oxygen and carbon-nitrogen bonds found in amines, alcohols, ethers, carboxylic acids and esters. Here, quantum dots produced using Stranski-Krastanow self-organized MBE growth on GaAs substrates provide an alternative high performance solution. We present results confirming broad area quantum dot lasers can deliver high optical powers of 12-W per emitter and high power conversion efficiency of 36% in this wavelength range. We review the designs that deliver this performance, prospects for increased performance and the potential for using quantum dots as high power sources at other wavelengths.

6456-12, Session 3

High-brightness, high-power 9xx-nm diode laser bars: developments at JENOPTIK diode lab

J. Sebastian, H. Schulze, R. Hülsewede, P. Hennig, M. Schroeder, J. Meusel, JENOPTIK Laserdiode GmbH (Germany)

We report on present advantages of high power 9xxnm diode laser bars for pumping of disc laser and especially for pumping fiber lasers and amplifiers.

The strong demand for reduce system costs needs to have a good compromise in improved diode laser power, conversion efficiency, reliability and beam quality leading to a simplified system designs.

Basis of the new generation for the 9xxnm laser diode bars at JENOPTIK Diode Lab is a low loss waveguide AlGaAs - structure with low vertical far field angle of 27° (FWHM).

Recently we demonstrate an output power in excess of 500W in cw operation from a diode laser bar with 50% filling factor and 3.0mm cavity length. This record was possible due to both high power conversion efficiency of >68 % and a optimised facet coating technology and also a excellent p- and n-side active cooling.

New results on conductive cooled high brightness laser bars of 20% filling factor with special emphasis to the needs of high efficiency fiber coupling will be presented.

Lifetime tests under long puls conditions have demonstrated a very high reliability for 120 W laser bars with 50 % filling factor and for 60 W laser bars with 20 % and 30 % filling factor.

Especially for QCW applications a new very high power laser bar with 70% filling factor reaching the 1kW peak power level is under development.

6456-13, Session 3

High-power, high-efficiency laser diodes at JDSU

M. G. Peters, V. V. Rossin, M. P. Everett, E. P. Zucker, JDS Uniphase Corp.

Laser diodes and bars with high efficiency, power, and reliability are critical for a wide variety of applications including direct material processing and pumping high power and efficient fiber lasers and solid state lasers. High power applications require management of power loss and heat dissipation often with excess power and space wasted on cooling of the laser sources. High electrical-to-optical conversion efficiency of semiconductor laser sources could lead to new applications where space, weight and electrical power are critical. As part of its ongoing involvement in the development of potentially industry-changing advanced technology, JDSU has been working on the DARPA Super High Efficiency Diode Sources (SHEDS) project with the ambitious goal of 80% conversion efficiency 80W 940nm bars and 480W bar stacks. We present the record efficiency results of the JDSU SHEDS program. Elements of the SHEDS design were used in the development of next generation broad area 9XXnm laser diodes. Further optimization for high-power operation resulted in achievement of 18.5W CW rollover power for a 940nm laser hard soldered to a sub-mount.

6456-14, Session 3

8-W reliable operation of 808-nm broad-area diode lasers by near-field distribution control in a multistripe contact geometry

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Due to their high efficiency and relatively simple manufacturing process broad-area (BA) devices are the most important type of high power diode lasers. However, at high output powers wide stripe devices suffer from intensity spikes in the near field and a strong broadening of the far field distribution.

In this paper, we present results of 808 nm BA lasers consisting of multistripe ridge waveguide structures. The device structure is based on a GaAsP single quantum well which is embedded in a super large optical cavity waveguide structure (SLOC) grown by MOVPE. The SLOC structure reduces not only the facet load but also results in low values for the vertical divergence below 19° (FWHM). The devices were fabricated by standard BA technology extended by an additional reactive ion etching step to form multistripe ridges. The latter consist of 18 ridges with 4 μm width and 11 μm pitch. The lasers were mounted epitaxial side down on

conduction cooled packages with dimensions 25 x 25 x 7.6 mm3.

An output power of more than 16 W in continuous wave operation at a temperature of 15°C and more than 13 W at a temperature of 25°C were obtained. The slope efficiency and the maximum wall-plug efficiency were 1.1 W/A and 50%, respectively.

The lateral near field is homogenous over the single stripes. The lateral far field shows a Gaussian profile up to 8 W. The devices have been operated without failure at an output power of 8 W for more than 3500 h.

6456-15, Session 4

Scalable high-power (>1kW/cm^2) diode laser stacks based on silicon monolithic microchannel coolers

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We describe the performance and reliability of high power vertical diode stacks based on silicon monolithic micro-channel coolers (SiMMs) operating at >1000W/cm2 CW at 808 and 940nm. The monolithic nature of these stacks makes them inherently robust and compact. Typical emitting dimensions for a 10-bar stack are ~8.8mm x 10mm with CW output power up to 1.5kW. Originally developed at Lawrence Livermore National Laboratory and now actively being developed for commercial applications at Coherent, this technology offers several advantages over current copper-based micro-channel coolers. These devices do not require use of DI water, strict monitoring and control of the pH level, careful control of the water velocity, or sealed cooling systems. The need for hydrostatic seals is also drastically reduced. A typical ten bar stack requires only 2 o-ring seals, compared to 20 such seals for a similar stack using copper micro-channel cooling. Mature and readily available wet etching technology allows for cost effective batch fabrication of the sub-mount structure while achieving repeatable high precision components based on photolithographic fabrication processes

6456-16, Session 4

Novel high-peak current pulsed diode laser sources for direct material processing

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Diode laser systems are well established for applications which demand high cw power. These applications are material processing like cutting and welding of metals as well as polymers where diode laser systems are more inexpensive and compact than solid state lasers. Even though the optical output power and the beam quality of diode lasers are increasing steadily, the use of these sources is generally limited to cw applications. For processes where ablating of material is demanded, however, conventional diode lasers are inferior compared to pulsed solid state lasers as diode lasers suffer from the absence of optical intracavity q-switching. Some examples of these applications are coating removal and marking.

To overcome this drawback, we have developed several diode laser systems that use high peak-current drivers and thereby allow to operate the diode lasers at currents up to 500 A. The pulse source was tested with fiber coupled single emitters, conventional diode lasers and customized AR-coated diode laser bars. With the new diode laser driver, a peak output power of 500 W can be achieved with pulse durations of approx. 100 ns. Polarization coupling of two bars increases the power by a factor of two. Thereby an output power of 1 kW can be demonstrated. These systems reach an intensity of 2 MW/cm2 per diode laser bar which is sufficient for ablating processes. We will demonstrate the design of the prototype systems as well as the results of basic research investigating the emission spectrum, the output power and the state of polarization of the pulsed diode laser sources.

6456-17, Session 4

High-power, high-brightness 100-W QCW diode laser at 940 nm

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9xxnm high power diode laser are requested for pumping Yb-doped solid state lasers. In many cases high brightness is mandatory for fibre coupled pump modules.

In this paper, we demonstrate 100W QCW diode lasers having an aperture width of 1mm only, improving the brightness by a factor of 5...10 compared to commonly used bars. We used a super large optical waveguide structure to reduce the facet load and a resonator length of 4mm. The waveguide design results in a very small vertical divergence of 14° FWHM only. The threshold current is about 8A and the slope efficiency is 70%. The lateral far field width is below 10°, including 95% of power. At 100W peak power the wall plug efficiency is around 50%.

At the conference we will present results for aperture widths between 0.86 mm and 2mm and results from first life time tests.

6456-18, Session 4

High-power, high-brightness, high-reliability laser diodes emitting at 800-1000 nm

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Power, brightness and reliability are the three most sought-after performance characteristics of high power laser diodes for applications in solid-state/fiber laser pumping, medical, material processing and printing. Achieving all three performance characteristics in a device operating at wavelengths 800 -1000 nm presents a significant technical challenge.

We have developed a unique range of infra-red high power lasers using quantum well intermixing (QWI) technology that deliver extremely high optical power and high brightness with good reliability. A modified ridge-waveguide structure with integrated QWI non-absorbing mirror (NAM) slabs at both facets has been realized allowing light from the active region to diffract out into the passive facet region to achieve a high-power, high-brightness output with a good beam profile. The robustness of the QWI technology is demonstrated in broad-area laser devices at 800 nm and 830 nm by high CW and pulsed powers with power densities in excess of 120 mW/micron. A far-field reduction layer is incorporated into the epitaxy design to increase emitter brightness without affecting the device efficiency. The far-field reduction layer also improves the coupling efficiency into an optical system.

The QWI process prevents degradation of the laser facet giving good lifetime data for a range of 8xx nm laser emitters. The optimized devices will be integrated into array bars and stacks for use in high-power systems under CW and pulsed conditions.

In summary, we have realized broad-area laser diodes with QWI passive mirrors for high-power, high-brightness and high-reliability operation.

6456-19, Session 4

100-W+ diode laser bars show > 71% power conversion from 790-nm to 1000-nm and have clear route to > 85%

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Focused development under the DARPA SHEDs program has lead to

extremely high power conversion efficiency in the 9xx-nm wavelength band, leading to bars with efficiency in excess of 74%. We review progress in advancing efficiency and detail the route to > 85% at room temperature. The 9xx-nm wavelength band is commercially used for pumping Ytterbium-doped solid-state crystals and fiber lasers - only one of many diode laser markets. Fortunately, the lessons learned under SHEDs are transferable to other wavelengths. We report breakthrough efficiency results in the 8xx-nm band, for example showing 71% power conversion efficiency from 790-nm bars at powers > 100-W for CW and QCW packaging and testing. These wavelengths are required for pumping Neodymium-doped crystals, as used in the majority of fielded high power Diode Pumped Solid-State Laser systems. High efficiency is delivered using low voltage SHEDs designs, in combination with work to optimize the performance of the quantum well.

6456-20, Session 4

Increased power of broad-area lasers (808 nm/ 980 nm) and applicability to 10-mm bars

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Solid state lasers require high power QCW pump sources with a good cost efficency. Increasing the efficiency and a better treatment of facets are basics to improve power limits of any diodes.

This paper is therefore about high power laser diodes with 150µm emitter at 808nm and 980nm in a single, double and quad structure.

For the investigated materials and structures electro-optical characteristics and power limitations at different pulse-lengths and duty-cycles are shown.

As no COMD-limit occurred at any tested QCW-mode and any current, a thermal roll over effect has been revealed, but it also limited the reachable power. This effect protects the 808nm and 980nm laser from COMD at maximum power of light.

Power of about 30 W at 45 A was emitted out of single emitter chips of 808nm and 980nm wavelength.

With increasing number of emitters the level of maximum power increases by arithmetic progression. This facet treatment and material promise to get 1kW QCW optical power out of a single laser-bar of 808nm or 980nm.

6456-22, Session 5

11-kW direct diode laser system with homogenized 55x20 mm^2 top-hat intensity distribution

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In comparison with other laser systems diode lasers are characterized by a unique overall efficiency, a small footprint and high reliability. However, one major drawback of direct diode laser systems is the inhomogeneous intensity distribution in the far field. Furthermore the output power of current commercially available systems is limited to about 6 kW.

We report on a diode laser system with 11 kW output power at a wavelength of 940 nm aiming for customer specific large area treatment. To the best of our knowledge this is the highest output power reported so far for a direct diode laser system. In addition to the high output power the intensity distribution of the laser beam is homogenized in both axes leading to a 55x20 mm^2 top-hat intensity profile at a working distance of 400 mm. Homogeneity of the intensity distribution is better than 90%. The intensity in the focal plane is 1 kW/cm^2 .

The diode laser system is based on three main submodules. This modular approach allows the customization of the total output power as well as the customization of intensity profile and focus dimensions. The total output power can be varied from several watts up to 11 kW. The customization of the homogenization optics allows homogenization in one or two directions resulting in line, rectangular or quadratic illumination profiles.

We will present a detailed characterization of the laser system, including measurements of power, power stability and intensity distribution of the homogenized laser beam. In addition we will compare the experimental data with the results of nonsequential raytracing simulations, which are in good agreement with the experimental data.

6456-23, Session 5

High-brightness fiber coupled diode laser systems

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There are many advantages of delivering optical power from high power laser diode arrays through an optical fiber. However, most high power diode lasers require complicated optical trains in order to couple their light into a fiber because of the poor beam quality. Recently, Nuvonyx has reported implementations of the single spatial mode, high brightness laser diode bar technology that exhibits much improved beam quality. Optical power from the high brightness laser diode arrays is coupled into a 400 micrometer core fiber with a 0.22 numerical aperture at power density levels exceeding 1.4 MW/cm^2. These systems are suitable as standalone industrial direct diode laser systems or as multi-kilowatt fiber laser pump sources. Nuvonyx will present experimental results of further development in its fiber coupled diode laser systems program. Results of higher brightness from smaller fiber core sizes and wavelength stabilized operation will be discussed.

6456-24, Session 5

Efficient high-brightness diode laser modules offer new industrial applications

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Fibre-coupled diode lasers have become an established source for many industrial applications due to their high wall-plug efficiency, minimal maintenance and cost per watt. Most diode laser systems could not compete against CO2 or DPSSL in industrial application like marking or cutting due to the lower brightness. Recent developments in high-brightness diode laser bars and beam forming systems with micro-optics is leading to new direct diode laser applications.

We present newly developed high power diode laser modules which are performing at outstanding brightness and their applications. The combination of recently designed laser diode bars on passive heat sinks and optimized micro-optics results to laser modules up to 50W out of a 50µm fibre with a 0.22 NA at one single wavelength.

The fibre coupled systems are based on diode lasers with a collimated beam of superior beam data, namely < 10 mm x 10 mm beam diameter (FW1/e2) and < 2.3 mrad x 2.3 mrad divergence (FW1/e2). Such free beam diode lasers deliver 30 W or 60 W output power.

The applications for such laser diode modules varies from direct marking, cutting and welding of metals and other materials up to pumping of fibre lasers and amplifiers.

The presentation of the technology will show a path to scale high-brightness laser systems to higher power levels. The combination of different coupling techniques will increase the power of up to 400W from a 200µm fibre at one single wavelength.

6456-26, Session 5

Concepts for modular high-power diode lasers as line generators

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Concepts of new high power diode lasers are presented which are designed to generate specific lines optimized for various applications, e.g.

printing, illumination, annealing, drying, or welding. These diode laser systems are unique due to their brightness, homogeneity, modularity and redundancy.

Exceptional specifications are required for laser lines in many applications. Printing with computer to plate systems need small spot size variations, high homogeneity and very good line straightness. Multiple laser diode bar systems or stacks should be modular, redundant and long living. These high power applications are typically related to material processing.

Currently, high brightness systems are mostly based on solid state lasers with certain disadvantages. Mainly, the peak to valley homogeneity of such laser systems is limited in the range of 50-85% due to coherence effects.

LIMO presents recent approaches for laser diode line generators to cover a broad range of relevant parameters: homogeneity of 90% up to 98%, line width of 45µm up to 3mm, line length of 5mm up to 1m, a power of a few Watts up to multiple kilo Watts, intensities up to 200kW/cm(c)˜ and wavelengths of 808/915/940/980nm.

The key to these high end laser systems is beam shaping with LIMO micro optics. These micro optics enable diffraction limited beam shaping to conserve the beam parameter product and brightness of the laser diode for a small line width and a large working distance. Micro lens arrays are used for homogenizers of either only the long axis of the line or even both axese.

The concepts rely on a high degree of modularity. The separation into light source modules and beam shaping modules allows even the implementation of universally available fibre coupled diode lasers. Special approaches for scaling of output power and line length are discussed in detail.

6456-27, Session 5

An innovative technique for fiber-coupled diode laser arrays

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The current techniques to couple a diode laser array into an optical fiber involves either multiple optical elements in free space, or multiple optical fibers. A 3D Integrated Waveguide System (IWS), that transforms a set of horizontal diode lasers to a set of vertical diode lasers, has been fabricated on a glass substrate. The IWS was designed for a 1cm diode laser array with 19 elements, 150 microns wide, on a 500 micron pitch. Thus, the front of the IWS consists of 19 waveguides, 157 microns wide, on a 500 micron pitch. The back end of the IWS consists of 19 vertical waveguides. The core of each waveguide is 157x4 microns, with a cladding layer of 4 microns between adjacent waveguides. The total waveguide area at the back end is 157x160 microns. The dimensions of the IWS are: 12mmx20mmx4mm. The IWS was not AR coated, but it was wedged to avoid laser rippling. We have used an n-light 40W diode laser array on a Cs package, with 19 elements. The IWS was aligned between the Cs package, and a 0.22NA, 200 micron diameter fiber. The optical coupling efficiency was 50%. The surface of the IWS and the structure of the waveguides were not optimized for high efficiency. With the above optimization, we anticipate efficiencies of about 70%. The waveguide approach consists of a small single element, and can be modified to couple several diode laser arrays into one optical fiber.

6456-28, Session 5

Novel high-brightness fiber coupled diode laser device

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Brightness becomes more and more important in diode laser applications like fiber laser pumping and materials processing. For OEM customers fiber coupled devices have great advantages over direct beam moduls: the fiber exit is a standardized interface, beam guiding is easy, and flexibility is nearly unlimited. In addition to the transport function the fiber serves as homogenizer: the beam profile of the laser radiation emitted from a fiber is symetrical with highly repeatable beam quality and pointing stability.

However, efficient fiber coupling requires an adaption of the slow-axis beam quality to the fiber requirements. Diode laser systems based on standard 10mm bars usually employ beam transformation systems to rearrange the highly asymmetrical beam of the laser bar or laser stack. These beam transformation systems (prism arrays, lens arrays, fiber bundels etc.) are expensive and become inefficient with increasing complexity. This is especially true for high power devices with small fiber diameters. On the other hand, systems based on single emitters are claimed to have good potential in cost reduction. Brightness of the inevitable fiber bundels, though, is limited due to inherent fill-factor losses.

At Dilas a novel diode laser device has been developed, which combines the advantages of diode bars and single emitters: high brightness at high reliability with a single emitter cost structure. Heart of the device is a specially taylored laser bar (T-bar), which epitaxial and lateral structure was designed such that only standard fast- and- slow axis collimator lenses are required to couple the beam into a 200µm fiber. Up to 30 of these T-bars of one wavelenght can be combined to reach a total of > 500W ex fibre in the first step. Going to a power level of todays single emitter diodes even 1kW ex 200µm fiber can be expected.

6456-29, Session 5

Fiber-coupled laser diode modules with wavelengths around 2 µm

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For common laser diode modules, laser diodes with wavelengths between 800 nm and 1000 nm are used, but there are new applications, which demand for a wavelength of 2 µm.

The wavelength range around 2 µm is extremely interesting for different applications, like the processing of plastics, medical applications as well as environmental analytics. The interest in lasers with this wavelength is based on the special absorption characteristics of different types of material: Numerous plastics possess an intrinsic absorption at 2 µm, so that the use of additives is no longer necessary. This is of great value especially for medical-technical products, where additives require a separate approval. Furthermore the longer wavelength allows the processing of plastics which are clear and transparent at the visible. In addition water, which is an essential element of biologic soft tissue, absorbs radiation at the wavelength about 2 µm with a very high efficiency. As radiation of this wavelength can be guided by glass fibers, this wavelength is very helpful for laser surgery.

Currently used lasers at the spectral range about 2 µm are solid-state lasers based on Ho- and Tm-doped crystals. These systems suffer from high purchase costs as well as size and weight. In contrast to this, diode lasers can be built more compact, are much cheaper and provide a higher optical output power.

At the Fraunhofer ILT, two types of fiber-coupled laser diode modules based on laser bars with wavelengths around 2 µm have been developed, which can be used especially for laser surgery and the processing of plastics. One module uses laser diodes with a wavelength of 2 µm, and a second combines two wavelengths (980 nm and 1950 nm) for cutting and coagulation of biological tissue at the same time. The two modules are presented, and realized systems are described.

6456-30, Session 6

High-power distributed feedback laser bars and stacks with 60% power conversion efficiency

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Multimode, Fabry-Perot, semiconductor diode lasers emitting near 975

nm wavelength are of particular interest for pumping the upper transition states of Yb, Er and Yb/Er co-doped solid state lasers. In particular, the 975 nm multimode diode lasers are very attractive pump sources for co-doped, dual clad fiber lasers and amplifiers, especially in pulsed mode operation. At this pump wavelength, the quantum defect is minimal and the absorption cross-section is much higher relative to the 920 nm transition states. Hence, shorter gain fibers can be used to mitigate deleterious nonlinear effects such as the Stimulated Raman Scattering (SRS) and the Stimulated Brillouin Scattering (SBS). We report on the integration of a second-order Bragg grating inside a broad-area semiconductor laser cavity forming a low-loss, weak distributed feedback (DFB) laser, which results in record 60% wall-plug efficiency. Single emitters, bars and stacks have been fabricated with each emitter achieving 0.3 nm emission bandwidth and wavelength tuning coefficient of 0.07 nm/K. Applications of these pump sources along with performance and reliability of these laser diodes will be discussed.

6456-31, Session 6

Volume Bragg grating external cavity for grating coupled surface emitted laser diode

G. B. Venus, V. K. Rotar, L. B. Glebov, O. V. Smolski, J. K. O'Daniel, E. G. Johnson, College of Optics & Photonics/Univ. of Central Florida

The use of external resonators for improvement of spatial and spectral parameters of high power semiconductor lasers has been studied for last decades. Recently a successful the use of volume Bragg gratings (VBG) recorded in a photo-thermo-refractive glass for high efficiency feedback for semiconductor lasers was demonstrated [1, 2]. Due to high angular and spectral selectivity of such diffractive elements, wide stripe edge emitter laser diodes (LDs) placed in an external cavity produced by a VBG emitted a narrow line with near diffraction limited beam divergence in a wide interval of pumping current. Conversion efficiency of an external cavity laser exceeded 95% in comparison with efficiency of a free running LD. The proposed technique is applied to new type of wide stripe grating coupled surface emitted laser (GCSEL). The special construction of the 1st order non resonant output grating coupler suppressed undesirable back reflection in an internal LD cavity down to 10-4 and provided efficient stable operation of GCSEL in external cavity with highly selective VBG feedback. Narrowing of spatial and spectral characteristics of such devices are demonstrated and analyzed for different parameters of external volume Bragg cavity. Obtained experimental results show wide perspective of using such devices for high power semiconductor laser design.

1. G.Venus, A.Sevian, V.Smirnov, L.Glebov "High-brightness narrow-line laser diode source with volume Bragg grating feedback" Proc. SPIE, Vol.5711, 2005, p.166-176

2. G.Venus, V.Rotar, L.Glebov "Semiconductor 1.7 W Volume Bragg Laser with Divergence Close to a Diffraction Limit" CLEO, May2006, Long Beach, CA

6456-32, Session 6

Fiber coupled diode laser of high-spectral and spatial beam quality with kW class output power

C. Wessling, M. Traub, H. Hoffmann, Fraunhofer-Institut für Lasertechnik (Germany)

High optical output power in the multi-kW range from a fiber coupled diode laser can reach the beam quality of lamp pumped solid state lasers. Direct diode laser application as deep penetration metal welding becomes feasible. Polarization and wavelength multiplexing are established techniques to scale the optical power of diode lasers at almost constant beam quality. By use of volume diffraction gratings in an external cavity laser it is possible to constrict the spectral bandwidth of diode lasers and to reduce the wavelength shift related to temperature or current injection. Due to the stabilization of the wavelengths multiplexing of diode laser beams at small distance of the center wavelengths can be realized.

The development of a fiber coupled diode laser is presented. The set up consists of twelve modules which serve for an average optical power of 1.5 kW. Each module utilizes dense wavelength multiplexing of two diode laser bars with a center wavelength spacing of 3 nm. The diode laser bars are wavelength stabilized at center wavelengths of 908 nm, 911 nm, 975 nm and 978 nm. The spectral bandwidth of all diode laser bars is within 1 nm in the full power range. Stable operation at an average power of 136 W at 908/911 nm and 115 W at 975/978 nm with a wavelength shift less than 0.1 nm is achieved by the modules.

Further coarse wavelength and polarization multiplexing and beam transformation will enable fiber coupling with a beam parameter product of about 30 mm mrad.

6456-33, Session 6

Wavelength stabilization of HPDL array: fast-axis collimation optic with integrated VHG

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Volume holographic gratings (VHG) provide the capability of narrowing and stabilizing the wavelength of semiconductor lasers by forming an external cavity laser (ECL). The standard configuration of these ECL's is to use a collimating lens followed by the VHG to provide feedback to the resonator and lock the wavelength. In this configuration both elements have to be carefully aligned with tolerances in the sub-μm and mrad range. The present paper presents a fast-axis collimation lens (FAC) with integrated VHG for locking a laser diode bar. Besides the advantage of having only a single element, the integrated element is also less sensitive to alignment tolerances with respect to the locking due to the large divergence angle of the uncollimated array compared to a collimated array. Using a standard AR coated array with 19 emitters an output power of P = 67,2 W was achieved. The spectral bandwidth was within 1nm over the whole power range. Due to high stability requirements in this application, glass was chosen as the VHG material. Though the refractive index is low compared to standard FAC lenses, the manufacturing process of the lens still guarantees a diffraction limited collimated beam.

6456-34, Session 6

Mode selection and phase locking of sidelobe emitting semiconductor laser arrays using an external cavity with a narrow-bandwidth volume grating

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A novel phase locked array design, based on direct reflection feedback among adjacent cavities using an external grating, is analyzed and proposed. As a result of both longitudinal and transverse wavenumber selection, caused respectively by the narrow grating reflection bandwidth and by the array geometry, only one among the free running cavity eigenmodes can couple into a phase-locked, collective array eigenmode. The coupled array mode is experiencing the high reflectivity of the grating and surpasses the low gain of the free running modes, experiencing only a much lower reflectivity from the cavity edge mirror (anti-reflective coating). Thus phase locking and single mode operation can be concurrently achieved.

6456-35, Session 6

Wavelength-tunable narrowband high-power diode laser stacks based on volume Bragg grating(r) technology

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We present a novel approach to achieving both wavelength stabilization and wavelength agility in high-power two-dimensional stacks of high-power laser diodes. This approach utilizes volume Bragg gratings(r) with Bragg period that varies as a function of position within the clear aperture of the element according to a periodic function with period equal to the spacing between the laser diode bars within the stack. The Bragg period varies linearly within each period so that translation of the volume Bragg grating element results in simultaneous tuning of the wavelength of all the bars in the stack. As a result, the wavelength of the stack is adjustable, stable and the emission line is narrowed to < 0.5 nm. This kind of laser diode stacks is particularly suitable for pumping of gaseous media with very narrow absorption lines, e.g. atomic vapors of rubidium, cesium, potassium etc.

OCIS codes: (140.2020) Diode lasers; (140.2010) Diode laser arrays; (050.7330) Volume holographic gratings.

6456-36, Session 6

Splicing asymmetric reflective array for combining high-powered lasers

P. Palffy-Muhoray, Kent State Univ.; J. P. Fontana, Liquid Crystal Institute, KSU; B. Taheri, AlphaMicron, Inc.

A splicing asymmetric reflective array (S.A.R.A.) is an optical device that has the capability of combing at least two broadband, polarization-independent, incoherent light beams into a single beam. In particular, SARA relates to a high power laser beam combiner that receives multiple laser beams and combines them into one beam with minimal loss. This beam combining could be done intra-cavity or externally depending on the application. A cascade of arrays incorporating the array and reduced size arrays may be used to combine more than two input beams into one. A three-dimensional array which alters the slope of each layer's length dimension can be used to combine four input beams into one output beam. We report on the first generation of S.A.R.A, describing our experimental apparatus and present results for splicing together two plane-polarized, phase incoherent, monochromatic laser beams into a single output with minimal loss demonstrating the basic principles of the SARA element.

6456-37, Session 7

Elimination of deionized cooling water requirement for microchannel-cooled laser diode arrays

E. F. Stephens, R. Feeler, Northrop Grumman Corp.

Several new laser diode packages have been developed that utilize the power of microchannel cooling for high-powered laser applications. The design of these new packages eliminates the need for deionized water, thereby making the packages very suitable for industrial laser applications. The thermal performance of these new packages is shown to approach that of industry-standard microchannel-cooled packages. In-depth characterization data as well as diode array lifetime and corrosion data are presented for arrays cooled by non-deionized water systems.

6456-38, Session 7

Highly reliable hard-soldered 1.6kW QCW laser diode stack packaging platform

P. K. Rosenberg, P. Reichert, S. Tolman, Coherent, Inc.

We describe the performance and reliability of multi-bar diode stacks assembled with hard solder attachment of the laser diode bar to the conduction-cooled package substrate. The stack package design is based on a modular platform that makes use of common piece parts to incorporate anywhere from 2-16 bars, operating at peak power of 100W/bar. In assembling diode stack packages, it is typical to use a soft solder material such as indium for P-side bar attachment into the package. Due to its low melting point and low yield stress, indium can provide a solder joint that transfers low stress to the laser bar. However, during QCW operation, indium is prone to migration that can cause device failure due to a number of well-known mechanisms. This shortcoming of soft-solder bar attachment can limit the number of shots the stack delivers over its operating life. By replacing the soft solder typically used for P-side attachment with a hard solder, it is possible to greatly reduce or eliminate certain failure modes, thereby increasing the operating life of the part. We demonstrate lifetime of > 1E9 shots (90% CL), at 80 W/bar, 250 usec/40 Hz pulses, and 50C package operating temperature.

6456-39, Session 7

Stackable air-cooled heatsinks for diode laser bars

T. R. Crum, J. Harrison, R. Srinivasan, R. L. Miller, Spectra-Physics Semiconductor Lasers

Micro-channel heatsink assemblies made from bonding multi-layered patterned metal sheets are commercially available and are often used for removing the high waste heat loads generated by the operation of laser diode bars. Typically, a laser diode bar is bonded to a micro-channel heatsink then stacked in an array to create compact high power diode sources for a multitude of applications. Under normal operation, the diode waste heat is removed by passing coolant (typically de-ionized water) through the channels of the heatsink. Because of this, the heatsink internal structure including path and overall channel size is dictated by the liquid coolant properties.

Due to the material characteristics of these conductive heatsinks, and the electrically serial stacking geometry, there are several restrictions imparted on the coolant liquid to maintain performance and lifetime. For best reliability, such systems require maintenance of both the conductivity and the PH of the coolant (e.g., de-ionized water), along with suitable particle filtration. In addition, the system components themselves may be drawn from a limited set of materials (e.g., plastic, stainless steel). These requirements often translate into undesirable cost and bulk, restricting their use in applications where minimal weight-to-power ratios are desired.

In this paper, we will demonstrate a novel modular stackable heatsink optimized for use with gaseous coolant that, in some applications may replace the existing commercially available water-cooled heatsink technology. We will demonstrate the various benefits over the existing available coolers while maintaining existing mechanical form factors and packing densities. We will also show thermal-fluid modeling results as well as operational performance curves for efficiency and power and compare these data to the existing commercially available technology.

6456-40, Session 7

Next generation of cooling approaches for diode laser bars

M. Leers, C. Scholz, K. M. Boucke, Fraunhofer-Institut für Lasertechnik (Germany)

The field of applications for diode laser bars is growing continuously. The

reasons for this are the growing width of available wavelengths and the increasing optical output power. In parallel to this the requirements for packaging for the high power diode laser bars increase and are more manifold. Expansion matched, non corrosive, non erosive, low thermal resistance and high thermal conductivity are some of the keywords for the packaging in the near future.

Depending on the thermal power density, two different types of heatsinks are used: active and passive. The active heat sinks can further be subdivided in micro- or macro-channel heatsinks.

The development of macro-channel heatsinks was necessary because of the limited life time of the common micro-channel heatsink. Especially erosion and corrosion effects are reduced by the bigger channels. By taking the increasing resonator length of the laser bars into account the cooling performance of the macro channel heatsink will be in many applications sufficient. In cases of high power loss densities there are still no alternatives for micro-channel heat sinks. New material combinations shall minimize the erosion and corrosion effects.

New raw materials like diamond composite materials with a higher thermal conductivity than copper and matched thermal expansion will find their working field at first in the passively cooling of laser bars. The next generation of active heatsinks will also be partly made out of the high performance materials. The point of time of this improvement depends on machining behavior, availability and price of the raw material.

6456-41, Session 7

Monolithically stacked high-power diode laser bars in quasi-continuous-wave operation exceeding 500 W

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In this paper we report on quasi continuous wave (q-cw) operation of monolithically stacked laser diode bars. Monolithically stacked laser diode bars consist of more than one laser diode grown on top of each other. In between every two laser diodes a tunnel junction is included to ensure proper current injection to all lasers.

In comparison to a standard laser operated at the same optical power level, the monolithic laser stack has a significantly reduced optical mirror load. Furthermore the required current is reduced drastically, which has positive consequences on both laser lifetime and diode driver costs. If one otherwise compares a monolithic integrated laser bar stack with a setup of three separate standard laser bars, the monolithic laser bar stack is characterized by very low costs per watt as well as a high brillance.

By using monolithically stacked laser diode bars we were able to exceed an optical power of 500 W in q-cw mode and are moving to even higher output levels. Typical wavelengths are in the range between 800 and 1000 nm.

6456-42, Session 7

Highly efficient and reliable 1 kW QCW laser stacks with diffraction limited fast axis beam collimation

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808 nm, QCW laser bars delivering peak power higher than 150 Watts were developed. The optimization of the tensile strain in the QW structure, the design configuration of the laser cavity together with an improved packaging technology lead to more than 55% wall plug efficiency when assembled as stacks . Due to the high characteristic temperature (T0, T1) values and high efficiency, the output power of these devices is almost insensitive to elevated heat sink temperatures. In addition, a collimation technique which significantly improves the beam quality of the laser stacks was developed. The active collimation method is flexible and allows for the control of different collimation requirements. The use of this collimation technique alongside with high quality microlenses allows for a reduction of the fast axis divergence to values as low as 3 mrad with minimal power losses. An automatic process control was developed allowing for the efficient attachment of the collimating microlenses in a highly reproducible fashion. The combination of the collimation technique with a reliable mounting and stacking technology supports the serial manufacturing of devices delivering 1 kW peak power in QCW operation. These QCW collimated diode laser stacks demonstrate stable operation and high reliability in the course of more than 6*108 shots at 2 % duty cycle. Another important advantage of the collimated stacks is their capability to withstand severe environmental conditions, maintaining high beam quality and performance.

6456-43, Session 7

Next-generation active and passive heatsink design for diode lasers

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Successful thermal and stress management of edge-emitting GaAs diode lasers is key to their reliability and performance in high-power operation. In addition to the optimization of epitaxial structures and die-fabrication processes, next-generation active and passive heatsink designs are required to achieve the performance demands of emerging applications. In this paper, we detail the development of both active and passive CTE-matched heatsinks with low thermal resistance, AuSn bonding and improved manufacturability. Examples of high-power device performance achieved with the new heatsinks are included in the presentation.

Among the designs are an active, mini-channel heatsink with a CTE of 6.6ppm/C and a thermal resistance of 0.43 C/W for a 30% fill-factor, 2mm cavity-length diode laser bar. The water flow in the heatsink is isolated from the electrical potential, eliminating the possibility of electrolytic corrosion. An additional feature of the integrated design is the reduction in required assembly steps.

Our next-generation passive CTE-matched bar heatsink employs a novel design to achieve a reduction of 16% in thermal resistance (compared to the predecessor product). CTE's can be engineered to fall in the range of 6.2-7.2 ppm/C on the bar mounting surface. Comparison of simulated and experimental data (both in cw and long-pulse operation) will be presented for several new heat-sink designs.

6456-52, Session 7

Active microcooler with matched CTE

T. Ebert, IQ Evolution GmbH (Germany)

New technology regarding manufacturing of micro cooling systems and selective laser melting was presented at Photonics West 2005; at Photonics West 2006 the first non-corrosive active micro coolers manufactured by this procedure were introduced to the auditorium. This presentation shows the latest results regarding active micro cooling systems for high power diode laser with a matched CTE.

After the first non corrosive micro coolers passed the tests regarding cooling performance, there were still two tasks which had to be accomplished: First one was the homogeneity of cooling. In order to achieve the homogeneity, the design of the supporting structure in front of the micro cooling structures was modified. Measurements of cooling performance and the range of the wavelength along the laser bar showed that with the modified structure a homogeneous inflow was achieved as well as homogeneous cooling along the laser bar. The presentation highlights the measurements and results. Second point of development was the quest for a material combination with an adequate thermal conductivity for keeping the cooling performance, but with a coefficient of thermal expansion that matches with the CTE of diode laser bar material. After testing several materials fitting to these requirements, only one material was left, which

was capable to machine workable micro coolers with the SLM procedure. The presentation contains the first results of the micro coolers with a matched CTE regarding thermal resistance, CTE and packaging with gold - tin solder.

6456-44, Poster Session

Pulsed tapered diode lasers

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Tapered lasers have proven their ability to generate high continuous wave output powers on the order of Watts with near diffraction-limited beam quality. For some applications, pulsed mode operation may be required. In the present study, we investigate the fundamental properties and behavior of tapered lasers under current-pulsing conditions.

For the investigation, the following structures are used: 4-mm single quantum well (SQW) tapered lasers with a super large optical cavity structure are realized with different geometries (lengths of ridge waveguide and tapered sections, flare angle of tapered section). The lasers are nominally 2 W at 3 A in continuous wave. Pulsed operation of these tapered lasers in the 810 nm spectral region is demonstrated. The pulsed output characteristics of lasers with six different physical geometries are presented and compared with continuous wave operation. Peak powers approaching 20 W are obtained with a pulse length of 100 ns at a repetition rate of 1 kHz. The slope efficiency of most of the lasers is approximately linear and above 1 W/A up to the highest output powers. Broadening of the output spectrum of the lasers is observed when high currents are applied. Investigation of the spectral variation across the laser near field is conducted. At low currents (<4 A) the beam quality of the pulsed lasers is observed to be comparable to continuous wave operation. Beam quality degradation under pulsed conditions is observed at high currents. For applications such as frequency doubling, where high peak power would increase efficiency, our investigation demonstrates that additional precautions have to be taken, i.e., either Bragg grating or external cavity designs should be employed in order to stabilize the output frequency.

6456-46, Poster Session

Lifetime testing of laser diode coolers

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The purpose of this paper is to report life-testing results of copper microchannel laser diode coolers. The testing is being done on coolers with 3 different internal designs at three different flow rates, ranging from 0.2 l/min. to 0.5 l/min. Water conductivity is kept constant at 5 microSiemens/cm, and the water temperature is maintained at 25C. The coolers do not have a voltage applied to them. The test is ongoing, but results up to 15,000 hours will be reported. Preliminary results indicate that lifetimes over 20k hours can be achieved with proper control of conductivity, and that flow rate and internal structure are secondary considerations compared to water quality. Also included is a comparison to other water coolers.

6456-47, Poster Session

Photosynthetically supplemental lighting for vegetable crop production with super-bright laser diode

Y. Hu, P. Li, J. Shi, JiangSu Univ. (China)

Although many artificial light sources like high-pressure sodium lamp, metal halide lamp, fluorescent lamp and so on are commonly used in horticulture, they are not widely applied because of the disadvantages of unreasonable spectra, high cost and complex control. Recently new light sources of light-emitting diode (LED) and laser diode (LD) are becoming more and more popular in the field of display and illumination with the improvement of material and manufacturing, long life-span and increasingly low cost. A new type of super-bright red LD (BL650, central wavelength is 650 nm) was selected to make up of the supplemental lighting panel, on which LDs were evenly distributed. Driving circuit was designed to power and adjust light intensity. System performance including temperature rise and light intensity under different currents and vertical/horizontal distance were tested. Photosynthesis of sweet pepper and eggplant leaf under LD was measured with Li-6400 to show the supplemental lighting effects. The results show that LD system can supply the maximum light intensity of 180 μmol/m2•s at the distance of 50 mm below the panel and the temperature rise is little within 1 ºC. Net photosynthetic rate became faster when LD system increased light intensity. Compared with sunlight and LED supplemental lighting system, LD promotion on photosynthesis is almost the same. Thus it is feasible for LD light source to supplement light for vegetable crops. Further study would focus on the integration of LD and other artificial light sources.

6456-48, Poster Session

Reliable operation of 785-nm DFB diode lasers for rapid Raman spectroscopy

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Long term wavelength stable light sources are most important for Raman spectroscopy. 785 nm is a commonly used wavelength for diode laser based light sources.

Here we will present DFB diode lasers emitting at 785 nm which opens up miniaturised long term stable high power excitation sources for Raman spectroscopy.

A DFB RW diode laser reaches at T = 30°C an optical output power of P = 150 mW at I = 250 mA. At this output power optical spectra of the DFB RW laser exhibiting a longitudinal single mode operation with a side mode suppression ratio of more than 45 dB. A reliable operation over more than 4500 hours will be demonstrated which open new fields for DFB RW lasers emitting at 785 nm in e.g. industrial and medical applications.

To reduce the integration time in Raman measurements a 785 nm DFB BA laser with an optical output power of more than 1 W was used as a high power excitation light source. Optical spectra measured up to 1.1 W reveal that more than 99 % of the laser power are contained within 0.6 nm corresponding to a spectral resolution of 10 cm-1 of commonly available Raman spectroscopic setups.

For Raman measurements of polystyrene we reached an integration time of 50 ms. This demonstrates the potential of high power DFB-BA diode lasers emitting at 785 nm for rapid Raman spectroscopic applications e.g. in sensors for process monitoring.

6456-49, Poster Session

High-power, high-brightness transmission through SMA-based fiber cables

T. A. Trebst, F. Schuberts, CeramOptec GmbH (Germany)

The transmission of high-power high-brightness laser sources through fiber cables requires specific designs of such cables. Two developments in recent years have let to increased demands. Firstly, the increase in power of diode laser bars has let to a demand for fiber cable transmission lines equipped with SMA-connectors but suitable for the increased power levels. Furthermore, stripping of residual claddings modes is frequently required. Secondly, applications of low-divergence laser sources such as Nd:YAG usually require tight focussing, thus maintaining the low-divergence in transmission lines with standard NA of 0.22 has become a pre-

requisite for these applications.

Specific fiber designs and a corresponding construction of the SMA-connectors address these needs. Typical examples will be presented.

6456-50, Poster Session

Dynamics of thermo-optical properties of semiconductor lasers

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The thermal behavior is an important characteristic for achieving optimal performance of pulse-operating semiconductor diode lasers. Especially, temperature of the p-i-n junction in the active region plays a critical role in proper work of these lasers. Therefore, electrical and optical parameters like threshold current, output optical power, and wavelength of oscillating modes are strongly dependent on junction temperature. Additionally, knowledge of the temperature distribution is significant in the integration processes and packaging design.

A technique of time-resolved laser spectra mapping, that allows measuring laser mode spectral characteristic for an arbitrarily selected moment within the pulse duration time, has been developed to assess thermo-optical properties of pulse-operating diodes. The broad contact lasers as well as external cavity lasers (ECL) were investigated. The devices were based on MBE grown InGaAs/GaAs SCH SQW heterostructures designed for room temperature emission at 980 nm. The broad contact p-type down lasers were mounted on a CVD Diamond heat sink.

Using time-resolved laser spectra mapping technique the emission spectra of the lasers were measured for consecutive chosen intervals within the pulse duration time. The emitted wavelength was found to be highly dependent on the time elapsing from the pulse start. A temperature shift of wavelength was clearly observed in the laser spectra map collected. A cross-section at the chosen time provided an extracted laser spectrum at the particular moment. The temperature increase of this region could be determined from the displacement of the center wavelength in the spectrum towards longer wavelength. The value of the temperature determined has been compared with the ones calculated from the Finite Element Method applying theoretical model proposed by Joyce and Dixon.

6456-51, Poster Session

High-power, highly reliable single emitter laser diodes at 808 nm

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High power laser diodes emitting at the wavelength of 808nm are widely used for pumping neodymium (Nd+) doped solid state lasers and fiber lasers, medical surgery, dental treatment and material processing. The applications demand the lasers can be operated reliably at high power. In general, the power is limited by catastrophic optical mirror damage (COMD) and heat dissipation. In this paper we present high power broad waveguide laser diodes at 808 nm with 400 mm aperture using InAlGaAs/AlGaAs/GaAs material system grown by MOCVD. Over 29W CW operation has been demonstrated mounted on a copper heat sink using indium solder with cavity length of 2 mm. The L-I curve rolles over at 29.5W, but the laser is still alive, and we can repeated test it again and again without catastrophic optical mirror-damage (COMD).

By optimizing broad wavelguide laser structure and doping profile, we achieved high efficiency, low vertical divergence angle, and good temperature characteristics under CW operation. With 2000 mm cavity, threshold current and slope efficiency are 1.5 A and 1.26 W/A, respectively; vertical divergence angle is 33 degree. A group of eleven devices were used for long term aging test at heatsink temperature of 50 °C under constant current of 12A, which is about 11W optical output power. The devices used for long-term aging have passed 100 hours burn-in under 12A at 50 °C. The estimated lifetime for these laser diodes would be over 100,000 hours for 10W CW operation at 25 °C. L-I-V, Ith, slope efficient, and far field are measured and studied as well.

6456-53, Poster Session

23-mW tunable diffraction limited light at 488 nm by frequency doubling of a broad-area diode laser using PPLN

A. Jechow, R. Menzel, Univ. Potsdam (Germany)

The laser system is based on second harmonic generation of a broad area laser diode and provides 23.2 mW of diffraction limited light with narrow bandwidth. It is tunable from 487.4 nm to 489 nm. The broad area laser diode is frequency stabilized in an external cavity that yields 800 mW of diffraction limited light. This infrared light is converted into the blue by use of a 1 cm PPLN bulk crystal with a conversion efficiency of up to 3.6 %/Wcm.

The setup depicted in Fig. 1 consists of a broad area laser diode in an external cavity driving a PPLN bulk crystal for second harmonic generation. The broad area laser diode is frequency narrowed and stabilized by a diffraction grating in a Littrow configuration in combination with a telescope of lenses L1 and L2 and a slit aperture.

To maintain optimal focusing parameters for the PPLN crystal an astigmatic correction by two crossed cylindrical lenses L3 and L4 is necessary. By tilting the grating and changing the PPLN temperature it was possible to tune the laser wavelength about 1.5 nm around 488 nm (Fig 3). Fig. 2 shows the output power behind the PPLN crystal as a function of the infrared pump light for different temperatures. The beam quality was better than $M(c)^{\sim} = 1.35$ for all cases.

6456-54, Poster Session

Welding laser hosted on a THS

M. Checchetti, Microptronics Srl (Italy)

The forced air Turbo Heat Sink / THS, an effective cooler for electronics, handles large energy flows. Its integral optics compacts the system. AlN, a ceramic, sports low TCE and high thermal conductivity; the deep, curved air-cooling channels are milled before firing; later, grinding forms a mounting plane with more groves to automate assembly. The AlN THS is available ??300mm.

The mounting plane solders directly, well spaced, the LDs, single channel or bars, and the electronics. A direct LDs mount at low density cuts the thermal losses to extend life; the hotter dices fit the rim. A μProcessor with IOs programs currents and timings; logs temperatures and powers; balances ageing.

Shallow groves, semi-kinematics elements and the window position the coupling optics. Few shared elements bend each divergent beam, moderately elliptical, large as possible. Finally, a common large mirror focuses all the beams; a MOPA configuration can boost accuracy.

The AlN THS and the parallel grooves position the optical shapers on a matrix; this orthogonal order fits cheap assembly methods and parts.

The selfstanding system sports consistent specific powers and can integrate more EO functions to automate welding etc.

Current Problems & Answers

P1. The current LDs mounting and cooling solutions are quite complex & an upgrade seems unlikely.

A1. In most cases, the above fits the assembly of raw LDs using a traditional pick and placer.

P2. The Edge Emitting / EE LDs, single or striped, are astigmatic while the lasing line is oriented poorly for a proper collective coupling with the following stage, lasing or plain FO, focusing etc.

A2. The fit can improve only spacing better the sources.

P3. Plain tap-water is not free and soon spoils those expensive μ-channel assemblies. Once assembled and instrumented, a bulky chillier or an heat exchanger costs more than the machine.

A3. Air is our only nearly infinite heat sink. The self-contained THS, a full fledged turbo machine, eases breathing from a surely cool, clean and dry region than discharging the warm air where safe.

P4. The industry needs lots of Lasing power and will need more and more. This trend includes very fast pulses, more narrow-band??, better integration with electronics and the surrounding world.

A4. A ceramic THS can be fairly large while a HMW-THS has no practical power limits.

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6457A-01, Session 1

Overview of the inter-orbit and the orbit-to-ground lasercom demonstration by OICETS

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OICETS is an engineering test satellite developed by Japan Aerospace Exploration Agency (JAXA) to carry out laser communication experiments. It was launched into low earth sun-synchronous orbit in August 2005. The functions of the satellite systems had been checked for first three months, and the acquisition and tracking of stars and planets was successfully performed. On December 9, 2005, the first bi-directional laser communications link between the OICETS and European Space Agency's geostationary satellite ARTEMIS was successfully established. The inter-orbit laser communication demonstration was successfully conducted over a period of six months since December 2005. We performed the experiment 90 times or more. Acquisition sequence, tracking performance and bit error characteristics were measured and evaluated. These results show the acquisition probability is more than 90% and the bit error rate are less than 10E-6. Additionally, the orbit-to-ground laser communication demonstration between the OICETS and the two ground stations, which are 1.5m-ground station of the National Institute of Information and Communications Technology (NICT) and a transportable ground terminal of German Aerospace Center (DLR) were successfully conducted in March 2006 and June 2006 respectively. OICETS had to change its attitude to carry out the orbit-to-ground laser communication. It forced very special satellite operation for success. These demonstration results indicate the possibility of establishing laser communication between the low earth orbit satellites to ground station.

The author presents overview of these demonstration progresses and results.

6457A-02, Session 1

Homodyne BPSK-based optical inter-satellite communication links

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Homodyne BPSK (binary phase shift keying) has distinct advantages compared to other optical modulation schemes, e.g. higher sensitivity and higher immunity against sunlight. Today, homodyne BPSK has been verified as a reliable technique for space applications. A free-space link through the atmosphere of 5.625 Gbps verified across 142 km demonstrates the robustness of the optical phase locked loop. June 2006 the first homodyne BPSK based laser communication terminal was delivered for in-orbit verification on the German LEO-satellite TerraSAR-X. With a second laser communication terminal to be delivered autumn 2006 an inter satellite link between NFIRE, a US LEO satellite and TerraSAR-X will be established in 2007.

The presentation summarizes the status of the in-orbit verification program and the laser communication terminals' performance and gives an outline of further activities planned.

6457A-03, Session 1

Results of the optical downlink experiment KIODO from OICETS satellite to Optical Ground Station Oberpfaffenhofen (OGS-OP)

N. Perlot, M. Knapek, D. Giggenbach, J. Horwath, M. Brechtelsbauer, DLR Standort Oberpfaffenhofen (Germany); Y. Takayama, T. Jono, Japan Aerospace Exploration Agency (Japan)

Optical LEO-downlink experiments from the Japanese OICETS to the optical ground station built by the German Aerospace Center (DLR) near Munich have been performed. This was the first optical LEO-downlink on European grounds. The ground station received a 50-Mbit/s OOK signal at 847 nm on its 40-cm Cassegrain telescope and sent two spatially displaced beacon beams towards OICETS. Five out of eight trials could be performed successfully while the other three were hindered by cloud blockage. A BER of 10-6 has been reached. The elevation angle above the horizon ranged between 2° and 45°. The Fried parameter and the scintillation were measured with instruments inside the ground station. The beacon power received by the LUCE Terminal onboard OICETS has also been recorded. This paper describes the setup of the experiment and highlights the results of the measurement trials.

6457A-04, Session 1

Multichannel high-data-rate optical transmission between ground and airborne platforms

D. W. Young, J. C. Juarez, J. E. Sluz, R. M. Sova, Johns Hopkins Applied Physics Lab.; J. Phillips, D. Driver, A. McClarin, AOptix Technologies, Inc.

This paper describes the results of an experiment where a Free-Space Optical (FSO) communications link was established between a ground terminal and an airborne terminal on a tethered aerostat. In the first part of the experiment, four 10 Gb/s WDM channels were transmitted from the aerostat to the ground terminal, demonstrating error-free performance over many 5 minute windows. In the second part of the experiment, both one and two WDM channels, each running at a native 40 Gb/s rate, were transmitted over the FSO link, demonstrating error free performance over short (30 second) timeframes, and bit error rates in the 10-6 range over longer term operation. During all tests, a 1 Gb/s optical Ethernet channel was run on a separate WDM channel. The paper will describe the test configuration as well as the results when running both single and multiple channels. The impact of the data rate as well as modulator design used for this application on the link integrity will be analyzed and discussed. It was found that the spatial dynamics of the aerostat as a function of time of day had an impact on the quality of the link - this will also be discussed. Modeling of potential penalty sources will also be provided, with comparisons made to data taken during the experiment.

6457A-05, Session 1

OPTEL terminal for deep-space telemetry links

G. C. Baister, Contraves Space AG (Switzerland)

Contraves Space AG is currently developing the OPTEL family of optical communications terminals. The optical terminals within the OPTEL family have been designed so as to be able to position Contraves Space for future opportunities open to this technology. These opportunities range from commercial optical satellite crosslinks between geostationary (GEO) satellites, deep space optical links between planetary probes and the

Earth, as well as optical links between airborne platforms (either between the airborne platforms or between a platform and GEO satellite).

For optical links between GEO satellites two OPTEL terminals have been developed together with ESA. A short range OPTEL terminal has been developed to provide the links between co-located GEO satellites whilst a medium range OPTEL terminal has been developed that can provide crosslinks (typically with up to 25'000 km link distance) between geostationary communication satellites carrying either conventional transparent Ku-band payloads or regenerative digital payloads.

The OPTEL terminal for deep space applications has been designed as an integrated RF-optical terminal for telemetry links between the science probe and Earth. The integrated architecture provides increased TM link capacities through the use of an optical link, while spacecraft navigation and telecommand are ensured by the classical RF link. The optical TM link employs pulsed laser communications to achieve robustness on the link to atmospheric degradation at the optical ground station.

The final OPTEL terminal provides communications links between airborne platforms. A prototype terminal has been developed for stratospheric links between high altitude platforms (HAPs). This OPTEL terminal operates at 1550nm technology and employs a robust acquisition and tracking concept to compensate for the atmospheric turbulence that contribute considerable fade statistics for the link.

This paper will present an overview of the space based and airborne system architectures that the Contraves Space family of OPTEL terminals have been designed to support and will focus on recent developments of the novel technologies and concepts needed for deep space communications links such as pulsed laser communications and robust acquisition and tracking concepts.

6457A-06, Session 2

Tracking and pointing characteristics of OICETS optical terminal in communication demonstrations with ground stations

Y. Takayama, National Institute of Information and Communications Technology (Japan); T. Jono, Japan Aerospace Exploration Agency (Japan); M. Toyoshima, H. Kunimori, National Institute of Information and Communications Technology (Japan); D. Giggenbach, N. Perlot, M. Knapek, DLR Standort Oberpfaffenhofen (Germany); K. Shiratama, NEC TOSHIBA Space Systems, Ltd. (Japan); J. Abe, Space Engineering Development Co., Ltd. (Japan); K. Arai, Japan Aerospace Exploration Agency (Japan)

The in-orbit laser communication experiments have been performed since the successful launch of the Optical Inter-orbit Communications Engineering Test Satellite (OICETS) on 23rd August 2005. We have carried out several kinds of laser communication demonstrations using the Laser Utilizing Communications Equipment (LUCE) of OICETS such as the inter-satellite laser communications with European Space Agency's geostationary satellite ARTEMIS, the ground-satellite communications with the 1.5m-ground station of the National Institute of Information and Communications Technology, and the ground-satellite communications with the transportable ground terminal of German Aerospace Center. Those trials enabled us to obtain valuable experiences and important data for further studies on the optical link qualities, the terminal characteristics, and the atmospheric effects on the communication channels.

The major differences in experimental conditions between the ground-satellite experiment and the inter-satellite demonstration are that the ground-satellite experiment is performed in much shorter distance between two optical terminals and that it is affected by the distortion of light due to the atmosphere. Therefore, we have chances to observe different performance characteristics of LUCE led by the ground-satellite experiments. For instance, the angular movement of the optical terminal in the ground-satellite communications is required to be faster than that in the inter-satellite experiments. Such a rise in the angular velocity of the terminal's movement causes to increase the tracking and pointing errors.

In this work, we present the LUCE's functional characteristics observed during the ground-satellite communication experiments. We especially focus on the tracking and pointing characteristics of LUCE based on some measured data.

6457A-07, Session 2

Communications system performance via an optical-phased array

C. W. Hindman, P. Collier, Air Force Research Lab.; J. P. Hunt, Schafer Corp.; S. L. Lacy, R. L. Moser, S. B. Alejandro, Air Force Research Lab.

Optical Phased Arrays (OPAs) have been proposed as key elements in future free-space laser communications systems for beam-steering applications due to their perceived SWaP and operational advantages over mechanical beam-steering devices. To assess the suitability of using OPAs for these applications, a laboratory experiment was conducted by passing high data rate (>1 Gbps) communications signals through a Boulder Nonlinear Systems OPA while changing phase profiles were actively being written to it. The time-varying power levels, eye diagrams and bit error rate tests were recorded at various input power levels and delta phase changes to characterize the OPA's performance. It was found that this OPA could be used for high data rate communications provided certain performance limits were not exceeded.

6457A-08, Session 2

Hybrid beam steering system for laser communication between mobile platforms

V. V. Nikulin, Binghamton Univ.; D. J. Nicholson, Air Force Research Lab.

For many practical needs, laser communication systems must support operation between mobile platforms. Engineering robust links; however, will depend on several innovations. In particular, successful pointing, acquisition, and tracking (PAT) require the use of a beacon signal and the capability of accurate and agile alignment of the line-of-sight (LOS) between the communicating terminals performed over a large field of regard. While mechanical devices, such as gimbals, offer relatively slow tracking over a very wide range, they lack in pointing bandwidth necessary for rejecting high frequency vibrations and beam deflection caused by the optical turbulence. In contrast, fast steering and especially non-mechanical devices, such as Bragg cells, enjoy very high bandwidth (on the order of several kHz), but their effective range is very small. Inherent limitations of both gimbals and fast steerers result in shortcomings of the entire PAT system when either of these devices is used as a sole beam steerer. Therefore, focus needs to be shifted to hybrid architectures, exploiting the advantages of the constituting elements. This paper demonstrates a system combining a robotic manipulator with two acousto-optic cells and presents the algorithm development and the simulation results.

6457A-09, Session 2

Earth image tracking in the long wave infrared for deep-space optical communications: feasibility study based on laboratory emulator

Y. Chen, J. Charles, H. Hemmati, Jet Propulsion Lab.

No abstract available

6457A-10, Session 2

Beam tracking system for a high-speed optical link

A. E. Dudelzak, A. S. Koujelev, Canadian Space Agency (Canada)

Optical communications involving moving parties require precise beam pointing and mutual tracking of communicating transceivers. The concept, design approach, and laboratory test results of optical tracking system for a demonstration of a Gbps-level free-space laser communicator are presented. The work objective has been development of a low-orbit satellite payload for high-speed optical intersatellite communications. This paper presents design of a demonstration terrestrial communicator with a 2.5-10 Gbps communication capability at distances of about 5-7 km. The tracking system consists of three sub-systems: a coarse tracker (a digitally controlled, motorized Maksutov telescope with a 100 fps acquisition sensor); an electro-optical fine tracker (an analog-controlled voice-coil actuator and a position sensor), and a nonlinear (liquid crystal-based) optical fine tracker. Efficient compensation of jitter of up to kHz and maintaining a microradian pointing precision have been demonstrated.

6457A-11, Session 3

Signal acquisition and timing for a free space laser communications receiver

G. Zogbi, L. M. Candell, MIT Lincoln Lab.

NASA anticipates a significant demand for long-haul communications service from deep-space to Earth in the near future. To address this need, a substantial effort has been invested in developing a novel free-space laser communications system that can be operated at data rates that are 10-1000 times higher than current RF systems. We will focus here on the receiver design which consists of a distributed array of telescopes, each with a Geiger-mode Avalanche Photo Diode (APD) array capable of detecting and timing individual photon arrivals to within a fraction of a nanosecond. Using an array of telescopes has the advantage of providing a large collection area without the cost of constructing a very large monolithic aperture. A key challenge of using a distributed array receiver is combining the detected photons from each of the telescopes so that the combined system appears as a single large collector.

This paper will focus on the techniques employed by the receiver to spatially acquire a deep-space downlink laser signal, synchronize the timing of all the photon arrivals at each telescope, and combine the photon detections from each telescope into a single data stream. Results from a hardware testbed utilizing this receiver concept will be shown that demonstrate an efficiency of less than one incident photon per bit at data rates up to 14 Mbps, while operating within 1 dB of the channel capacity.

6457A-12, Session 3

Link performance of linear mode photon counting detectors

W. H. Farr, D. Q. Zhu, M. W. Wright, J. M. Kovalik, K. Quirk, J. Gin, B. Moision, M. K. Cheng, M. Nakashima, Jet Propulsion Lab.; D. V. Nguyen, Texas A&M Univ.

Linear mode photon counting detectors can support higher countrates per detector element than Geiger mode avalanche photodiodes. We compare the uncoded and coded end-to-end link performance of aphotomultiplier tube, hybrid photodiode, arsenic doped silicon, andniobium nitride detectors in emulated deep space link scenarios fromone to fifty megabits per second.

6457A-13, Session 3

Mitigation of optical turbulence effects using a modified simplex optimization approach: experimental study

R. M. Khandekar, V. V. Nikulin, Binghamton Univ.

Dynamically changing turbulence in the atmosphere distorts the wavefront of the laser beam propagating through it. The resulting spatial and temporal fields of the refractive index lead to performance degradation in the form of reduced signal power and increased BER, even for short link ranges. An electrically addressed liquid crystal spatial light modulator (SLM) can be used to correct the optical path difference (OPD) pattern resulting from the atmospheric distortions. Approximating the phase profile of the distorted beam using well known Zernike formalism reduces the complexity of controlling each pixel of the SLM. Real time correction of the wavefront can be achieved using the Simplex optimization procedure by Nelder and Mead. Previously, some modifications have been proposed to overcome the local minima problems as well as the faster convergence. Yet the better and faster performance could be achieved by more accurate prediction of the simplex initialization along with the modifications in the simplex procedure. This paper presents the experimental results of such modifications to the earlier proposed system.

6457A-14, Session 3

Improving bit error rate through multipath differential demodulation

Y. K. Lize, École Polytechnique de Montréal (Canada); L. C. Christen, S. Nuccio, A. E. Willner, Univ. of Southern California; R. Kashyap, École Polytechnique de Montréal (Canada)

Differential phase shift keyed transmission (DPSK) is currently under serious consideration as a deployable data-modulation format for high-capacity optical communication systems due mainly to its 3 dB OSNR advantage over intensity modulation. However DPSK OSNR requirements are still 3 dB higher than its coherent counter part, PSK. Some strategies have been proposed to reduce this penalty through multichip soft detection but the improvement is limited to 0.3dB at BER 10-3. Better performance is expected from other soft-detection schemes using feedback control but the implementation is not straight forward.

We present here an optical multipath error correction technique for differentially encoded modulation formats such as differential-phase-shift-keying (DPSK) and differential polarization shift keying (DPolSK) for fiber-based and free-space communication. This multipath error correction method combines optical and electronic logic gates. The scheme can easily be implemented using commercially available interferometers and high speed logic gates and does not require any data overhead therefore does not affect the effective bandwidth of the transmitted data. It is not merely compatible but also complementary to error correction codes commonly used in optical transmission systems such as forward-error-correction (FEC). The technique consists of separating the demodulation at the receiver in multiple paths. Each path consists of a Mach-Zehnder interferometer with an integer bit delay and a different delay is used in each path. Some basic logical operations follow and the three paths are compared using a simple majority vote algorithm. Numerical results show that the scheme improves receiver sensitivity by 1.1 dB at BER of 10-3.

6457A-15, Session 3

Chaotic communication in radio-over-fiber system based on optoelectronic feedback semiconductor laser

M. Tsai, F. Lin, National Tsing Hua Univ. (Taiwan)

Chaotic communication in radio-over-fiber (RoF) system based on optoelectronic feedback (OEF) semiconductor laser is studied numerically. Performance of different message encoding schemes, including additive chaotic modulation (ACM) and on-off shift keying (OOSK), are compared. By taking into account the attenuation, nonlinearity, dispersion, and amplifier spontaneous emission noise in the fiber module and the path loss, additive white Gaussian noise, and multipath effect in the wireless channel, system performance including synchronization error, eye diagram, quality factor Q, and bit-error-rate for different transmission lengths and message bit-rates are investigated. While both schemes are possible to achieve a BER < 10-9 which it is the benchmark set by the conventional communication, we have demonstrated that the OOSK scheme is better suitable for long distance RoF transmission. On the contrary, while the ACM scheme is sensitive to the perturbation in the wireless channel, it shows moderate decoding results in the fiber-only scenario. In this paper,

effects of parameters mismatch between the synchronized transmitter and receiver lasers and the security of this communication system are also addressed.

6457A-32, Session 3

Design and evaluation of a virtual quadrant receiver for 4-ary pulse position modulation/ optical code division multiple access (4-ary PPM/O-CDMA)

A. J. Mendez, Mendez R&D Associates; V. Hernandez, Univ. of California/Davis; R. M. Gagliardi, Univ. of Southern California; C. V. Bennett, Lawrence Livermore National Lab.

M-ary pulse position modulation (M-ary PPM) is an alternative to on-off-keying (OOK) that transmits multiple bits as a single symbol occupying a frame of M slots. Unlike OOK signaling, PPM does not require thresholding and instead performs a comparison test among all slots within a frame; the resulting slot decision determines the bit sequence. Combining PPM with optical code division multiple access (PPM/O-CDMA) adds the benefit of supporting many concurrent, asynchronous bursty PPM users. While the advantages of PPM/O-CDMA are well known, implementing a receiver that performs the com¬parison test can be difficult. This paper describes the design and performance of a novel differential array receiver for M-ary PPM/O-CDMA (M = 4), where the received signal is mapped onto an xy-plane whose quadrants define the PPM slot decision. The receiver is called a virtual quadrant receiver due to its logical similarity to laser spot trackers based on quadrant detectors; however, it does not require detector arrays physically laid out as a quadrant. Rather, the receiver yields a quadrant's coordinates by virtue of an associated control law. The implementation described does not require buffering or nonlinear optical operations and incorporates planar lightwave circuits (PLC) for compact design. Detailed numerical simulations and laboratory measurements illustrate the concept and investigate the effects of multi-access interference (MAI) and optical beat interference (OBI) on the slot decisions. Results show that MAI and OBI may drive the control law to declare incorrect quadrant coordinates, depending on the number and phasing of the concurrent PPM users.

Conference 6457B: Atmospheric Propagation of Electromagnetic Waves

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6457B-16, Session 4

Simulating partially coherent fields and other special beam classes in turbulence

G. Gbur, The Univ. of North Carolina at Charlotte

There is a wide body of evidence which suggests that partially coherent beams are better suited for atmospheric applications than their fully coherent counterparts. Most results have been restricted to special classes of beams for which analytic expressions for their propagation have been found. We discuss methods of simulating partially coherent beams in turbulence, and also investigate the advantages/disadvantages of using other special beam classes.

6457B-17, Session 4

Propagation of arbitrary random beams in turbulent atmosphere

O. Korotkova, Univ. of Rochester; G. Gbur, The Univ. of North Carolina at Charlotte

The combination of an angular spectrum representation (in space-frequency domain) and of the second-order Rytov's perturbation theory is applied for description of the second-order statistical properties of arbitrary (coherent and partially coherent) stochastic fields (whether scalar or electromagnetic) which propagate in turbulent atmosphere. The propagation is restricted to weak regime of atmospheric fluctuations. First we introduce the new method for scalar fields and we derive the expressions for the cross-spectral density function, from which the spectral and the coherence properties of the propagated fields can be determined.

Next we extend the new technique to electromagnetic domain, i.e. we derive the expressions for the elements of the 2x2 cross-spectral density matrix of the electric field from which its spectral, coherence and polarization properties can then be found. We illustrate the new method by applying it to propagation of several model beams through the atmosphere. In particular, we consider Gaussian beam, Bessel beam, Gaussian Schell-model beam in their scalar or electromagnetic versions. We find that the results obtained on the basis of the new theory are in good agreement with those obtained earlier by standard techniques. Thus, the new theory allows to calculate the statistical properties of fields (beam-like or not) generated by sources with arbitrary spectral, coherence and polarization properties which propagate in weak atmosphere.

6457B-19, Session 4

Atmospheric turbulence profiling by detection of the test beam's wave function

A. I. Khizhnyak, V. Markov, MetroLaser, Inc.

This report discusses the detection of the turbulent atmosphere disturbed laser beam with phase-shifting interferometer. We have demonstrated that this technique enables for instantaneously measuring of the wavefront and wave-function of the distorted beam. Direct detection of the wave-function allows determining the correlation functions of various orders, including the mutual coherence function (MCF) that is of particular interest. As of today the MCF can't be measured by any other known methods. The results of the laboratory tests of this technique for characterization of the beam that passed trough a random phase-screen with Kolmogorov spectrum of the phase perturbation are discussed. A comparative analysis of characterization of the laser beams perturbation by using known approaches and the proposed one allows to conclude that the proposed method based on MCF measurement is optimal. It should be very effective when, for example is applied to control an adaptive mirror unit in a scheme of turbulent atmosphere compensation.

6457B-20, Session 4

Scintillation index for N Gaussian laser beams with different wavelengths in weak atmospheric turbulence

A. Peleg, J. V. Moloney, The Univ. of Arizona

We study the scintillation index of N lowest order Gaussian laser beams with different wavelengths in weak atmospheric turbulence. Assuming a Von Karman turbulence spectrum and slow detector response and using the Rytov approximation we calculate the longitudinal and radial components of the scintillation index for typical free-space laser communication setups. We find the initial beam separation that minimizes the longitudinal scintillation and corresponds to the optimal beam configuration. Further reduction of the longitudinal scintillation is obtained by optimizing with respect to both initial beam separation and initial spot size. The longitudinal scintillation of the optimal N-beam configurations is inversely proportional to N, resulting in a 92% reduction for a 9-beam system compared with the single beam value. The existence of the minimum of longitudinal scintillation is not very sensitive to the form of the turbulence spectrum. Moreover, the radial scintillation values for the optimal N-beam configurations are found to be significantly smaller than the corresponding single beam values, and this reduction effect also grows with increasing N. Further insight into the reduction of intensity fluctuations is gained by analyzing the self- and cross-intensity contributions to the scintillation index.

6457B-30, Session 4

Propagation of partially coherent beams in a convective medium

A. Carbajal-Domínguez, Universidad Juárez Autónoma de Tabasco (Mexico)

Atmospheric conditions change throughout the day, from turbulence to convective conditions depending on solar irradiation and soil temperature. It is a necessity for optical telecommunications technologies to study propagation of partially coherent beams under convective atmospheric conditions because these are predominant during daytime in tropical regions. In this work, a theoretical and experimental study of the propagation of partially coherent J0 Bessel beams trough a convective medium is presented. Experimental results show that phase singularities are preserved.

6457B-21, Session 5

Tunable high-power high-brightness VECSELs as partially coherent sources for lasercom

J. V. Moloney, The Univ. of Arizona

We propose combining tunable, spectrally narrow, TEM00mode, optically-pumped vertical external cavity semiconductor lasers (VECSEL) to produce partially coherent sources for lasercom applications. The VECSEL devices are under development as part of a JTO MRI project at Arizona and we have already achieved over 10 Watts per laser from pumped spot sizes of 500 mm diameter. Coherent Inc. have achieved a record output of 50 Watts at 975 nm from a similar device pumped over a 900 mm spot.

The VECSELs have low M2 (< 1.4), are spectrally narrow (< 0.1 nm), wavelength tunable and can be spectrally combined using PTR glass volume gratings.

We are independently studying propagation of 2, 4 and 9 TEM00 laser beams, as models for the VECSELs, with different wavelengths in weak atmospheric turbulence. We find the optimal configurations of the 2, 4 and 9 laser beams with respect to the longitudinal scintillation index and show that the longitudinal scintillation for these configurations is smaller by 53%, 82% and 92%, respectively, compared to a single beam with the same total power. A further advantage of semiconductor active structures is the relative ease of high data rate modulation. We have recently developed a full 3D space-time simulation approach to simulating these VECSEL devices with the aim of exploring hybrid modulation approaches.

6457B-22, Session 5

Dual-frequency multifunction lidar

R. Diaz, S. Chan, J. Liu, Univ. of California/Los Angeles

The design and performance of a multifunction continuous wave dual-frequency lidar system is presented. The system is based on the use of the nonlinear dynamics of an optically injected semiconductor laser. Under proper operating conditions, the laser emits a dual-frequency beam with a broadly tunable microwave separation. The two optical lines are coherently locked to each other using an external microwave synthesizer, resulting in a stable microwave beat frequency. The lidar system is capable of simultaneous velocity and range measurement of remote targets. The velocity is measured from the Doppler shift of the microwave beat frequency. The stability of the microwave beat frequency enables accurate measurement of low velocities. In addition, the stable locking enables long-range measurements because of the long microwave coherence length. Ranging is accomplished by extracting the time-of-flight information carried on the residual microwave phase noise. We demonstrate preliminary measurements of velocities as low as 26 um/s and range measurement of 3.5 km with 2% accuracy.

6457B-23, Session 5

Performances of liquid crystal spatial light modulator (LCSLM) as a wavefront corrector for atmospheric turbulence compensation

D. Cai, N. Ling, W. Jiang, Institute of Optics and Electronics (China)

Liquid crystal spatial light modulator (LCSLM) has a series of attractive characteristics as a wavefront corrector of adaptive optical system used for compensation for atmospheric turbulence effect such as compactness, high density integration, low cost and possibility of batch production. However, it also has some limitations such as effective only on polarized light, chromatic aberration and low response speed. In order to investigate these pros and cons in detail, a series of experiments and analyses have been conducted using a LCSLM Model P256 of Boulder Nonlinear System. The nonlinear phase response to applied voltage was measured for different wavelengths. The coupling between neighboring elements and response time were also measured. The error of phase wrapping for multi-wavelength wavefront of broad spectral band light was studied. Possible ways to solve the polarizing problem were analyzed. The fitting capability to Zernike polynomials was demonstrated. An adaptive optical system with this LCSLM and Shack-Hartmann sensor was close-looped. As a result, the applicability of LCSLM for different applications will be evaluated and discussed.

6457B-24, Session 5

On the use of Gaussian filter functions for adaptive optics

M. Assad, Lockheed Martin Co. and Univ. of Central Florida; L. C. Andrews, Univ. of Central Florida

For adaptive optics systems, the use of aperture filter functions calculated using various Zernike modes can be useful in removing lower-order aberrations caused by atmospheric turbulence. Traditionally, these filter functions are calculated using the step function depicting a hard aperture which introduces integrals which are sometimes difficult to integrate and need to be done numerically. In this paper, we will examine the use of a Gaussian approximation to the step function which will lead to a form we can interpret analytically. We will then evaluate the effectiveness of the new filter functions and compare results with those results from the conventional filters.

6457B-25, Session 5

The black fringe wavefront sensor: white-light real-time analog phase measurement without a computer

R. J. Tansey, A. Honkan, H. M. Chan, Lockheed Martin Advanced Technology Ctr.

White light interferometry techniques currently used to obtain surface height scans and rms roughness are combined with am demodulation algorithms to produce a wavefront sensor capable of real time adaptive optics correction. This new adaptive optics device, called the black fringe wavefront sensor (bfwfs) , has been developed over the last two years at Lockheed Martin's Advanced Technology Center.

The bfwfs is different from other wavefront sensors which can be adapted to white light sources but which require wavefront reconstruction (lateral shear, rotational shear ,Shack-Hartmann) or which employ phase stepping algorithms or Fourier techniques. The black fringe device produces real time analog voltages in parallel channels to control or measure phase at the measurement plane.

Results of experiments will demonstrate phase accuracies obtained at Khz rates using 16 channel and 64 channel arrays. In addition, open loop influence functions, actuator poke tests, and closed loop Bode plots will be shown from tests performed with a Mems mirror. Evidence will be given of multikilohertz phase measurements using several different types of incoherent sources including tungsten lamps, LED's, superluminescent laser diodes, and multiline multimode lasers.

The bfwfs uses a fully parallel architecture which will allow analog control of most wavefront correction devices used today, including deformable mirrors, Mems mirrors, liquid crystal spatial light modulators, and bimorphs. This control does not require a computer or special processor other than a minimum of multiply and divide circuits. A final discussion will describe the results of tests in which a radial shear interferometer combined with the bfwfs allows correction of atmospheric or local loop disturbances.

6457B-18, Session 6

Free space optical system performance for laser beam propagation through non-Kolmogorov turbulence

I. Toselli, Politecnico di Torino (Italy); L. C. Andrews, Univ. of Central Florida; R. L. Phillips, Florida Space Institute

Free space laser system performance is limited by atmospheric turbulence that has been described by Kolmogorov's power spectral density model for many years because of its simplicity. Unfortunately several experiments have been reported that show Kolmogorov theory is incomplete to describe atmospheric statistics properly, in particular in portions of the troposphere and stratosphere. In this paper we present a Non-Kolmogorov power spectrum which uses a generalized exponent instead of constant standard exponent value 11/3. Using this new spectrum we carry out analysis of Beam Spread, Scintillation index, Probability of fade, SNR and BER as variation of the spectrum exponent.

6457B-26, Session 6

Critical issues encountered in experiments and measurements involving optical turbulence

F. D. Eaton, Air Force Research Lab.

The successful design and operation of high energy laser (HEL) and laser communication systems require a comprehensive and thorough knowledge of the real turbulent atmosphere coupled with high-fidelity realistic propagation models. To date, modeling and simulation of laser beam propagation through atmospheric turbulence have relied upon a traditional theoretical basis that assumes the existence of homogeneous, isotropic, stationary, and Kolmogorov turbulence. Results are presented of the real impact of the refractive index structure parameter ( ) on laser beam propagation including effects of non-classical turbulence as well as inner ( ) and outer scale ( ) effects. Observations also clearly show turbulence is often layered and is produced by wave activity and episodic events such as Kelvin-Helmholtz instabilities. Other critical turbulence issues involve the relationship between mechanical and optical turbulence and the relationship of turbulence with heat exchange parameters. Data presented addressing these issues were obtained from four systems:

a) a new measurement platform using a free-flying balloon that lifts a ring with a boom upon which are mounted fine wire (1-μm diameter) sensors to measure high-speed temperature and velocity fluctuations

b) a new system using a kite/tethered blimp platform that obtains both profile and measurements over time at a fixed altitude

c) a 50 MHz radar at Vandenberg Air Force Base that senses at high temporal and spatial resolution to 20 km ASL

d) an FM-CW radar that is the premier boundary layer system.

Methods of calibration and problems of interpreting results from the measurement systems will be discussed.

6457B-27, Session 6

Backscattering under intense pulse propagation in air

O. K. Khasanov, T. V. Smirnova, O. M. Fedotova, Institute of Solid State and Semiconductor Physics (Belarus); A. P. Sukhorukov, M.V. Lomonosov Moscow State Univ. (Russia)

The self-action of powerful pulsed beam in Kerr medium is known to result in self focusing which is originated from transverse gradients of a refractive index. In addition under pulse propagation its longitudinal gradient occurs causing partial backward-reflection of the incoming beam. At present, very little is known about it, except for the general belief that it is small. However, small-magnitude mechanisms can have a large effect in nonlinear self-focusing in bulk medium. The study how this effect may influence on the pulse propagation is especially important from the standpoint of large potential applications in modern science and engineering.

In this work we investigate analytically and numerically the role of the backscattering in the non-linear dynamics of powerful light pulse in the atmosphere Application of the eikonal related to the nonlinear phase increment allows to reduce Maxwell equations to the set of equations of non-linear Schrödinger type for forward (incident) and backward (reflected) waves. Backscattering process is investigated in dependence on the ratio of input pulse power to critical one, pulse duration and its wavelength. As analysis shows, in the case of the only Kerr nonlinearity effect the intensity of backward wave can reach more than 10 percents of forward wave when above ratio exceeds 30:1. Moreover, the beam exhibits a multifoci behaviour along the propagation axis. From our point of view, the pulse self-focusing results in an increase of high-frequency part in the spectrum of the trailing pulse and in that way makes for the self-reflection.

6457B-28, Session 6

High-intensive vortex pulsed-beam propagation in the atmosphere

O. K. Khasanov, T. V. Smirnova, O. M. Fedotova, Institute of Solid State and Semiconductor Physics (Belarus); A. P. Sukhorukov, M.V. Lomonosov Moscow State Univ. (Russia)

This work is devoted to a high- power femtosecond tubular pulsed beam dynamics in air under photoionization conditions. We base on the numerical solution of the system of modified nonlinear (3+1)D Schrödinger equation for an electric field envelope and kinetic equation for free electron density. The competition of Kerr nonlinearity and plasma defocusing is taken into account. The variational approach predicts the vortex pulsed beam multifoci behavior when its input power is close to critical one and the loss is negligible. The input beam power increase results in growth of defocusing factors related to the plasma domination. The interaction of a singular pulsed beam with nonlinear dielectric medium stipulates higher plasma densities in comparison with gaussian pulsed beams, at this the free electron number increases with increasing the beam topological charge. The process of the electron plasma formation due to multiphoton ionisation in this case is responsible for a nonlocal character of the light-matter interaction. This may be the main factor for the attainment of vortex beam stability condition, favouring the establishment of a quasi-soliton regime of radiation propagation over a distance exceeding several diffraction lengths. The effect of delayed (Raman) contribution is considered.

6457B-29, Session 6

Humidity contribution to Cn2 over 600m pathlength in tropical marine environment

E. S. Oh, C. O. Font, G. C. Gilbreath, Naval Research Lab.; M. P. J. L. Chang, Univ. de Puerto Rico Mayagüez

We present new optical turbulence structure parameter measurements, Cn2, over sea water between La Parguera and Magueyes Island (17.6N 67W) on the southwest coast of Puerto Rico. The 600 meter horizontal paths were located approximately 10 meters above sea level. No data of this type has ever been made available in the literature. Based on the data, we show that the Cn2 measurements are an order of magnitude less during the daylight hours as compared to equivalent land data. This strong evidence reinforces our previous argument that humidity must be accounted for to better ascertain the near surface atmospheric turbulence effects, which current Cn2 models fail to do.

6457B-31, Session 6

Enhanced performance of low-power (<60mW) femtosecond free space optical communication system over conventional CW operation

P. A. Corrigan, R. Martini, Stevens Institute of Technology; T. M. Chaffee, Attochron, LLC.

Low power, 1.5μm femtosecond light exhibits lower attenuation though the New York area against a comparable CW system. This is confirmed with indoor fog studies. The enhancement is accounted for with reduced scattered power.

Conference 6458A: Laser Applications in Microelectronic and Optoelectronic Manufacturing XII

Monday-Wednesday 22-24 January 2007

Part of Proceedings of SPIE Vol. 6458A Photon Processing in Microelectronics and Photonics VI

6458A-01, Session 1

Assembly and integration of thin bare die using laser direct-write

A. Piqué, R. C. Y. Auyeung, N. Charipar, H. Kim, Naval Research Lab.; S. A. Mathews, The Catholic Univ. of America

Laser-based direct-write (LDW) processes offer unique advantages for the transfer of unpackaged semiconductor bare die for microelectronics assembly applications. Using LDW it is possible to release individual devices from a carrier substrate and transfer them inside a pocket or recess in a receiving substrate using a single UV laser pulse, thus per-forming the same function as pick-and-place machines currently employed in microelectronics assembly. However, conventional pick-and-place systems have difficulty handling small (< 1mm2) and thin (< 100 micrometers) components. At the Naval Research Laboratory, we have demonstrated the laser release and transfer of intact 1 mm2 wafers with thicknesses down to 10 microns and with high placement accuracy using LDW techniques. Furthermore, given the gentle nature of the laser forward transfer process it is possible to transfer semiconductor bare die of sizes ranging from 0.5 to 10 mm2 without causing any damage to their circuits. Once the devices have been transferred, the same LDW system is then used to print the metal patterns required to interconnect each device. The use of this technique is ideally suited for the assembly of microelectronic components and systems while allowing the overall circuit design and layout to be easily modified or adapted to any specific application or form factor including 3-D architectures. This presentation will describe how the LDW process can be used as an effective laser die transfer tool and will present analysis of the laser-driven release process as applied to various types of silicon bare dice.

This work was supported by the Office of Naval Research.

6458A-02, Session 1

Excimer laser processing of novel materials for spintronic and optoelectronic applications

M. Tabbal, American Univ. of Beirut (Lebanon)

The interaction of the highly energetic pulsed excimer laser beam with a target material induces non-equilibrium physico-chemical processes that could be harnessed to synthesize a variety of novel technologically attractive materials. In this talk, we will overview our most recent results on excimer laser processing of thin films and surfaces:

1- Remote Plasma Pulsed Laser Deposition (PLD) of chromium oxides: laser ablation takes place in an oxygen ambient activated by a microwave plasma source in order to generate new chemical pathways enabling greater control of the composition and nanostructure of the films. Indeed, the use of the remote plasma was found to promote the formation of higher oxidation states of Cr, such as the half-metallic CrO2 phase as opposed to the anti-ferromagnetic phase, Cr2O3, which is dominant in films grown in the absence of plasma activation. The formation of the CrO2 compound, which is of great interest to the field of spintronics, has been confirmed by Magnetic Force Microscopy and Infra-Red spectroscopy. The dependence of the chemical bonding and structural characteristics of the films on growth conditions will be discussed.

2- Pulsed Laser Melting (PLM) of ion implanted silicon: the combination of ion implantation and PLM can lead to the formation of silicon supersaturated with S, at levels several orders of magnitude greater than the solubility limit. Such a material displays strong sub-bandgap infra-red absorption, and could have potential applications in the fabrication of Si-based opto-electronic devices. Optical absorption studies indicate that the incorporation of high concentrations of S (up to 0.6 at.%) and the highly efficient crystallization of the implanted layers by the laser melting process (as confirmed by Transmission Electron Microscopy) induce the strong sub-bandgap absorption. The photovoltaic and photoluminescent properties of the laser crystallized S-Si layers will also be presented.

6458A-03, Session 1

Micro welding of electronic components with 532nm laser radiation

F. Otte, A. Ostendorf, U. Stute, T. Stehr, Laser Zentrum Hannover e.V.

Laser micro-welding of electronics parts using the wavelength λ = 1064 nm is state-of-the-art technology. However, in these parts some metals that needs to be welded, especially copper and gold, show low absorption rates of under 4 % for the infrared wavelength range. Further, for increasing temperatures above the melting point of these metals, the absorption rate rises erratically. Since the fusion time point is dependent on different factors, it cannot be calculated precisely beforehand. This makes process control difficult and decreases the process window for laser micro-welding of these materials.

On the other hand, these metals show a ten-times higher absorption rate for the wavelength λ = 532 nm, meaning the use of a frequency-converted Nd:YAG laser becomes interesting for micro-welding. In this paper, investigations on laser micro-welding using a frequency-converted laser at the wavelength of λ = 532 nm were carried out. In order to evaluate the laser process, on a demonstrator board electrical components (TSSOP) with a pitch of 0.5 mm were welded directly onto the copper strip conductors with heights of d = 70 μm.

6458A-04, Session 1

Processing of semiconductors and metals by laser-induced air breakdown plasma

A. V. Kabashin, A. Trudeau, M. Meunier, École Polytechnique de Montréal (Canada); W. I. Marine, Univ. de la Méditerranée-Aix Marseille II (France)

A recently introduced method of laser-induced air breakdown processing 1-4 has been used to treat semiconductor (Si, Ge) and metal (Zn) targets in ambient air. In this method, plasma of the air breakdown, produced near the target by pulsed radiation from a CO2 laser (wavelength 10.6 microns), is used to locally erode a target and thus produce highly porous, nanostructured layers. We show that the formed layers exhibit interesting photoluminescence properties. In particular, nanostructured Si and Ge provide strong PL UV - visible range (2.0 eV and 3.2 eV bands for Si; 2.2 eV and 3.0 eV bands for Ge), whereas in the bulk these materials do not emit visible light. In contrast, for ZnO layers, formed on Zn, provide an intense exciton emission in the UV range (380-385 nm), while defect-related PL bands were weak and could be completely removed by the varying fabrication parameters. Furthermore, ZnO layers were found to exhibit random lasing effect. Applications of nanostructured semiconductor and ZnO layers in optoelectronics and biosensing are discussed.

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6458A-05, Session 1

Thermodynamics of double-pulse laser irradiation of silicon

P. Lorazo, Ecole Polytechnique de Montreal (Canada) and Univ. de Montreal (Canada); L. J. Lewis, Univ. de Montreal (Canada); M. Meunier, Ecole Polytechnique de Montreal (Canada)

The thermodynamics of ablation involved in double-pulse laser irradiation of silicon are investigated within a recently developed model combining Monte Carlo and molecular-dynamics for carrier and atom dynamics, respectively [1]. In our simulations at fixed total injected energy, a first, 500 fs pulse at the threshold fluence for melting initially melts the semiconducting crystal over an approximate depth of 10 nm below the surface; a second pulse with duration between 500 fs and 50 ps then couples with the resulting metallic liquid to cause the rapid expansion and ejection of the molten material. The total ablated mass and velocity of the ejected species are found to depend on the pulse duration of the second pulse. In general, our results confirm the experiments of Stoian et al. [2] which demonstrate the possibility to manipulate the properties of the plume by a suitable choice of the temporal profile of the incident laser energy.

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6458A-06, Session 2

Time-resolved imaging of explosive phase change in metals

C. Porneala, D. A. Willis, Southern Methodist Univ.

Phase explosion is a non-equilibrium boiling process resulting from homogeneous vapor nucleation in a superheated liquid near the critical point. Phase explosion may occur during nanosecond laser ablation since heterogeneous nuclei responsible for normal boiling do not have sufficient time to grow. Understanding the explosive phase change process is critical for developing models of material removal, and requires time-resolved diagnostics. A time-resolved shadowgraph technique was developed which was capable of probing ablation with nanosecond time exposures and nanosecond time delay resolution. Experiments were performed to investigate the transition from normal surface vaporization to phase explosion during nanosecond laser ablation of aluminum. The threshold nature of phase explosion was observed by a discontinuous jump in the ablation depth at a fluence of approximately 5.2 J/cm2. Shadowgraph images captured weak vaporization below 5.2 J/cm2 and shock waves induced by the rapid vaporization. At higher fluences, the expulsion of large droplets and vapor was observed as a result of phase explosion and the subsequent expulsion of molten material. The expulsion process began shortly after the end of the laser pulse, consistent with existing estimates of homogeneous nucleation time lags in the research literature.

6458A-07, Session 2

Laser-imaging diagnostics of debris behavior from laser-produced tin plasma for EUV-light sources

T. Okada, Kyushu Univ. (Japan)

The behavior of debris generated form a laser-produced plasma (LPP) using a tin (Sn) target for the extreme ultraviolet (EUV) light source at 13.5 nm, that will be used in the next generation optical lithography system, has been studied using a laser induced fluorescence (LIF) imaging system. When a thin Sn film was used as a target material, the depletion of the Sn atoms was clearly observed along the Nd:YAG laser beam, indicating that the mass-limited target is effective to reduce the emission of the neutral atoms. The LIF system was also used for in-situ study on the interaction between the fast ions generated from plasma and a mirror substrate, where a silicon (Si) wafer was used as a dummy substrate for the EUV optics.

6458A-08, Session 2

Time-resolved force and ICCD Schlieren imaging study of TEA CO2 laser ablation of liquid and polymer

J. Lin, J. E. Sinko, A. V. Pakhomov, The Univ. of Alabama/ Huntsville

Time-resolved force measurements and Intensified Charge-Coupled Device (ICCD) Schlieren imaging techniques were applied to investigate dynamic processes of force generation in the laser ablation of various liquids and polymers. A TEA CO2 laser operated at 10.6 μm, 300 ns pulse width, and up to 10 J pulse energy was used to ablate liquid and polymer. Net imparted impulse and coupling coefficient were derived from force sensor data and relevant results will be presented. Time-resolved ICCD Schlieren imaging was used in conjunction with dynamic force techniques to expose the various dynamics processes in time line. The effects of laser irradiance and sample surface curvature on the force generation will be examined.

6458A-09, Session 3

Fabrication of bio-chips by laser ablation

Y. Yoshida, Toyo Univ. (Japan)

Currently, in many fields such as blood test and DNA analysis, the demand to quickly analyze the components in a small amount of fluid with high accuracy has increased. Therefore, μ-TAS (Micro Total Analysis System), a miniaturization and integration of electromechanical parts that inject, mix, stir, separate and extract fluids, as well as containing the element that is necessary for analysis of fluids such as grooves and cisterns, has received a lot of attention.

The objective of our research is to create a high quality μ-TAS for accurate blood tests at a low price. Laminated resins and micro fabrication by lasers are used as a method to create μ-TAS. A pulse laser of ultraviolet region was used to form the flow path and so on. Numbers of heat-hardening resin-films were piled up a soda glass. A laser fabricated a part of the channel at the each film every lamination, and then 3-D structure microchannel was fabricated. The channel sizes are widths of 10-400μm and depths of 30-90μm.

Using this method, we succeeded in creating a three-pronged micro-fluidic device to study blood cells lined up in a row formation. We also succeeded in fabricating an artificial capillary-vessel micro-fluidic device to observe the erythrocyte deformability.

6458A-10, Session 3

Fabrication of a microfluidic bioarray device using laser-machined surface microstructures

T. Sato, R. Kurosaki, A. Narazaki, Y. Kawaguchi, H. Niino, National Institute of Advanced Industrial Science and Technology (Japan)

Fabrication of microfluidic devices used for various bioanalysis often requires the high precision surface micro-structuring of the transparent materials. However, the transparent materials are generally hard and brittle, which makes precision surface micro-structuring difficult. As a solution, we have developed a technique for laser micromachining of transparent materials using organic solution, named laser-induced backside wet etching (LIBWE). By this technique, microstrucutres with 1 micrometer resolution can be fabricated within 1 milimeter squear area. Such microstructures can be arranged to form microfluidic systems with specific functions. It was reported that color-encoded microbeads with surface func-

tional groups randomly arranged in a microwell array can be used as a microarray system. This concept of bead array is considered to meet a remaining challenge in microarray analysis systems, a cost-effective production of the device. Another challenge in microarray is a reduction in the reaction time. By designing microstructure appropriately the beads array can be formed within microchannels. Such device should meet both challenges. In the present work, we will report on a novel microfluidic device incorporating two-dimensional array of microbeads with 10 ƒÊm diameter. This work was in part supported by the Industrial Technology and Research Grant Program from NEDO of Japan.

6458A-11, Session 3

Fabrication of OLED display by an ultrashort laser: selective patterning of thin metal electrod

Y. Ito, Y. Onodera, R. Tanabe, Nagaoka Univ. of Technology (Japan); M. Ichihara, H. Kamada, Tokki Corp. (Japan)

Organic light emitting diode (OLED) is now in practical use and also a subject of active research and development. In industrial production of OLED displays, one of the key technologies is patterning of electrodes, especially a metal electrode, which is usually made on a thin layer of organic compounds. Laser machining of the electrode is one of the possible techniques. Difficulties in machining of OLED come from the fact that OLED has multi-layered structures consisted from very thin layers of different materials, one of which is highly heat- and chemical-sensitive organic material. The OLED sample has indium tin oxide (ITO) electrode of about 150 nm thick at the bottom. The organic electro-luminescence material of less than 200 nm is deposited on it and the top is aluminum electrode of 100 to 150 nm thickness. We have used an ultra-short fiber laser to the patterning of the aluminum electrode and fabricated a display panel of the OLED successfully. To investigate the process in detail, we have constructed an ultra-fast imaging system, with sub-picoseconds time resolution and carried out a time-resolved imaging of the process. It is found that the underlying layer affects much to the machinability of top metal layer. The ITO layer seems to enhance the machining efficiencies of aluminum electrode: the ablated spot size becomes larger for that on ITO, even though the pulse energy is kept constant.

6458A-12, Session 3

Effect of CO2 laser irradiation on the performances of sol-gel-derived Er3+-activated SiO2-ZrO2 and SiO2-HfO2 planar waveguides

C. Goyes, Univ. del Valle (Colombia); C. Armellini, M. Ferrari, A. Chiasera, Y. Jestin, M. Montagna, A. Chiappini, Univ. degli Studi di Trento (Italy); G. C. Righini, Istituto di Fisica Applicata Nello Carrara (Italy); E. Solarte, A. Casas Bedoya, Univ. del Valle (Colombia); A. Devia, Univ. Nacional de Colombia (Colombia); C. Meacock, Instituto Superior Tecnico (Portugal)

Erbium activated SiO2-ZrO2 and SiO2-HfO2 planar waveguides doped with Er3+ ranging of 0.5 and 5 mol% were prepared by sol-gel route using dip-coating deposition on silica glass substrates. Aim of this work is to present an alternative method for planar optical waveguides processing based on CO2 laser irradiation (wavelength, 10.6 um). Optical and spectroscopic effects of pulsed and continuous CO2 laser irradiation are evaluated; the thermal conventional annealing effect for this system is reported for comparison. All the planar waveguides were optimized in order to confine one propagating mode at 1550 nm. X ray diffraction and optical spectroscopy showed that after an adapted pulsed CO2 laser annealing, the resulting materials showed a crystalline environment. An increase of approximately 0.04 has been observed on 70SiO2-30HfO2 planar waveguide after continuous CO2 laser annealing; also a similar effect of CO2 laser irradiation on the refractive-index change in planar waveguides was detected in all irradiated SiO2-ZrO2 planar waveguides. We have observed that continuous CO2 laser annealing can lead to waveguides with a lower attenuation coefficient, 0.80 and 1.2 dB/cm \@ 632 nm for silica-hafnia and silica-zirconia waveguides respectively, in respect to the attenuation coefficient higher that 2 dB/cm, measured for thermal annealed waveguides. When pumped with 514.5 nm continuous-wave laser light, pulsed CO2 irradiated waveguides show the 4I13/2 → 4I15/2 emission band with a bandwidth of 12 nm. Before and after conventional thermal annealing, the 4I13/2 level decay curves presented a single-exponential profile with a lifetime of 4.1 and 5.7 ms respectively, but the lifetime increases up to 8.1 ms, after pulsed laser annealing treatment.

6458A-14, Session 4

DPSSL for direct dicing and drilling of dielectrics

D. Ashkenasi, M. Schwagmeier, Laser-und Medizin-Technologie GmbH (Germany)

New strategies in laser micro processing of glasses and other optically transparent materials are being developed with increasing interest and intensity using diode pumped solid state laser systems generating short or ultra-short pulses in the optical spectra at good beam quality. Utilizing non-linear absorption channels, it can be demonstrated that ns green (532nm) laser light can scribe, dice, full body cut and drill (flat) borofloat and borosilicate glasses at good quality. Outside of the correct choice in laser parameters, an intelligent laser beam management plays an important role in successful micro processing of glass. This application characterizes a very interesting alternative where standard methods demonstrate severe limitations such as diamond dicing, CO2 laser treatment or water jet cutting, especially for certain type of optical materials and/or geometric conditions. Application near processing examples using different DPSSL systems generating ns pulsed light at 532nm in TEM00 at average powers up to 10W are presented and discussed in respect to potential applications in display technology, micro electronics and optics.

6458A-15, Session 4

UV-laser ablation of fused silica mediated by solid coating absorption

J. Ihlemann, Laser Laboratorium Gottingen e.V. (Germany)

Micro patterning of fused silica by laser ablation is very challenging due to the lack of absorption in the whole spectral range from the deep UV to the near IR. Beside vacuum UV lasers emitting at 157 nm or femtosecond lasers inducing multi photon absorption, indirect methods utilizing external absorbers are applied. Established methods like LIBWE and LIPAA are applicable in a backside configuration, i.e. the laser beam has to pass the workpiece before inducing ablation at the backside. This causes restrictions concerning the shape of the workpiece, i.e. generally a flat front surface is necessary. We propose an indirect ablation method that can be applied for both, back side and front side processing.

The fused silica substrate to be machined is coated with a UV-absorbing oxide film. This film is irradiated using an excimer laser leading to ablation of the film and, at sufficiently high fluence, to surface ablation of the fused silica substrate. The ablation depth in the silica can be controlled by the fluence in excess to the threshold. The remaining coating in the unexposed areas is removed afterwards by large area irradiation of the whole surface at a fluence above the threshold of film ablation, but below the threshold of substrate ablation.

6458A-16, Session 4

Physical mechanisms of fast structure modification of glass-like materials under laser action

V. P. Veiko, St.-Petersburg State Univ. of Information Technologies, Mechanics and Optics (Russia)

There are many experimental facts already accumulated about fast laser structure modification of bulk glass, porous glass, glass-ceramics, glass films etc.

In some sense these different phenomena have one common point: all of them have an extremely high speed under laser heating which properly is not more than the other type of heating source comparatively with traditional heat treatment of glass [1].

Two most important peculiarities of laser heating are marked:

1) nonequilibrium (non-stationarity) of laser heating due to high speed of energy loading regarding the inertness of the glass material structure (where a diffusion and a viscosity play an important role in a structure modification).

2) nonhomogenity due to a locality of laser irradiance, which leads to appearance of a high-rate thermal gradients and additional forces - thermogradient force and “fonon wind”, and additional mechanisms like vacancies drift play a sufficient role.

Correspondingly two main mechanisms of structure modification are considered:

1) the theory “Liquid as Vacancies Deformed Crystall (L-VDC) [2] and

2) thermogradient model of laser-induced crystallization (TGM).

Mechanism of laser densification of porous glass laser amorphization of glass-ceramic and laser crystallization of bulk glass and glass-films are considered from the general point of view.

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6458A-17, Session 4

Photo-ionization of wide-bandgap dielectrics by high-intensity radiation of ultrashort laser pulses

V. E. Gruzdev, J. K. Chen, Univ. of Missouri/Columbia

High intensity of laser radiation and short pulse duration are two of the characteristic features of ultra-fast laser-material interactions. In this study, we concentrate on reliable description of photo-ionization in wide band-gap materials since it can be a dominating process in many ultra-fast laser-material interactions. By examining the traditional models widely employed for description of the photo-ionization, we found that they do not include contribution form Bragg-type reflections of oscillating electrons at edges of Brillouin zone due to the very specific energy-momentum relations utilized. Moreover, we showed that all the existing approaches are only valid for intensity about 1 TW/cm2. To accurately characterize the laser photo-ionization of wide band-gap materials by high-intensity pulses, we proposed a new approach based on cosine-type energy-momentum relation and the calculation procedure of L.V. Keldysh. It was found that suppression of multiphoton ionization takes place at intensity exceeding 1 TW/cm2. It was followed by a singularity on intensity dependence of the ionization rate appearing at intensity close to 10 TW/cm2 for most wide band-gap materials. As a result of analytical calculations, we obtained a rigorous expression for dependence of the singularity threshold on laser and material parameters. The presented theoretical predictions were compared versus experimental data and shown to be capable of explaining some experimental regulations. Some basic propagation effects in transparent solids were investigated by employing the new ionization model in the framework of a simple approach based on the intensity-transfer equation and the rate equation for electron density. In this part of our presentation we concentrated on the problem of radiation penetration into the ionized material at intensity close to the singularity threshold.

6458A-18, Session 5

Ultrastrong photosensitivity in chalcogenide waveguides for on-chip filter applications

B. J. Eggleton, The Univ. of Sydney (Australia)

This paper reviews our recent progress on fabricating ultra-strong photo-induced period structures in low-loss chalcogenide rib waveguides. We use stable Sagnac interferometer to create high-quality Bragg gratings and long-period gratings with tailored filter characteristics and demonstrate integrated nonlinear device functionalities. We also investigate the photosensitivity dynamics and stability of the induced gratings.

6458A-19, Session 5

Inscription of optical waveguides in Z-cut lithium niobate by circularly polarized 1.0-ps laser pulses

A. H. Nejadmalayeri, P. R. Herman, Univ. of Toronto (Canada)

Over the past decade, ultrashort pulse laser processing has become a viable method of fabricating buried guided wave optics in various types of glasses, but shown only modest success with several types of transparent crystals. In lithium niobate (LN), waveguide writing is particularly challenging because of the crystal’s unusually strong nonlinear response and acute sensitivity to damage. To date, laser-formed waveguides in LN was possible only at slow fabrication speed, and yielded waveguides that were often non-permanent and had high propagation loss. Recently, we demonstrated the importance of laser polarization and pulse duration in mitigating these undesirable effects in LN [1]. Here, we report what we believe to be the first demonstration of telecom-band room temperature stable waveguides in LN, fabricated by direct exposure to ultrashort laser pulses. The fabrication speed of ~0.6 mm/s is 10 to 100 times faster than previous reports, and provides waveguides with record low losses of 0.7 and 1.0 dB/cm at wavelengths of 1300 and 1550 nm, respectively. By exploring a wide range of laser pulse durations (50 fs to 1 ps) and polarization states (linear TE, linear TM, circular), a narrow laser processing window was discovered defined by surprisingly long 1-ps pulse duration and the requirement for circularly polarized light. This paper presents the LN waveguide characteristics together with the optimized laser processing conditions for low loss and good mode matching to telecom fiber.

1. A. Nejadmalayeri and P.R. Herman, Ultrafast laser waveguide writing: Lithium Niobate and the role of circular polarization and picosecond pulsewidth, to appear in Opt. Lett.

6458A-20, Session 5

Thermal annealing of fused silica after and during fs-laser waveguide writing

J. J. Witcher, Univ. of California/Davis; W. J. Reichman, Lawrence Livermore National Lab. and Univ.of California/Davis; D. M. Krol, Univ. of California/Davis

To gain insight into the mechanism and stability of structural modification associated with fs-laser waveguide writing we have studied the effects of temperature, both after and during waveguide writing in fused silica using an amplified Ti-sapphire, 1 kHz rep-rate, fs-laser system. The defects and structural changes in the glass were characterized using transmission imaging, confocal fluorescence and confocal Raman spectroscopy.

The first part of the study investigated the thermal stability of waveguides written in fused silica. Identical waveguides were written in several samples, all at room temperature. After writing, the samples were annealed at temperatures ranging from 100 to 1100 C. Once annealed, the samples were cooled back to room temperature and Raman and fluorescence spectra and transmission images were collected.

In the second part of the study, the fused silica samples were heated to temperatures ranging from 100 to 700 C and then waveguides were writ-

ten at the elevated temperatures into the samples using the kHz rep-rate fs-laser system. These waveguides were written with the same laser parameters as in the first part of the study, for comparison.

The results show that fluorescence features due to laser-induced defects disappear at lower temperatures than Raman features associated with three-membered SiO rings. We will also compare the samples annealed after writing to the samples written at elevated temperatures and discuss the results in the context of kHz vs. MHz rep-rate fs-laser writing of waveguides in glass.

6458A-21, Session 6

Formation of silicon structures in silicate glass by femtosecond laser

K. Miura, Y. Shimotsuma, M. Sakakura, S. Kanehira, K. Hirao, Kyoto Univ. (Japan)

We have fabricated silicon structures deposition in silicate glass prepared with metallic aluminum in the starting material. It was confirmed that Si can be deposited from silicate glass with dispersed metallic Al by femtosecond laser irradiation and successive annealing. Small Si-rich structures such as oxygen-deficiency (O-deficiency) defects or Si clusters transform into larger, but still nano-sized, Si particles only using the focusing irradiation of the laser, and Si-rich structures are grown on micro-size particles due to the thermite reaction promoted by heat treatment. We also discuss what effect the irradiation from focusing the laser pulse has on the Si deposition process in the laser-irradiated region by using a time-resolved transient lens method with a sub-picosecond laser pulse. Localized high-temperature, high-pressure, and the generation of shock waves appear to be very important in forming the Si-rich structures that are related to the growth of Si particles. That is, the diffusion of oxygen by shock waves and the existence of Al-rich structures are important for forming Si-rich structures such as Si clusters achieved by Si-O bonds continuously breaking under high temperature. Therefore, the focusing irradiation of femtosecond lasers is a very useful for forming Si structures inside glass. Our findings have opened up new possibilities in the field of Si-integrated devices or Si photonics.

6458A-22, Session 6

Direct written Bragg grating structures in optical waveguides

G. D. Marshall, M. Ams, N. Jovanovic, A. Fuerbach, J. A. Piper, M. J. Withford, Macquarie Univ. (Australia)

We report on the development of directly written Bragg grating structures written using the point-by-point (PbP) technique in index guided waveguide structures. Using a low repetition rate amplified femtosecond laser and precision translation stages we have recently demonstrated the inscription of waveguide-Bragg gratings (WBGs) in fused-silica femtosecond-laser direct-written (FLDW) optical waveguides for use in the communication standard C-band [1]. Furthermore we are developing monolithic lasers based on these FLDW waveguides and WBGs written in active glasses such as Erbium doped phosphate glass. Such devices could serve as miniature signal sources in photonic systems. To help elucidate the factors of importance to such a device we have undertaken a parallel body of work in which we have fabricated PbP gratings in Erbium Ytterbium doped active fiber lasers where they have initially served as the output coupler component. In preliminary tests such fiber lasers have generated 20 W output power of which 80% is contained in a narrow line width (sub 100 pm) single linear polarization making these gratings ideal for use in fiber laser applications requiring subsequent non-linear conversion. Further results from both fiber and planar waveguide based devices, and their applications will be presented.

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6458A-23, Session 7

X-ray diffraction studies of ultrafast bond softening

D. A. Reis, Univ. of Michigan

We present results from a novel stroboscopic sfemtosecond laser pump and x-ray probe technique that was used to measure the transient interatomic potential of photoexcited bismuth approaching a solid- solid phase transition. These experiments were performed at the Sub- picosecond Pulse Source at the Stanford Linear Accelerator Center and made use of the inherent timing jitter associated with linear- accelerator-based x-ray sources to randomly sample the dynamics of bond-softening and coherent optical phonon generation as a function of photoexcited carrier density. The results are in good agreement with first principles constrained density functional calculations.

6458A-24, Session 7

Effect of amplified spontaneous emission pedestal on femtosecond laser pulse interaction

V. V. Semak, The Pennsylvania State Univ.

The overview of research conducted in the Pennsylvania State University that target temporal characterization of a pulse produced by the commercial femtosecond laser systems is presented. The effect of nanosecond pedestal component that, according to the experiment and simulation results, contains significant (possibly up to 50 % or higher) fraction of the total pulse energy is discussed. The experimental data on material drilling rates and melting are overviewed supporting results of temporal characterization of laser pulse.

6458A-25, Session 7

Nonlinear response in optical materials using ultrashort laser technology

D. Ashkenasi, Laser-und Medizin-Technologie GmbH (Germany)

Ultra-short lasers with elevated peek powers combined with fairly moderate single pulse energies are able to induce very interesting non-linear optical interaction channels, such as multi-photon absorption, self-phase modulation and self focusing. These non-linear optical effects can be utilized to obtain surprising material reactions inside the bulk of optical dielectrics. With a certain degree of physical understanding and engineering experience, the material reaction can be controlled and optimized to generate e.g. internal markings, wave guides, 3d data storages or diffractive optical elements. As an example, laser-induced coloring of several type of glasses have been obtained at ultra-short bulk excitation, showing a strong resemblance to surface defects observed in most glasses after ionizing (e.g. X- and gamma-ray) hard radiation treatment. These laser-induced “color-centers” can alter the optical properties in dispersion and extinction locally in a well-defined volume, which can be described as a local change in the complex refractory index (n+ik). The implementation of this new technology can be characterized as “nik-engineering”. New experimental results on laser-induced sub-surface modifications utilizing near infrared femtosecond and picosecond laser pulses inside different types of transparent dielectrics are presented and discussed in respect to the potential of “nik-engineering”.

6458A-26, Session 8

High-repetition rate micromachining results

G. Matras, Univ. Jean Monnet Saint-Etienne (France) and Univ. Jean Monnet/ Lab. TSI (France); N. Huot, E. Audouard, Univ. Jean Monnet Saint-Etienne (France)

Ultrashort duration laser sources are considered as a promising tool for new micromachining applications : precise microdrilling and microcutting on various materials. Cutting is achieved without burning, and the cut

surface remains undamaged. Several years ago, micromachining results obtained with our 1 KHz source were reported, resulting in establishing ablation rate curves in different materials such as copper or silicium.

Increasing the repetition rate with a similar output pulse energy doesn't necessary mean microprocessing speed performing. 10 kHz repetition rate appears to be a critical value beyond which the delay between two successive pulses becomes so short that the interaction between the material and the first pulse is not completed when the following pulse arrives.

We investigated this possible phenomenon by carrying out the same micromachining operations at 10 and 15 kHz repetition rates.

This research benefits from a recently developed ultrashort duration source based on an innovative and single non-cryogenic regenerative amplifier which produces after compression up to 350-μJ and 60-fs pulses at a 10 and 15 kHz repetition rates.

6458A-27, Session 9

Rapid prototyping of frequency selective surfaces by laser direct-write

S. A. Mathews, M. S. Mirotznik, The Catholic Univ. of America

In this presentation we describe the use of laser direct-write for the rapid prototyping of both passive and active frequency selective surfaces. Frequency selective surfaces are generally described by a periodic array of metallic features (i.e. crosses, loops, grids...) that when properly designed can pass or reject specific frequency bands of incoming electromagnetic radiation. While simple frequency selective surfaces are relatively straight forward to design and fabricate, operational demands, particularly military, have motivated the design and fabrication of much more complicated patterns. These new designs combine features of significantly different length scales, randomly dithered patterns and combinations of passive and active elements. We will demonstrate how laser direct-write is an ideal tool for the rapid prototyping of these new more complicated frequency selective surface designs. We will present experimental results for both passive and active devices as well as optically transparent frequency selective surfaces by laser patterning ITO coated glass.

6458A-28, Session 9

Selective metallization of photosensitive glass using near-IR femtosecond laser

Y. Hanada, K. Sugioka, K. Midorikawa, The Institute of Physical and Chemical Research (Japan)

Selective metallization of photosensitive glass (FOTURAN) is demonstrated by femtosecond laser direct writing followed by Cu electroless plating process. Irradiation of femtosecond laser makes it possible to selectively deposit copper thin films with strong adhesion on the irradiated area with a linewidth as narrow as a few microns. A conventional metallization process relies on metal deposition by vacuum evaporation, sputtering, and chemical vapor deposition (CVD), which are widely applied in microelectronic industries today; however, these methods require photolithographic process with many steps for micropatterning. In the meanwhile, our selective metallization technique is completed by only 2 steps: (1) irradiation of the glass by femtosecond laser and (2) Cu electroless plating process. In addition, multiphoton absorption of femtosecond laser realizes metallization of internal walls of hollow structures embedded in the glass. The FOTURAN glass used in this study contains silver ions that are reduced to silver atoms and then precipitated by the femtosecond laser irradiation. Therefore, we regard the mechanism of this plating process as the reducing reaction of metal ions in the electroless plating solution. In this talk, we investigate fundamental properties of the plated films such as electric properties and adhesion of the thin metal film. In addition, we demonstrate electrode formation in some three-dimensionally microstructured samples for bio-chip applications.

6458A-29, Session 9

Improved writing method of bimetallic grayscale photomasks

G. H. Chapman, J. M. Dykes, D. K. Poon, C. Choo, J. Wang, J. T. K. Tsui, R. Tu, Simon Fraser Univ. (Canada)

This paper discusses a novel grayscale photolithography technique which utilizes a compound photomask: a bimetallic grayscale layer deposited on a conventional chrome photomask. The binary image on the chrome mask defines the boundary of the pattern, while the grayscale image creates the 3D structures. The grayscale-defining layer is created by laser writing the photomask using a 488/514 nm argon laser. Laser power needs to be kept below a threshold level to ensure the optical density of the chrome-blocking regions remain unchanged. Experiments suggest that 4OD to 0.3OD grayscale patterns can be created with almost no OD change in the chrome-blocking area. Using Sn/In/Cr and Bi/In/Cr photomasks, 3D micro-optic structures have been successfully fabricated in SU-8 photoresists with thicknesses from 60-100 um. Experiments show that reproducible high aspect ratio 3D structures can also be created on SU-8 photoresist using this novel technique. Work was done to determine how modifying the characteristics of the writing method such as the rescanning, raster-scan step size, and laser overlap can affect the resulting OD and smoothness of the film. Preliminary results have shown that rescanning Bi/In and Sn/In masks using the same laser power can result in a smoother photomask surface and a reduction in OD by 20% at 0.1W laser power. At higher exposure powers, the improvement in OD becomes negligible since most of the film is oxidized on the first scan. By improving the optical performance of the photomask, one can improve the smoothness and accuracy of the resulting 3D structures.

6458A-30, Session 9

Room-temperature deposition of a conducting polymer by resonant IR laser vaporization

H. K. Park, S. L. Johnson, R. F. Haglund, Jr., Vanderbilt Univ.

We report the room-temperature deposition of poly(3,4-ethylenedioxythiophene) (PEDOT:PSS) by infrared laser vapor deposition (IR-LVD) on a variety of flexible substrates. PEDOT:PSS is one of the most commonly used hole transport materials in polymer light-emitting devices (PLEDs), and until now could only be deposited using liquid phase techniques such as spin coating or inkjet printing. However, we have successfully grown thin films of PEDOT:PSS in a vacuum environment by using a tunable infrared laser to vaporize the material.

A commercially obtained suspension of PEDOT:PSS (1% by weight in water) was frozen in liquid nitrogen to form a solid target and mounted in a vacuum chamber. An infrared laser tuned to a wavelength resonant with the solvent vibrational mode was focused gently onto the surface of the target to form a vaporized plume of material which condensed on a nearby substrate. When the frozen PEDOT:PSS solution was used and the laser was tuned to the O-H stretching mode of water, however, only non-conductive films were produced. The addition of a co-matrix, in this case N-methyl-2-pyrrolidinone (NMP), to the solution before freezing was necessary in order to insure the conductivity of the deposited films. Concentrations of NMP ranged from 1-50% by weight without much variation in conductivity observed for different concentrations. Typical conductivities of these films were 0.2 S/cm which is comparable to spin coated films of PEDOT:PSS. FTIR spectroscopy revealed that the local electronic structure of the deposited films was similar both to spin coated films and to the initial frozen target.

6458A-32, Session 10

Tunable Bessel beams for pulsed laser materials processing

E. J. R. B. McLeod, C. B. Arnold, Princeton Univ.

Bessel beams are nondiffracting, self-healing, and have a different inten-

sity profile from Gaussian beams. These features can be beneficial for laser material processing. Bessel beams are typically created using axicons, diffractive elements, or holographic methods. In this study, we present a novel approach to creating such beams using a Tunable Acoustic Gradient Index of Refraction (TAG) lens. An amplified ultrasonic signal is used to establish a steady-state density fluctuation within a liquid effecting an oscillatory variation in local index of refraction. Light propagating through this liquid produces a Bessel-like beam whose properties primarily depend on driving amplitude, frequency, geometry and liquid properties. The theory behind the lens operation, its degrees of control, experimental results, and applicability to laser-materials processing will be presented.

6458A-33, Session 10

Enhancing silicon cutting performance by shaping the focused beam

L. R. Migliore, Coherent, Inc.

Individual devices have been saw-cut (“singulated”) from wafers since the invention of the integrated circuit. As circuits get smaller and wafers get thinner, however, the limitations of mechanical processes begin to interfere with productivity. Saws tend to chip thin wafers. Newer, more porous “low-k” dielectrics also are prone to chipping when mechanically cut.

Improvements in laser cutting speed are useful to the wafer dicing industry, while the edge quality of the singulated product must be maintained at a level that can withstand the stresses of packaging the device. A significant increase in process rate can be achieved by altering the beam characteristics of a frequency-tripled Nd Q-switched laser to produce an elliptical focused spot. The fracture strength of the edges, as measured by bend testing, was equivalent to that obtained from slower cuts made with a circular focused spot.

6458A-34, Session 10

Structured beam shaping for precision laser dicing of multilayered substrates

T. E. Lizotte, O. P. Ohar, T. Tuttle, Hitachi Via Mechanics USA, Inc.

Laser dicing of wafer based products such as light emitting diodes can have various and multiple layers of passivation coatings or multiple coatings of conductors and dielectric films on top of the bulk wafer substrate. These complex multi-layered structures require high finesse processing to ensure high yields, quality dicing and efficient processing. Such processes have become very complex over the years as new devices become miniaturized, requiring smaller dicing kerfs, greater precision and reduced heat effects to minimize substrate micro-cracking and maintain device integrity over its projected lifetime. These newer processes often involve the sequential use of single or multiple lasers, such as UV DPSS and IR DPSS lasers to penetrate various and differing material layers. Development of structured beam shaping optics that allow for two or more differing energy densities within a focused beam will provide opportunities for pre-processing of thinner cover layers while following through with a higher energy density to cut through base substrates. This paper will describe the development of a dual energy density beam shaping optical system designed for dicing wafers with delicate thin film coatings. The diffractive optic design will be described, including optical metrology, its functional testing with resulting dicing processing data on Sapphire wafers.

6458A-35, Session 10

Compensator optics to improve the stability of laser beam delivery systems that utilize beam shaping technology

T. E. Lizotte, Hitachi Via Mechanics USA, Inc.

Focused and directed laser beams are commonly used for a variety of processes, such as drilling of blind, through and microvias, cutting, laser imaging, dicing of substrates and modification or customization of integrated circuits. Such processes have become very complex, often involving the concurrent or sequential use of single or multiple lasers, such as UV DPSS and IR CO2 lasers. The general object of such processes is to reliably direct, focus and concentrate the energy of the laser at a desired spot or image plane on the surface of object being processed. Several recurring problems of conventional laser systems directly effect how the laser process will perform. These problems are often referring to as, beam wobble or pointing instability which is a radial deviation from an optimum centerline and is often related to variations in pulse energy of the laser beam, which is also termed as pumping jitter. Another problem is referred to as thermal drift, which again causes the axis of the laser beam to drift from an optimum centerline. Thermal drift is generally due to changes in the parameters of the laser, such as duty cycle, heating during operation and changes in power level. Thermal drift tends to remain parallel to the optimum center line, but drifts laterally. These two issues greatly effect how well beam shaping optics, such as aspheric flat top generators or diffractive beams shaping optics perform. When illuminated poorly the beam shaping optics will produce undesirable effects such as hotspots. This paper will describe how pointing instability and thermal beam drift can be compensated to ensure that downstream beam shapers are illuminated optimally to produce the required beam profile.

6458A-36, Session 10

Compact EUV source and optics for direct structuring of surfaces

A. Bayer, F. Barkusky, C. Peth, H. Töttger, K. R. Mann, Laser-Lab. Göttingen e.V. (Germany)

In recent years technological developments in the area of extreme ultraviolet lithography (EUVL) have experienced great improvements. So far, intense light sources based on discharge or laser plasmas, light guiding and imaging optics, as well as detection devices are already available. Currently, the application of EUV radiation apart from microlithography, such as metrology, high-resolution microscopy, or surface analysis comes more and more into focus. The aim is to make use of the strong interaction between soft x-ray radiation and matter for surface-near probing, modification or structuring techniques.

In this contribution, we demonstrate the surface-near direct structuring of different polymeric materials as well as lithium fluoride crystals using EUV radiation with a wavelength of 13.5 nm. The setup consists of a table-top EUV source based on a laser-induced plasma and a modified Schwarzschild objective with a resolution down to 1 μm. The mirrors of the employed objective were coated with Mo/Si multilayers, providing a transmittance of around 42 % (reflectivity ~65 % \@ 13.5 nm per mirror). With a demagnification factor of 10 small foci are generated, leading to spot diameters of 30 μm in plasma imaging mode and down to 1 μm in mask imaging mode, respectively.

The EUV energy density of ~100 mJ/cm(c)¯ obtained in the focus is sufficient to observe direct photo-ablation of polymers, e.g. PMMA. Thus, material interaction studies are currently in progress. The investigations revealed already that in contrast to common excimer laser ablation there are no incubation pulses when using EUV radiation. For lower energies the ablation rate is found to be linear with respect to the applied dose, whereas for higher energies a saturation behavior is observed. The mechanism of the process is briefly discussed. An additional diffraction experiment revealed the potential of the setup to generate periodic interference patterns with feature sizes in the sub-μm-range.

By EUV irradiation of LiF samples surface-near defects within the crystal lattice are formed. These color-centers (mainly F2- and F3+-color centers) are known to be stable at room temperature. They are able to emit characteristic radiation in the visible range after optical excitation with a wavelength around 450 nm. In the future structured areas of such color centers could be used as laser-active gain medium in distributed feedback lasers.

6458A-37, Session 11

Laser fabrication of nanomaterials in solution

F. Mafune, K. Yamada, H. Muto, The Univ. of Tokyo (Japan)

Gold nanoparticles with an average diameter of ≈8 nm (Au≈15000) were irradiated with a tightly focused pulse laser at 355 nm in an aqueous solution of sodium dodecyl sulfate (SDS). Transient absorption spectra of the solution were measured at 25 - 100 ns after the laser irradiation. The observed transient absorption around 720 nm is assignable to the 2p←1s transition of solvated electrons produced via multiple ionization of the gold nanoparticles. The nascent charge state of the gold nanoparticles was estimated from the transient absorbance. The dependence of the charge state on the SDS concentration shows a gradual increase from ≈+60 to ≈+70 in the 2x10 - 4 - 3x10 - 4 M range and an abrupt increase up to ≈+710 at the critical micelle concentration (CMC) of SDS; 8x10 - 3 M. TEM measurements after the laser irradiation reveal that the gold nanoparticles fragment into Au~1000 at SDS concentration of 3x10 - 4 M, whereas they are significantly dissociated into Au≈100 above CMC. The observed correlation between the nascent charge states and the extent of size reduction of the gold nanoparticles after the laser treatment indicates that the size reduction is caused by the Coulomb explosion of the highly-charged gold nanoparticles. The mechanism of laser-induced size reduction is quantitatively discussed based on the liquid drop model.

6458A-38, Session 11

Patterning microconductor on flexible polymer using nanosecond laser ablation of metal nanoparticle film

S. Han, T. Lim, S. Lee, J. Chung, Korea Univ. (South Korea); S. H. Ko, C. P. Grigoropoulos, Univ. of California/Berkeley; J. Moon, Yonsei Univ. (South Korea)

Drop on demand inkjet printing of metal nanoparticle solution and the subsequent sintering at a reduced temperature due to melting temperature depression of nanoparticles is expected to give new opportunity in the area where micro-conductor pattern need to be fabricated at a temperature compatible to polymer film in a cost effective way, such as printed circuit board, flexible electronics, etc. However, the typical resolution of inkjet printing (>10-20um), which is mainly governed by the nozzle diameter and statistical variations of droplet impact and spreading, is an issue.

Previously, we proposed hybrid printing method utilizing laser curing and ablation to overcome the resolution of current DOD inkjet processing. In this work, nanoparticle films (silver nanoparticles synthesized by poyol method and alkanethiol protected gold nanoparticles synthesized by two phase method) were ablated using frequency doubled Nd:YAG nanosecond laser and the ablation patterns were characterized by atomic force microscopy. In addition, sintering characteristics were studied using thermal analysis (thermo gravimetry analysis, differential scanning calorimetry) and resistivity measurement.

6458A-39, Session 11

Lithography free high-resolution inkjet-printed OFET(organic field effect transistor) fabrication on polymer by laser processing

S. H. Ko, H. Pan, C. P. Grigoropoulos, Univ. of California/Berkeley; D. Poulikakos, ETH Zurich (Switzerland)

The low temperature fabrication of OFET(organic field effect transistor) on the flexible polymer substrate is presented in this paper. A drop-on-demand (DOD) ink-jetting system was used to print gold nano-particles suspended in Alpha-Terpineol solvent, PVP (poly-4-vinylphenol) in PGMEA (propylene glycol monomethyl ether acetate) solvent, semiconductor polymer (modified polythiophene) in dichlorobenzene(oDCB) solution to fabricate OFET on flexible polymer substrates. Short pulsed laser ablation enabled finer electrical components to overcome the resolution limitation of inkjet deposition. Continuous Argon ion laser was irradiated locally to evaporate carrier solvent as well as to sinter gold nano-particles. In addition, a new selective ablation of multilayered gold nanoparticle film was demonstrated using the SPLA-DAT(selective pulsed laser ablation by differential ablation threshold) scheme for sintered and non-sintered gold nanoparticles. Finally, selective ablation of multilayered film was used to define narrow channel of a FET (field effect transistor) and semiconductor polymer solution was deposited on top of channel to complete OFET (organic field effect transistor) fabrication.

6458A-40, Session 11

Laser production and processing of metal nanoparticles with controlled features

J. A. Gonzalo, J. Margueritat, V. Resta, J. Siegel, C. N. Afonso, Consejo Superior de Investigaciones Científicas (Spain)

Metal nanoparticles are interesting for many applications both on surfaces and embedded. Examples are catalysis, SERS, sensors and several optical devices. In most cases, nanoparticles with very well defined features, i.e. dimensions or shape, as well as controlled distribution are required.

Laser techniques can be used to both produce nanoparticles and manipulate them on surfaces in order to tailor their features to the particular application. One of the most promising techniques for their production is pulsed laser deposition that allows not only producing nanoparticles on surfaces but also embedding them in complex materials such as oxides with a nanometer control of their in-depth distribution or shape. This contribution aims to illustrate these possibilities by providing examples of Ag or Au metal nanoparticles produced by pulsed laser deposition both embedded in an oxide and on surfaces. Layered structures or oriented rods / nano columns can be produced whose features can on the one hand be designed to match the particular application. On the other hand, the features can be selected in order to study fundamental problems such as particle interactions phenomena due to their proximity (i.e. Ag-Ag) or to their different nature (Ag-Co). In the case of nanoparticles produced on surfaces, the possibility to control their features by laser irradiation will be illustrated. Results will be presented showing the importance of effective laser fluence rather than laser wavelength on the results achieved, as well as the thermal response of the substrate on which the nanoparticles are supported.

6458A-41, Poster Session

Laser direct-write and crystallization of FeSi2 micro-dot array for NIR light-emitting device application

A. Narazaki, R. Kurosaki, T. Sato, Y. Kawaguchi, H. Niino, National Institute of Advanced Industrial Science and Technology (Japan)

We successfully fabricated beta-FeSi2 micro-dot array utilizing laser direct-write deposition and laser crystallization.

FeSi2 in the beta crystalline phase is a promising eco-friendly semiconductor because of NIR electroluminescence used for optical networking as well as abundant components reserve on the earth and non-toxicity. However, preparation of beta-FeSi2 film generally required high-temperature multi-processes which hamper its integration and performance reproducibility. On the other hand, we found that the laser-induced melt generated by laser ablation (droplet) tends to precipitate as the beta phase at lower temperatures.

The presentation will describe a new approach to fabrication of FeSi2 micro-dots with controlled size and position using laser-induced forward transfer. An amorphous FeSi2 film deposited on a silica glass was used as a material source. One side of the film was faced with a silicon substrate and the other side was irradiated with a KrF excimer laser pulse

with a micro-pattern. After single-shot irradiation, FeSi2 micro-dots array was transferred onto the silicon substrate. Successive laser crystallization improved the crystallinity, resulting in beta-FeSi2 micro-dot array formation.

6458A-42, Poster Session

Holographic femtosecond laser processing by use of a spatial light modulator

S. Hasegawa, Y. Hayasaki, The Univ. of Tokushima (Japan)

Femtosecond laser processing provides high spatial resolution and causes reduced thermal destruction of a target as a result of the ultrashort interaction time between the laser pulse and the material. Furthermore, when a femtosecond laser pulse is tightly focused in a transparent material, a void and a refractive index change are formed inside. Therefore femtosecond laser processing is one attractive technology in the field of nanofabrication, and widely used to fabricate a next-generation of three-dimensional (3D) optical devices.

The wide practical applications are still limited by the high photon cost in comparison to traditional laser processing. The strategy to enhance the appeal of femtosecond laser processing is to improve the throughput of laser processing, and to perform an efficient use of laser pulse energy. There are two possible methods to achieve high-speed laser processing. One method is scanning processing. Although this method can perform arbitrary large-scale patterning, it requires a high-repetition laser, a high-speed optical switching device, and a high-speed scanning device. Another method is parallel processing. The multiple-beam interference method has been proposed to make 3D periodic structures. To fabricate an arbitrary structure, a computer-generated hologram (CGH) is used. We have recently demonstrated a holographic femtosecond laser processing system with parallel, arbitrary, and variable patterning features, which were achieved by using a liquid crystal spatial light modulator (LCSLM) displaying the CGH. The current issue of the parallel processing method is the uniformity of diffraction peaks. In this paper, we demonstrate two-dimensional and three-dimensional parallel processing of glass.

6458A-43, Poster Session

Measuring some characteristics of a supersonic air microjet

J. G. Velasquez-Aguilar, G. Toker, Univ. Autónoma del Estado de Morelos (Mexico)

Recent years have seen considerable research in the field in the fluid of dynamics of supersonic air micro jets (SAMJ) due to their potential use in applications such as micro-propulsion, cooling of MEMS components and fine particle deposition and removal, which could be useful for microelectronic and optoelectronic manufacturing. With that visualization and investigation of the supersonic air micro jet as a weak phase object represent serious problems for classic interference methods.

Although in literature the numerous experiments are described, which were performed with help of the micro-Schlieren system with a large magnification (see for example Phalnikar et al. 2001), qualitative analysis shows that studying SAMJ by different “fringe” techniques, such as interferometry is more attractive due to their powerfulness and flexibility. Most powerful and applicable interference techniques are holographic ones (Gopalan 2001, Mizukaki et al. 2000) since they possess remarkable advantages over classic approaches.

Application in present paper reference beam and shear dual-hologram methods conjointly makes more successful measuring characteristic densities, density gradients and studying a jet structure: weak shocks following by expansion waves. The effect of fast transition to a transonic regime accompanying the disintegration of a jet was observed and densities in transition region were evaluated. As a whole, method of dual-hologram interferometry has showed their self-descriptiveness, flexibility and utility for optical diagnostics of a weak gas dynamic micro object - the supersonic air micro jet.

6458A-44, Poster Session

Fabrication of ZnO nanorods by pulsed laser deposition method with catalyst-free process and its properties

R. Nishimura, T. Sakano, T. Okato, M. Obara, Keio Univ. (Japan)

Recently, ZnO nanostructures have been studied, because the optical and electrical properties of ZnO can be changed by the unique structures. ZnO nanorods is promising among the many nanostructures, because it shows large surface area, high aspect ratio and quantum confinement effect. Therefore, the ZnO nanorods would be a candidate for a gas sensor, dye-sensitized solar cell and electron field emitter. For device applications, it is very important to control the growth of the high quality ZnO nanorods. Pulsed-laser deposition (PLD) is an efficient method to grow ZnO nanostructures, but it usually requires metal catalyst to assist the vapor-liquid-solid growth. The metal catalyst can be a contaminant within the nanorods, so that the catalyst-free growth process is anticipated.

In this study, we fabricated the ZnO nanorods on Si substrate through a two-step process without the metal catalyst. As for a first step, ZnO powder dispersed on Si substrate is thermally annealed. After the annealing, we have obtained ZnO seeds layer which acts as catalysts to grow nanorods. Secondly, ZnO is deposited on the seeds layer by PLD in argon environment. A KrF excimer laser is focused on the ZnO target surface at a fluence of 3 J cm-2. After the deposition, we have successfully fabricated the ZnO nanorods. The length of nanorods are up to 4 μm with a typical diameter of 100 nm. We characterize the properties of nanorods using x-ray diffraction, x-ray photoemission spectroscooy and cathode luminescence spectroscopy. We will also discuss the growth mechanism and the controllability of diameter, length and density of the nanorods on a nanometer scale.

6458A-45, Poster Session

Pulsed laser processing of shallow micro-optical structures; ablation vs. lithography

J. E. A. Pedder, A. S. Holmes, Imperial College London (United Kingdom)

Pulsed UV laser machining is an established method for production of 2.5D and 3D features in a wide variety of materials. In addition to direct laser patterning by ablation, exposure of photoresist using pulsed lasers can eliminate the need for large area contact photomasks.

Several mask projection techniques have been developed for the efficient fabrication of dense arrays of repeating 3D microstructures. These techniques offer outstanding repeatability and allow the fabrication of large area arrays used in display applications.

Half-tone machining, either by ablation or exposure, allows the production of high quality shallow features where the surface roughness from other laser machining techniques would be unacceptable. Such features could be used as diffuser or directing plates for LCD display panels.

Features produced by lithography typically exhibit low surface roughness but have more complex fabrication processes. We will discuss the surface roughness of shallow features produced by half-tone lithography and half-tone ablation in photoresist and polycarbonate respectively.

6458A-46, Poster Session

Effects of surface roughness on cell-surface interactions

J. P. Ulerich, L. C. Ionescu, J. Chen, W. W. Soboyejo, C. B. Arnold, Princeton Univ.

Laser surface modifications of bio-compatible materials have been shown to be an effective method to improve compatibility and promote cellular growth and adhesion. In this presentation, we examine the influence of

laser parameters on the resulting surface characteristics with particular emphasis on multiscale roughness. Nanosecond laser micromachining (355 nm DPSS Nd:YVO4) is used to produce periodic grooves on the surface of Titanium-6 Aluminum- 4Vanadium alloy. The groove width, pitch, and depth are fixed to the desired spacing for promoting cell growth and the roughness is control by varying incident laser parameters, number of passes, surrounding environment, and the translation distance between sequential laser pulses. Surfaces are characterized for chemical composition, corrosion resistance, and roughness on multiple length scales prior to testing cell interactions. Osteosarcoma cells are seeded on these surfaces and examined with respect to their growth and adhesion after different incubation times and compared to results on control surfaces. Results indicate that roughness on the micron scale helps promote cell growth while smaller scale roughness can decrease the ability for cells to adhere to the surfaces. These results will be discussed in the context of laser induced surface modifications and control of machining parameters.

6458A-48, Poster Session

Laser-light materials processing with control of microstructure parameters

Y. N. Bulkin, RFNC-VNIIEF (Russia); G. A. Turichin, V. K. Syssoev, Lavochkin Scientific and Production Association (Russia); G. Alekseev, Lavochkin Research and Production Association (Russia)

The prototype of laser-light hybrid technology set has been developed on the base of pulse-periodic Nd:YAG laser and powerful arc lamp. Prototype design has been improved to increase the power and to broaden the spectrum of lamp radiation. Different lamp gases were tested to increase a light efficiency. For explanation of the peculiarities and advantages of laser-light hybrid welding the analytical-numerical mathematical model of heating zone with consideration of radiation absorption coefficient temperature dependence and heat-mass transfer problem has been developed. Marangoni effect and evaporation energy loses were taken into account. The influence of hybrid laser-lamp thermal cycle shape on size of nano-scale carbide precipitation as well as material microstructure and plasticity of steels has been simulated with developed model and experimentally observed. Mild steel, alloyed steel and Ti were used as materials for experiments. Experiments proved, that it is possible to get bainite microstructure instead martenite one by means laser-light hybrid treatment. Obtained results show, that usage of laser-light source instead of laser source for thin plate welding allow to homogenize the heat affected zone microstructure, decrease a micro hardness deviations and increase of technological plasticity up to 30% in comparison with laser welding.

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6458B-51, Session 1

Femtosecond laser-induced self-organized surface and bulk periodic structures for applications in biophotonics

E. S. Simova, C. Hnatovsky, R. S. Taylor, D. M. Rayner, P. B. Corkum, National Research Council Canada (Canada)

The development of key components for biochip and lab-on-a-chip devices for fast efficient analysis of nano/pico-liter volumes of bio-chemical reagents and biological species has been a central task in materials science. Micro- and nanofluidic channels are amongst these components. An important application of nanofluidics is separation science, which needs porous materials with pore sizes below 1 μm realized as membranes of variable thickness in a lab-on-a-chip environment. Currently, the fabrication of biochip devices is mainly based on well established lithographic and nanoimprint techniques which, however, lack 3-D capability. Femtosecond laser-assisted micromachining can provide a single platform technology for the realization of 3-D lab-on-a-chip devices in transparent dielectrics, as well as integration with optical waveguides and components.

In this work, we show 3-D high aspect ratio microfluidic channels fabricated by femtosecond irradiation of fused silica with subsequent etching in diluted hydrofluoric acid. We demonstrate an all-optical control of the etch rate by varying the polarization state of the laser writing beam and show that highly selective chemical etching is caused by the formation of polarization-dependent ordered nanocracks and disordered nanostructures inside the femtosecond laser modified zones. Further, we demonstrate that direct femtosecond laser writing can be used to fabricate nanoporous capillaries in bulk fused silica, where the morphology of the porous structures depends on laser writing parameters. Laser induced dye fluorescence shows penetration into the porous channels over millimeter distances. With this technique it should be possible to make nanoporous membranes of variable thickness integrated into a micro-nanofluidic channels in fused silica. We also use femtosecond laser light to create polarization-dependent self-ordered periodic nanoslots on the surface of fused silica wafers for the purpose of aligning metallic nanoparticles for Surface Enhanced Raman Scattering (SERS) applications. This direct writing technique has a sub-diffraction resolution of below 10 nm. It features high throughput of writing periodic nanoslot arrays over centimeters with each nanoslot of hundred microns length and a high aspect ratio. Control of the slot's width from 10 to 50 nm is achieved through selective chemical etching.

6458B-52, Session 1

Stability of biofunctionalized surface of GaAs

X. Ding, Univ. de Sherbrooke (Canada); G. Marshall, F. Bensebaa, National Research Council (Canada); J. J. Dubowski, Univ. de Sherbrooke (Canada)

No abstract available

6458B-53, Session 1

Atomic layer deposition of atomic mirror for silicon

T. Fujimoto, Y. Shiomi, H. Kumagai, A. Kobayashi, Osaka City Univ. (Japan)

There have been significant progresses in atom optics utilizing laser cooling technique in recent years. Above all, we have been interested in an atomic mirror for silicon, which can reflect silicon atoms that is very important as the atomic species of semiconductor materials. The atomic mirror consists of two layers on a Sapphire substrate, and then atoms are reflected by the dipole forces from evanescent waves caused by the light reflected internally and totally at the interface of different refractive indices. In this study, we have constructed some structures of the atomic mirror to enhance the evanescent waves significantly when the resonant deep ultraviolet light is irradiated from the backside of the atomic mirror.

We tried atomic layer deposition techniques for preparation of both Al2O3 and TiO2 thin films, whose surface and interface roughnesses should be as controllable as those of a metal-oxide x-ray mirror that one of authors demonstrated. In order to achieve the predicted enhancement of the evanescent waves, atomic layer deposition of the layer with the higher refractive index is especially important. It has found that absorption can be suppressed considerably by adding Al(CH3)3 precursor gas to the alternate introducing cycle of TiCl4 and H2O2 precursor gases, at below 400 nm. This effect can improve homogeneity and flatness of layers, significantly. In the presentation, we will present the atomic layer deposition of an atomic mirror in detail.

6458B-54, Session 1

Femtosecond laser nanostructured substrates for surface-enhanced Raman scattering

E. D. Diebold, E. Mazur, Harvard Univ.

We present a new substrate for efficient surface enhanced Raman scattering (SERS). Using a train of focused frequency-doubled femtosecond laser pulses from a regeneratively amplified Ti:Sapphire laser, we fabricate submicron surface structures on a silicon wafer. After irradiating the silicon wafer with 400nm, 100fs laser pulses in a cuvette of water, we observe the formation of an array of spikes, each approximately 500nm tall and 200nm wide. The wafer is scanned across the beam to form an arbitrarily-sized nanostructured area. When covered with a thin film of a noble metal, the structured surface exhibits a strong enhancement of the Raman signal as measured using micro-Raman spectroscopy. To quantify the surface enhancement factor of the device, we cover the surface with a self-assembled monolayer of benzenethiol. The Raman surface enhancement factor of the structured area is measured to be approximately 10^6. These inexpensive, reproducible, and efficient SERS substrates show great promise for use in chemical and biological sensing, as well as demonstrate yet another application for ultrafast laser technology.

6458B-55, Session 1

Growth of supported gold nanoparticles: the influence of substrate material, temperature, and laser irradiation

N. Borg, D. Blázquez-Sánchez, C. Hendrich, H. Ouacha, F. Hubenthal, F. Träger, Univ. Kassel (Germany)

In order to tailor the optical properties of metal nanoparticles for different applications, a variety of parameters must be considered and modified. Here, the substrate material as well as its temperature during growth has been varied systematically to clarify the influence of these parameters. Gold nanoparticles with radii ranging from 0.5 to 12 nm were prepared under ultrahigh vacuum conditions by deposition of gold atoms on quartz, sapphire and titanium dioxide substrates followed by Volmer-Weber-growth. As a consequence of this self-organised assembly we obtained nanoparticle ensembles with a broad size and shape distribution where the shape is strongly correlated to the size of the nanoparticle. We measured the influence of the substrate material, and the temperature on the

shape of the particles. In addition, the method of laser assisted growth has been applied to further tailor the nanoparticles. This technique was developed in our group [1,2] and takes advantage of the optical properties of metal nanoparticles to overcome the correlation between the shape and the size, the objective being to produce nanoparticles with desired, well-defined shapes and variable sizes. Depending on the wavelength and the fluence of the laser light we can stabilise the mean axial ratio of the gold nanoparticles at values ranging from 0.16 to 0.98 independent of size.

[1] Wenzel et al., Appl. Phys. B 69, 513 (1999).

[2] Ouacha et al., Appl. Phys. B 81, 663 (2005).

6458B-56, Session 2

Laser-based techniques for innovative biosensing

I. K. Ilev, U.S. Food and Drug Administration

The field of photonics biosensors, including both laser- and fiber-optic-based ones, is an intensively active area of modern biophotonics technologies because these sensors are potential alternatives to conventional medical methods for diagnostics and monitoring of diseases. They offer a minimally invasive, highly sensitive and accurate means for measurement and control of various physical and biomedical quantities. Biosensor techniques and devices utilizing minimally invasive biophotonics technology are rapidly finding their way into the mainstream for early disease diagnostics, laser therapy, in situ optical biosensing and bioimaging. In this work, we present the fundamental principles and features of the most significant innovative photonics biosensor technologies. This includes description of basic biosensor systems as well as key optical elements of these systems such as: typically used biomedical lasers and incoherent light sources, various biosensing optical fibers including their advanced properties and critical parameters, and effective light modulator and detector systems. Among the most effective and well-developed biosensor techniques, we consider biophotonics chemical, evanescent, combined, clinical and nano-biosensors. In addition, we present a novel concept that has been recently developed for noninvasive high-resolution confocal biosensing based on simple apertureless fiber-optic confocal designs including either dual-confocal or single-fiber sensor systems. The method can be employed for precise micron/submicron/nanoscale sensing of the optical properties of various cellular/intra-cellular components, tissue layers and bulk samples.

6458B-57, Session 2

Monocrystal photonic opal films and hetero-structures

A. I. Plekhanov, Institute of Automation & Electrometry (Russia); D. V. Kalinin, V. V. Serdobintseva, Trofimuk United Institute of Geology, Geophysics and Mineralogy (Russia)

Photonic crystals (PhC) form an exciting new class of optical materials that can greatly affect optical propagation and light emission. It well known that in currently available research grade opals as PhC it is technical impossible to make opals without defects. It is very important to develop the technique in order to get monocrystal PhC with larger size. We report on the realization of thin film opals. Scanning electron microscopy reveal the high quality of these films. Opal films were grown on transparent substrate using silica beads with different diameters (160-300 nm) by convective vaporization of alcohol colloidal suspension. Each film consist of 15-20 monolayers of silica beads so the reflectance of such films achieved up to 90%. One advantage of a thin film opal over bulky opal is the orientation of the crystallites in the thin film with the [111] axis normal to the surface. Opaline films should be made ideally with a controllable number of layers. It is easy to make opal-based hetero-PhC by assembling from two or three or more different opal films, grown successively on top of each other. We have studied optical and luminescent properties of such films and hetero-PhC infiltrated by organic dyes.

6458B-58, Session 2

Probing the chemical role of ambient O2 in the formation of carbon nanotubes via excimer laser ablation

G. Radhakrishnan, P. M. Adams, The Aerospace Corp.; L. S. Bernstein, Spectral Sciences, Inc.

Room-temperature ablation of a composite graphite-metal target, at 248 nm, in O2, produces large-channeled (50-150 nm) multiwalled carbon nanotubes. We find that the formation of these carbon nanotubes is dependent on the ambient gas employed during ablation. Such nanostructures are not produced in inert atmospheres of Ar or in high-vacuum. High-resolution, in-situ, time-resolved emission spectroscopy has been used to track the evolution of species (C2, C3, Ni/Co) in the ablation plume, in different ambient gas atmospheres. Spectral fits on low and high-resolution spectra reveal time-dependent vibrational-rotational temperatures for C2 that are different in O2 compared to Ar. Spectral modeling shows that the vibrational-rotational temperatures for C2 produced in O2 remain at ~ 5000 K for nearly 20 msec, but drop rapidly in Ar. Plume chemistry in other gases such as N2 and H2O and correlations to the corresponding ablation products have also been investigated. The key role of exothermic reactions occurring in the plume, and that of radiative cooling will be discussed.

6458B-59, Session 2

Laser induced coalescence of gold nanoparticles - molecular dynamics study

H. Pan, S. H. Ko, C. P. Grigoropoulos, Univ. of California/ Berkeley

This article investigates the laser-induced coalescence of two gold nanoparticles. The molecular dynamics method is coupled with the discrete dipole approximation (DDA) to predict the dynamic behaviors of the coalescence process in complex electromagnetic field on atomic level. Using the proposed method, local absorption and optical forces induced by laser illumination can be calculated and the dynamic neck growth process is obtained. The effects of laser power density, pulse duration, polarization, inter-particle distance and particles size on the neck growth process and structure of the neck are examined in details.

6458B-60, Session 2

Effects of surface asymmetry on femtosecond second-harmonic generation from metal nanoparticle arrays

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We describe experiments aimed at distinguishing between possible mechanisms of second-harmonic generation (SHG) in lithographically prepared arrays of metal nanoparticles. It is well-known that even harmonics cannot be generated by electric dipole-dipole interactions in centrosymmetric systems. The experiment employs two basic sample geometries. In previous work, and in the first set of arrays, the NPs are left exposed to air, producing an asymmetric local dielectric environment with ITO on one side and air on the other. In the second set, we coat the arrays with ITO, thus producing a centrosymmetric environment in which any SHG observed can not be due to asymmetry in the medium, but to nonlocal or retardation mechanisms in the particles. The arrays are fabricated using focused ion-beam lithography and vapor deposition of the metal, followed by standard lift-off protocols , This procedure yields typical NP dimensions between 60 nm and 150 nm in diameter, and between 15 nm and 30 nm in height, as characterized by scanning electron and atomic-force microscopy. By tuning the NP resonances to the excitation wavelength the SHG signal can be substantially enhanced. Surface melting effects are minimized by the use of ultrashort (12-fs) pulses which give high intensity while allowing us to work at relatively low fluence.

6458B-61, Session 3

Self-organized embedded silver nanocolumns produced by pulsed laser deposition for plasmonics

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Metal nanoparticles are receiving renewed attention due to the development of nanotechnologies as they are essential in many fields such as photonics, plasmonics, catalysis, medicine or biology among others. Their possible application relies on the control of their size and shape, as their properties are directly related to their morphology. Therefore, the development of techniques able to tailor the size and shape of nanoparticles, either supported on substrates or embedded in a host is a crucial stage for the widespread use metal nanoparticles.

Pulsed laser deposition allows the production of nanocomposites consisting of silver nanoparticles embedded in a host, the nanoparticles being organized in layers whose separation can easily be controlled through the deposition parameters. This technology has been extended to produce nanocolumns by reducing the distance between consecutive layers until each silver “layer” interacts with the previous one. In that case the spherical nanoparticles self-assemble and form nanocolumns. In the present work we have optimized the deposition method to produce nanocolumns having aspect ratios up to 25. TEM and GISAXS analysis confirms the production of nanocolumns having diameters in the range 2.5-3.0 nm and large aspect ratios. Optical extinction spectra show the presence of two surface plasmon resonances (SPR) in the visible corresponding to the transverse and longitudinal modes of the nanocolumns. These SPR modes are well separated, thus confirming large aspect ratios for the as-deposited nanocolumns. The optical extinction spectra of embedded nanocolumns show a blue shift of the transverse SPR when increasing the aspect ratio, while the longitudinal SPR does not show a significant red shift as opposite to what is predicted by theoretical models.

6458B-62, Session 3

Control of shape and distribution of silver nanoparticles in glass by ultrafast laser irradiation

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Glass containing spherical silver nanoparticles shows a strong extinction band in the visible range due to the surface plasmon resonance (SPR) of the particles. Irradiating this material with intense, ultrashort laser pulses leads to permanent changes of its optical properties. In particular, using linearly polarized femtosecond pulses, we observed strong dichroism as a consequence of transforming the particles to ellipsoidal shapes with a preferential orientation. While in this femtosecond time regime field-driven electron and ion-ejection control the properties of the generated particles, nanosecond irradiation leads to considerably different changes: in that case mainly the spatial distribution of particles is reorganized, and thermally driven diffusion processes are important. If nanosecond irradiation is applied to a glass-metal nanocomposite, which was pre-structured by electric-field driven particle dissolution with a Si photonic crystal as electrode, a regular array of considerably large silver spheres in glass can be produced.

In this paper we describe the various changes of metal nanoparticle shape and distribution which we have observed after irradiating of glass-metal nanocomposites using laser pulses with temporal width from femto- to nanoseconds, and discuss potential technological aspects of the optical microstructures produced by this technique.

6458B-63, Session 3

Modification of noble metal nanoparticles in a silica matrix by pulsed tunable infrared laser irradiation

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We have used pulsed tunable infrared laser irradiation to modify the optical and physical properties of metal nanoparticles in a SiO2 substrate. The nanoparticles were fabricated by implanting high-energy Au+ or low-energy Ag+ ions at a dose of 6.1016 ions/cm2. The substrate temperature was held at 400 degrees Celsius during implantation. The depth of the nanoparticles was well within the 1/e absorption length of the SiO2 substrate at our primary wavelength of 8μm. The infrared laser beam generated by a picosecond free electron laser (FEL) was then scanned across the implanted surface at various fluences. The optical absorption spectra of the gold implanted sample show that the absorption maximum at 520 nm, which is related to the presence of gold colloids, increases with laser fluence. On the other hand, the absorption maximum at 415nm in the spectra of the silver- implanted sample decreases with increasing laser fluence and shifts to slightly lower wavelengths. In both cases a visible change in the color of the sample is observed, a clear indication of changes in the size distribution of the nanoparticles. Previous experiments used nanosecond excimer lasers which directly interact with the nanoparticles to modify their size and size distribution in different matrices. Our successful modification of the nanoparticles by excitation of the matrix vibrational modes, rather then melting of the nanoparticles, shows another possible approach to the processing of nanocomposite optical materials.

6458B-64, Session 3

Pulsed laser deposition of nanoparticles with nano- and femtosecond pulses

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Nanoparticle alloys of magnesium and nickel have been created by pulsed laser deposition with nano and femtosecond pulses. The affect of background pressure on nanoparticle size has been investigated. Great interest exists in the controlled creation of Mg_Ni nanoparticles for hydrogen storage applications. The small physical size of the nanoparticles decreases the diffusion distance for hydrogen absorption while the Mg_Ni blend increases the kinetics of absorption and desorption by lowering the energy barrier. However, the addition of Ni decreases the atomic weight percentage of absorbed hydrogen; therefore, great control of nanoparticle size and composition is needed for advanced energy storage applications. This paper explores the affects of pressure for nano and femtosecond pulse durations. Nanoparticle films deposited were investigated with x-ray diffraction (XRD), an atomic force microscope (AFM), a scanning electron microscope (SEM), and energy dispersive x-rays (XRD).

6458B-69, Session 3

Fabrication and characterization of optical negative-index metamaterials

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Metamaterials, i.e. artificial engineered structures with properties not available in nature are expected to open a gateway to unprecedented electromagnetic properties and functionality unattainable from naturally occurring materials. Negative-index metamaterials (NIMs) create entirely new prospects for guiding light on the nanoscale, some of which may have revolutionary impact on present-day optical technologies. We review this new emerging field of metamaterials and recent progress in fabrication of NIMs and demonstration of a negative magnetic permeability and negative refractive index in the optical and visible ranges, where applications can be particularly important.

6458B-65, Session 4

Mechanisms of nanoparticle formation by short laser pulses

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Numerical modelling is performed to study cluster formation by laser ablation. The developed model allows us to compare the relative contribution of the two channels of the cluster production by laser ablation: (i) direct cluster ejection upon the laser-material interaction, and (ii) collisional sticking, evaporation and coalescence during the ablation plume expansion. Both of these mechanisms are found to play important roles in defining the final cluster size distributions.

Plume cluster composition is correlated with plume dynamics. The results of the calculations demonstrate that cluster precursors are formed during material ablation. Then, plume expansion and cooling take place leading to the overall decrease in the reaction rates. Growth of larger clusters can be observed at this stage. Calculation results explain several recent experimental observations.

6458B-66, Session 4

TEM investigation of laser-induced periodic surface structures on polymer surfaces

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Laser Induced Periodic Surface Structures (LIPSS) may have numerous applications, ranging from biomaterial applications to LCDs, microelectronic fabrication and photonics. However, in order to control the development of these structures for their particular application, it is necessary to understand how they are generated.

It is widely agreed in the literature that the optical process responsible for LIPSS generation is the interference of a surface scattered wave with an incoming wave. However, the full detail of what occurs within the material as a result of the modulated illumination pattern is still not known. It is as yet not definitively clear if LIPSS is an ablative process or occurs due to other factors such as migration of polymer chains due to the electric field vector of the polarized beam, changes in surface tension in a melt region of the polymer or flow of melt material due to modulation of intensity leading to an undulating temperature distribution on the surface.

We report our work on investigating the melting that occurs during LIPSS formation. LIPSS were generated on three polymer surfaces - PET, amorphous polycarbonate and orientated crystalline polycarbonate - which were irradiated with a polarized ArF excimer laser (193 nm) beam with fluences between 3 and 5 mJ/cm2.

The structures were imaged using a Transmission Electron Microscope (TEM), which facilitated investigation of changes in the polymer structures and consequently the depth of the melt zone that accompanies LIPSS generation.

We also present theoetical calculations of the temperature-depth profile due to the interaction of the low fluence 193 nm laser beam with the polymer surfaces and compared these calculations with our experimental results.

6458B-67, Session 4

Efficient coupling between guided optical modes in ZnO nanowire-waveguides and tapered silica fibers

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We combine top-down and bottom-up processes for the fabrication of photonic nanowires to efficiently inject and extract light from waveguide modes of ZnO nanowires lying on low refractive index silica aerogel substrates. Our approach relies on the emission of propagating modes of the light field from a tapered silica fiber and the efficient coupling of the emitted field into the high-index ZnO nanowires. We show that this approach provides a robust and surprisingly efficient technique to study the waveguiding properties of semiconductor nanowires. The experimental results are confirmed and quantified by numerical simulations of the different coupling processes using a finite difference time domain approach. We discuss potential applications of this technique for further experiments, which combine passive and active nanoscale photonic elements.

6458B-68, Session 4

Pulsed laser heating for controlled growth and processing of SWNTs

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A high power, pulsed Nd:YAG laser system has been used as a localized heat source to explore rapid growth and processing of single walled carbon nanotubes (SWNTs). Pulsed laser heating provides precise temporal and spatial control of heat pulses to investigate nucleation and growth mechanisms and site-specific annealing of nanostructures. It also offers the possibility for laser direct-writing of nanotube and nanowire devices. The heating time can be precisely controlled by choosing the proper laser power, repetition rate, pulse width and number of laser pulses. Growth temperatures are monitored using fast, in situ optical pyrometry. The growth of carbon nanotubes using a pulsed laser-assisted chemical vapor deposition (PLA-CVD) technique under single and multiple heating pulses reveals that, in contrast to conventional thermal CVD all the carbon nanotubes produced are single walled. Growth rates are easily estimated by this technique, and rates are sufficient to "write" individual SWNT field-effect transistors by PLA-CVD on pre-defined electrodes. The resulting SWNT transistors exhibited pronounced ambipolar transport characteristics with on/off ratios up to 1000.

6458B-70, Session 4

High-power laser vaporization synthesis of single wall carbon nanotubes and nanohorns

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Many interesting applications of single-wall carbon nanotubes (SWNTs) require large quantities of nanomaterials with well-controlled diameters, lengths, and purity. Unlike low temperature chemical vapor deposition techniques, high temperature laser vaporization (LV) approach produces SWNTs with a narrow range of diameters that are attractive for different applications. However, typical yield for as-produced SWNT material using low power scientific lasers is very low.

In this talk a laser vaporization approach will be discussed for high volume synthesis of single wall carbon nanotubes (SWNTs) (~ 6 g/h) and single wall carbon nanohorns (SWNHs) (~ 9 g/h) based on a high average power industrial Nd:YAG laser (~ 600 W average power, 10 kW maximum intensity, 0.5-50 ms pulse width, 1-500 Hz repetition rate). Investigation of high-temperature SWNT and SWNH synthesis was concentrated upon the effect of laser power, pulse width, and repetition rate on controlling the growth time, temperature, and confinement of ejected material from laser-vaporized C and C/Ni/Co targets under high-power laser vaporization conditions. Two optimized regimes for SWNTs vs. SWNHs synthesis were identified at 1100°C: multiple short pulses with low energy (0.5 ms, 5J , 80 Hz, 500 Torr Ar) for SWNTs and single long pulses with high energy (20 ms, 90 J, 20 Hz, 760 Torr Ar).

A 3D model of heat transfer in the targets including irradiation with a moving laser beam was developed. The total ablation yield and the heat losses due to heat conduction, target evaporation, black body radiation, and cooling by the surrounding buffer gas were calculated at different laser irradiation conditions. The temperature of the target surface was calculated and compared with in situ fast pyrometry (2 ms time resolution)

measurements. As a result the thermal conductivity of the ablation targets was estimated (25 W/mK) and two different regimes of ablation were predicted: ablation by individual laser pulses and cumulative ablation. Using this model optimization of laser beam scanning rate and pattern has been performed to achieve uniform target erosion during long time laser vaporization synthesis of SWNTs and SWNHs.

High-speed videography (50,000 frames/s) and in situ pyrometry of the target surface were used to record and model the evolution of the ablation plume and the target temperature, respectively, using variable laser pulse widths and intensity profiles. These diagnostics were correlated with in situ differential mobility analysis of the formed clusters and ex situ high resolution TEM analysis of the products for pure carbon targets and carbon/catalyst targets. Pure carbon targets were found to produce single-wall carbon nanohorns (SWNHs) for millisecond and longer pulses. Through the variation of pulse width, growth times (6-23 ms) and growth rates (~ 1 nm/ms) for SWNHs were estimated for the first time, indicating that single-wall carbon structures can form at comparable rates without catalyst as with catalyst.

In situ differential mobility analyzer (DMA) measurements were performed for the first time during laser vaporization of pure graphite target for synthesis of SWNHs. It was found that particle size distribution depends on the laser pulse width and the mean electric mobility diameter (~ 70 nm at 0.5 ms and ~ 120 nm at 20 ms) is shifted to the smaller sizes at shorter laser pulses. This result correlates with our TEM observations that smaller nanohorns containing smaller individual units are forming in the case of the shorter laser pulses. These measurements provide insight into the growth mechanism of SWNTs by laser vaporization and explain the necessity of the relatively short pulses for high yield production of SWNTs. These results show that feedstock carbon nanoparticles with a relatively small size and optimal composition are required to enable their further catalytic conversion into SWNTs. We also discovered that small carbon nanoparticles (15-60 nm) could be sublimed from the laser produced carbon soot at the ambient furnace temperatures exceeding 950 ?C. This indicates that at high temperatures the subunits of SWNHs can exist as individual entities.

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6458B-71, Session 4

Recent advances in the optical spectroscopy of single-walled carbon nanotubes

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The optical properties of single-walled carbon nanotubes (SWCNTs) have attracted broad interest for several reasons. Optical spectroscopy provides the preferred method of determining nanotube structure. Optical spectroscopy also offers an excellent method for examining the unique physics of the excited states of these model 1-dimensional systems. Further, understanding of the optical properties is critical for the development of various promising optoelectronic applications of carbon nanotubes.

In this paper, we describe recent progress in our experimental ability to probe SWCNTs and the resulting improved understanding of their excited-state properties. We will discuss application of two-photon spectroscopy, with its distinctive selection rules, to demonstrate that the electronic transitions in semiconducting SWCNTs are excitonic in character, with binding energies as large as 300-400 meV. These strong electron-electron interactions are also responsible for rapid exciton-exciton annihilation, as we have demonstrated experimentally. Although ensemble measurements are adequate for many purposes, the ability to probe individual SWCNTs opens up many new possibilities. We will describe the newly developed technique of Rayleigh (elastic) light scattering spectroscopy, a method that provides single nanotube sensitivity for both semiconducting and metallic SWCNTs. Several applications of this method will be presented.

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6459-01, Session 1

Requirements and potentialities of packaging for bioreactors with LTCC and polymers

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The main focus of this article lies on the development of a novel joining technology for LTCC ceramic and polymer sub-assemblies utilising laser radiation.

The ceramic multilayer LTCC technology is an established serial technology for the production of sensors (e.g. pressure, pH, impedance) and actuators (e.g. piezoelectric oscillator). Micro-fluidic systems made of polymers by injection molding processes are inexpensive and reliable. It is also feasible to manufacture large micro-fluidic systems on basis of LTCC ceramic. But those systems are more expensive than equal systems made of polymer due to the higher material costs of LTCC. Another disadvantage of ceramic is that the material is not transparent and therefore not suitable for optical analyses.

Aim of the research is to develop inexpensive, multifunctional sensor systems by combining LTCC based sensor and actuator technology with injection molded polymer based micro-fluidic systems.

The system analyses the cellular growth in a micro-biological reactor with LTCC based sensor for temperature and impedance measurement. Impedance measurement is used to detect changes in cellular growth as a response of the cells to applied substances. Transparent polymer covers allow visual monitoring. The new method for joining of polymer and ceramic parts has the potential to facilitate developments in various fields of research. For example new and less expensive micro fluidic systems for biological and chemical analyses can be developed, for instance a micro capillary electrophoresis on a chip.

6459-02, Session 1

Laser welding of micro plastic parts

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Only few welding processes for plastics meet the special demands of microtechnology. Laser transmission welding has distinctive advantages like low mechanical and thermal load of the joining parts. Thus the laser is a joining tool which is particularly suitable for the welding of micro plastics parts. Contour welding is a process variant of laser transmission welding enabling the welding of complex and even three-dimensional weld contours. In addition to that, this is a very flexible process which can be easily adapted to changing part geometries. So far it is only applied for welding plastic parts of macroscopic scale in the industrial practice. Recent research at the Institute of Plastics Processing in Aachen shows that it is possible to use this process to weld complex micro parts, as well.

A micro plastic part with a three-dimensional weld seam geometry of a width of only 300 microns was designed and welded using a high power diode laser with a focus diameter of 230 µm. Welding experiments with amorphous thermoplastics show good results yielding high ultimate tensile strengths of the weld and preserving the microstructure in good order. Certain semi-crystalline plastics, however, strongly widen the laser beam by scattering due to the semi-crystalline structure. So the beam diameter can exceed the width of the weld seam leading to a plastification of large regions of the mircopart and the destruction of the fine weld seam structure. Thus in the field of welding micro plastic parts the choice of the material plays a decisive role regarding the possible application of high-power diode lasers.

6459-03, Session 1

Hybrid micro-optical system integration by laser beam soldering

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We investigated the packaging of hybrid microptical system on ceramic printed circuit boards by means of laserbeam soldering. Thick- and thinfilm metallizations on ceramic platforms made of Al2O3, LTCC or DCB on AlN not only provide integration structures for electronic wirings and circuit assembly as well as excellent thermal connections with varying thermal conductivities, they also suit for the soldering assembly of microoptical components, thus forming “all-soldered” hybrid electrooptical systems that are temperature and longterm-stable. In principal we characterized the joining characteristics, dealing with wetting behaviour of the ceramic platforms, their different heat spreading capabilities and the narrowed process windows for fluxless soldering. Additionally the focus was on the achievable accuracy during the laserbeam assembly process. Singlemode coupling accuracies in the lower micron and submicron range were realized by optimized joining geometries and introduced guiding elements. Optimized process parameters, especially a minimized reflow energy, the regime of its input and the sequential layout of sets of solder joints lead to the possibility to created fibercoupled assemblies that provide more longterm stable characteristics when compared to adhesively bonded assemblies. Thus laserbeam soldering as a micropackaging technology enables for the small footprint integration of high precise systems that contain optical, electrical and thermal functionality.

6459-04, Session 1

Laser-based rework in electronics production

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Even nowadays, the defect-free production of electronic devices without rejects or rework is hardly attainable. Defective electronic devices often have to be reworked manually. The problems of this practice are an inconstant quality of the reworked solder joints and a high degree of physiological stress for the employees.

This paper deals with a possible system technology for realizing an automated laser based rework process with a high degree of process stability. The solution presented is a pick- and place unit with integrated galvanometer scanner and a fibre coupled diode laser for quasi-simultaneous soldering processes as well as a pyrometer based process control for realizing constant soldering and rework results. This system technology permits the generation of rework strategies taking account of defect type, electronic component and the norm IPC-610.

In addition to an automated system technique the quality of laser reworked solder joints is important as well. The quality depends on the growing of intermetallic phases at the diffusion zone between solder, pads and leads, the formation of acceptable wetting angles and the providing of high mechanical stability as well as good electrical properties throughout product life. Investigations of attainable quality after laser based rework processes with different lead-free solder materials on different substrate finish variants - like HAL, chem. Sn, NiAu, Ag and OSP - will be discussed in this paper. The results of this test series lead to different strategies of energy input.

6459-05, Session 2

Combined laser texturing and molecular vapor deposition for wetting angle control

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We have used laser micromachining to texture a selection of materials on the micrometer scale. By mimicking the so-called lotus effect we have dramatically increased the contact angle for a number of materials. The Cassie-Baxter model of contact angles show that it is possible to render a basically hydrophilic substrate hydrophobic by using a proper surface texture. Likewise, texturing of hydrophobic surfaces can increase the contact angle even further. Thus, there are fundamentally two ways to achieve very large contact angles, or superhydrophobicity, namely by altering the materials wetting properties in a chemical manner or by altering the topology of surface.

By using a combined process of laser micromachining and Molecular Vapour Deposition (MVD), we are able to demonstrate control of the contact angle on a very wide selection of materials, regardless of their prior surface energies. The MVD process effectively modifies the outermost molecular layers to become hydrophobic, and the combined MVD and laser process thus adds the hydrophobic contributions from the surface chemistry as well as the topology.

We demonstrate how the surface engineered materials can be used to control droplet formation, to restrict fluid flows in, e.g., Lab-on-a-Chip systems and to enhance barrier-effects.

6459-06, Session 2

Laser-assisted modification of polymers for microfluidic, micro-optics, and cell culture applications

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Since several years, laser-assisted patterning of polymers is investigated for the direct fabrication of polymeric prototypes in microsystem technology, e.g. for capillary electrophoresis chips in bio-analytical applications. In many cases the laser process induces a chemical, physical and topographical change in the laser treated surface. This material modification can significantly influence the functionality, e.g. for micro-optic, microfluidic or biological devices. In this contribution we will present our current research results in laser-assisted modification of polystyrene (PS) and polymethylmethacrylate (PMMA) with respect to applications in micro-optics, micro-fluidics and cell culture applications. For this purpose the refractive index change, the wettability and the adsorption of proteins and the adhesion of animal cells were investigated as function of laser- and processing parameters. The possible change of surface chemistry was characterized with X-ray photoelectron spectroscopy.

The local UV-laser-assisted formation of chemical structures suitable for improved cell adhesion was realized on two- and three-dimensional PS surfaces. Above and below the laser ablation threshold two different mechanisms were detected. In the one case the produced debris was responsible for improved cell adhesion, while in the other case a photolytical activation of the polymer surface including a subsequent oxidization in oxygen or ambient air leads to a highly localized alterations of protein adsorption from cell culture media and increased cell adhesion. The highly localized control of wettability on polymeric surfaces was investigated for PS and PMMA. In the case of PS the dynamic advancing angle could be adjusted between nearly 0° and 150°. This was possible for a suitable exposure dose and an appropriate choice of processing gases (helium or oxygen). A similar but not so significant effect was observed for PMMA below the laser ablation threshold. For PMMA the dynamic advancing angle could be adjusted between nearly 50° and 80°. The adjustment of wettability for microfluidic application will be discussed.

Finally, new approaches for a rapid manufacturing of optical single-mode waveguides made of PMMA will be presented. For this purpose a high repetition excimer laser radiation source was used in combination with a flexible mask technology. The waveguides were characterized for the visible optical range and for 1550 nm. The obtained structures reveal absorption losses in the order of 1.4 dB/cm up to 5 dB/cm. The integration of integrated optical waveguides in micro-fluidic devices will be demonstrated.

6459-07, Session 2

Rapid prototyping of microfluidic components by laser beam processing

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Prototypes and small batches of micro-fluidic parts from polymers often cannot be produced competitive by micro-moulding or hot embossing due to tool making costs. Laser techniques do not require any special tools if processing is fully software controlled. In comparison to mass production techniques the time to get the first part is thereby drastically reduced.

The tooling concept consists of an ablation module and a joining module. First, micro-channels are ablated very precisely by deep UV radiation from an ArF excimer laser and then sealed by diode laser welding of cover plates. Setting-up of an economical laser machine tool requires development of an high-repetition rate ArF excimer laser capable of pulse rates above 1 kHz. The laser head for contour welding can be fitted on the ablation module, but for welding of larger quantities a dedicated mask welding module is preferred. The tooling concept is proven to be successful in producing parts for medical or bio-analytical devices.

Design studies for micro-mixers can be accelerated when numerical simulation and testing of cheap parts made of polymers are combined. If an indicator reaction is performed at ambient temperature without chemical aggressive agents there is no need to use high performance materials. After verification of the mixing properties either small lot fabrication by laser techniques or mass production by e.g. slip casting is used to produce micro-reactors made of more resistant materials.

Further, laser technology is successfully employed to prove a new concept for a shear stress sensing device at the walls of fluidic ducts. An array of filiform hairs is produced by laser drilling of a negative mould which is filled up with a casting resin. Thereby variations of pattern, diameter and length of micro-hairs can be made easily. When the sensor array is placed inside an optically transparent duct the deflection of single micro-pillars is read out by a special illumination and capture device. Then the deformation forces and shear stress can be calculated.

6459-08, Session 2

Laser micromachining of optical biochips

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Optical biochips may incorporate both optical and microfluidic components as well as integrated light emitting semiconductor devices. They make use of a wide range of materials including polymers, glasses and thin metal films, which are particularly suitable if low cost devices are envisaged. Precision laser micromachining is an ideal flexible manufacturing technique for such materials with the ability to fabricate structures to sub-micron resolutions and a proven track record in manufacturing scale up.

Described here is the manufacture of a range of optical biochip devices and components using laser micromachining techniques. The devices employ both microfluidics and electrokinetic processes for biological cell manipulation and characterisation. Excimer laser micromachining has been used to create complex microelectrode arrays and microfluidic channels. Excimer lasers have also been employed to create on-chip optical com-

ponents such as microlenses and waveguides to allow integrated vertical and edge emitting LEDs and lasers to deliver light to analysis sites within the biochips.

Ultra short pulse lasers have been used to structure wafer level semiconductor light emitting devices. Both surface patterning and bulk machining of these active wafers whilst maintaining functionality has been demonstrated. Described here is the use of combinations of ultra short pulse and excimer lasers for the fabrication structures to provide ring illumination of in-wafer reaction chambers.

The laser micromachining processes employed in this work require minimal post-processing and so make them ideally suited to all stages of optical biochip production from development through to small and large volume production.

6459-09, Session 3

Development of micromirrors in optical-electric printed wiring boards using excimer laser

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An optical wiring board is expected to be a substitute for conventional electric printed wiring board in the near future, because it has very wide transmission bands and non-inductiveness. In the optical wiring board, it is very important for optical coupling between electrical devices such as VCSEL/PD and optical waveguides. Various optical coupling methods have been studied by many researchers, for example grating couplers and micro-mirrors fabricated by cutting 45-degree V shaped blade. Using excimer laser with 248 nm wavelength, we have developed the 45-degree micro-mirrors in the polymer optical waveguide constructed by newly developed epoxy resin. The three-dimensional laser processing technology for controlling the mask aperture size on the laser beam is effective for fabricating the 45-degree mirror. The size of the mirror was about 80 micrometer width. Although the periodical micro patterns have appeared on the surface of the mirrors, we have successfully removed the patterns by the technique of smoothing. Smoothing process has been carried out by the additional laser irradiation with weak and/or strong energy. The obtained surface roughness of the mirrors was less than 60 nm (Ry). The evaluation of the optical loss using laser with 670 nm wavelength resulted in the less than 0.5 dB, indicating sufficient mirror performance.

6459-10, Session 3

Femtosecond laser microfabrication of subwavelength structures in photonics

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Femtosecond (fs) laser inscription is one of the enabling technologies for manufacturing of sophisticated photonic devices. It is quickly becoming one of the mainstream methods for microfabrication of the flexible 3D structures. Typically, Bragg gratings (BG) are ubiquitous components in many composite devices where wavelength selectivity is ultimately required. Manufacturing of the BGs in bulk material is a challenging technological problem involving 10 nm accurate fabrication of periodic perturbation of refractive index within or in the vicinity of the waveguide. Femtosecond inscription is a unique technology enabling the fabrication of both the wave guide and the grating in the same set up. The major problem is a submicron pitch size for variation of refractive index required for the First Order BG (FOBG) due to diffraction limit. Photonic applications often imply pitch size of 260 nm to provide the required grating period of 535 nm in fused silica. As an example, we describe the fabrication of the periodic structure of 25 mm long with a pitch size of 260nm in fused silica. This pitch size is less than a third of the wavelength of the laser light used (800 nm Ti:Sa laser). This is the smallest period for BG manufactured in the bulk of glass sample. We have also performed detailed adaptive numerical modelling of such submicron inscription. It turns out that a submicron regime regime requires a supercritical self focusing to produce 100 nm plasma filaments.

6459-11, Session 3

Optical properties of aligned nanowire arrays

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Nanowires (NWs) have been identified as useful building blocks for nanoscale electronic and thermoelectric devices. The interaction of light with these nanowires is of great interest for applications such as self-assembly, laser processing of nanowires and nanophotonic devices.

In the current work, we investigate the optical properties of aligned silicon nanowires on a quartz substrate. We find that the polarization and angle of incidence strongly affect these properties. The wires display strong polarization anisotropy and a periodic variation in optical properties with incidence angle. Theoretical calculations based on classical Mie theory corroborate these results. Near-field Finite Difference Time Domain simulations also show the effect of polarization on the interaction of light with nanowires.

Applications of these results in nanowire alignment, detection, selective melting and ablation and laser processing are discussed.

6459-12, Session 3

Laser annealing of silicon nanowires

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Semiconductor Nanowires are promising building blocks for the next generation of electronic devices, chemical and biological sensors and photonic systems. Dopant activation in these nanowires has commonly been accomplished by thermal annealing. Laser Annealing has emerged as an attractive technique of fabricating ultra-shallow junctions in MOS devices, owing to its low thermal-budget. Rapid heating and cooling of the samples limits the diffusion of dopants, aiding the formation of shallow junctions. Additionally, the damage to underlying layers and substrate tends to be minimal. Furthermore, laser annealing is compatible with flexible plastic substrates since it is a low-temperature process.

In this work, we successfully demonstrate non-melt laser annealing of silicon nanowires (SiNWs) as an efficient method for the electrical activation of implanted dopants and restoration of crystalline structure in the wires. The KrF Excimer (248nm) and Nd:YAG (532nm) lasers were employed in this study. By controlling the lasing parameters - fluence and number of pulses, dopant activation levels comparable to Rapid Thermal Annealing (RTA) were achieved.

Post annealing structural characterization showed that laser annealing can remove the residual implantation damage. In situ electrical measurements of boron-implanted SiNWs were used to study the dopant activation during the pulsed laser annealing process. Even though the melting threshold of the nanowires in laser annealing process was found to be lower than that for bulk silicon, it was possible to provide sufficient energy for the activation of dopants without melting or damaging the wires. Electrical monitoring data was found to be consistent with structural characterization results.

6459-13, Session 4

Femtosecond laser plasmonic ablation by gold nanoparticles

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In this work, we provide experimental evidence of "plasmonic ablation," which takes advantage of the enhanced plasmonic scattering of femtosecond laser pulses in the near-field of gold nanoparticles to vapor-

ize various materials with nanoscale resolution.

To demonstrate the feasibility of plasmonic ablation, we deposited 75 nm gold nanoparticles onto the surface of a silicon wafer and irradiated with a single 100fs laser pulse at 780nm. The laser polarization is at a 45° angle to the silicon surface. Calculations indicate that a gold particle of diameter 80nm has a near-field enhancement of approximately 25 and have negligible absorption properties when irradiated at 780nm. The induced dipole interacts with the underlying substrate and causes ablation in the region directly next to the nanoparticle. The pit profile, having a depth of 20nm, follows the expected dipole pattern. These results show that the surface of silicon can be ablated with a fluence of 0.25mJ/cm2, which is a great reduction from the threshold fluence of 100mJ/cm2.

The use of plasmonics in ablation most notably provides the ability to ablate structures below the diffraction limit. There are two inherent advantages to using gold nanospheres to perform plasmonic ablation: (1) ability to ablate materials deep within a sample instead of just of the surface and (2) ability to irradiate large volumes of material. This type of technology will have direct impact on the fields of laser-assisted nanomachining and biomedical science.

6459-14, Session 4

Deep-UV laser-based nanopatterning with holographic techniques

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Subwavelength structures (SWSs) can function as versatile optical elements such as anti-reflection layers, phase plates, and polarization separators. To achieve such SWSs, we have studied the potential of a pair of holographic lithography techniques, each with a different optical configuration. One configuration is for interference between two mutually coherent beams in free space and the other is for interference between two diffracted waves beneath a high-density phase grating. Holographic technology is superior to photomask lithography and nano-imprinting in producing SWSs in that it enables the fine structures of SWSs to be concurrently formed on large substrates.

Resist patterns having a pitch of 140 nm were produced over areas measuring 4 inches in diameter by using two-beam interference with a 266-nm CW laser and an interference angle of 72 degrees. The resist patterns were transferred onto substrates to make SWSs. A simulator was developed to achieve resist patterns that exhibit a desirable shape. The simulator is capable of precisely predicting light intensity distributions in resist, thus providing data on optimal exposure conditions.

Meanwhile, it has been proven that using a phase grating that generates a desired interference field makes the optical setup more compact and more stable, with no risk of being disturbed by air in the light paths. With the phase grating fabricated by holographic lithography and ion etching, subwavelength resist patterns with a 140-nm period were obtained. Only two diffracted waves from the grating, the 0-th and 1-st orders, were used for interference exposure.

The current study demonstrates that, from a practical point of view, holographic lithography may be highly effective in manufacturing SWSs.

6459-15, Session 4

Machining hole arrays in polyimide using a UV solid state laser and predetermined temporal pulse patterns

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A high power solid state UV laser was used to make arrays of reproducible percussion-drilled micron-sized holes in polyimide. An optical switch was employed as a pulse picker to select specific patterns of pulses from the high repetition rate laser beam. The ability to control and vary the number of pulses per burst and the time between bursts enhanced the drilling rate while minimising thermal damage around the holes. The optimum pulse patterns were determined experimentally. A photodiode acted as a breakthrough sensor to end the drilling and optimise the exit hole size and quality. Results compared well with computer simulations of the drilling process based on thermal modelling of the laser/material interaction.

6459-16, Session 4

Processing benefits of high-repetition-rate and high-average-power 355-nm laser for micromachining of microelectronics packaging materials

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It has been shown that micromachining of polyimide using a mode-locked high repetition rate, 80 MHz, 355nm laser is more efficient than the Q-switched laser at same power level in terms of material removal rate. In this study we have explored and characterized the benefits of using a high repetition rate, high average power laser for micromachining of various microelectronics packaging materials that have different thermal properties. The removal rate and quality of machining have been analyzed against the difference in thermal properties of the material. The implications of the results observed are also discussed from practical manufacturing perspective.

6459-17, Session 4

New high-repetition-rate, high-energy 308 nm excimer laser for material processing

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High power excimer lasers are well established as work horses for various kinds of material processing. The applications are ranging from drilling holes, trench formation, thin film ablation to the crystallization of amorphous-Si into polycrystalline-Si. All applications use the high photon energy and large pulse power of the excimer technology. The increasing demand for micro scale products has let to the demand for UV lasers which support high throughput production.

We report the performance parameters of a newly developed XeCl excimer laser with doubled repetition rate compared to available lasers. The developed laser system delivers 900 mJ stabilized pulse energy at 600 Hz repetition rate. The low jitter UV light source operates with excellent energy stability below 1% (rms). The outstanding energy stability was reached by using a proprietary solid-state pulser discharge design.

The high pulse frequency of 600 Hz will boost the throughput of numerous established applications and opens the market for line production with high reprate requirement.

6459-18, Session 4

Potentials of fiber laser technology in microfabrication

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Over the recent years the novel fiber laser technology and its potentials have been exciting laser manufacturers as well as users of laser technology in research and industry. Fiber lasers with their excellent beam quality promised noticeable advantages and improvements in high precision and micro material processing. Besides the excellent beam quality there are more advantages of the fiber laser technology such as compact installation size, high laser efficiency, moderate system price and easy to be integrated. The paper presents the results of extensive comparative tests of short pulse fiber laser systems and a common q-switch rod solid state laser with nearly identical system parameters. The intention was to

determine the specific advantages in practical application work. Where are the advantage and how large are the improvements? Therefore three typical applications of laser micro machining have been chosen - drilling, cutting and lateral material removal. By choosing different materials like stainless steel, silicon and ruby a broad field has been examined. Distinct improvements have been proven in several applications especially in precision and surface quality of the created structures. Under almost identical conditions the fiber laser achieved more narrow cutting kerfs compared to the rod laser system. As a result of higher cutting speeds were realized.

6459-19, Session 5

High-precision small geometry laser trimming for emerging microelectronics devices

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Laser trimming of microelectronics devices has enabled the fabrication of high precision and high performance components and networks. Market demands for decreasing package size and higher performance components have pushed the current laser trimming technology to its limits. To meet the challenges, laser trimming system manufacturers have been working on the new generation based on significant advances in laser technology, software tools, and related system technologies. These new systems can achieve higher accuracy needed for processing devices with ever shrinking dimensions and tighter tolerances while offering maintenance-free operation and flexibility in today's demanding production environments. We will present in this paper the latest advancement of laser based trimming systems. Future directions will also be discussed.

6459-20, Session 5

Laser patterning of thin films for high-tech devices on flexible and large-area substrates

R. M. Allott, P. Grunewald, P. Sykes, A. Henwood, Exitech Ltd. (United Kingdom)

Pulsed laser sources are widely used for the micro-processing of materials from the structuring and patterning of surfaces to the direct machining of devices. This paper describes recent advances in laser micro-processing techniques for the patterning of thin films with high accuracy and precision over large areas up to Gen. 8 (2.2 x 2.4 m).:Submicron-thick inorganic, metallic and organic films used on solar panels, sensors and flat panel display devices are often patterned using mask projection methods with both Nd:YAG and excimer laser sources. These industries are rapidly moving towards both flexible architectures and larger panels for volume manufacturing. Techniques developed such as Synchronised Image Scanning (SIS) and Bow Tie Scanning (BTS) have enabled high precision machining of complex patterns at high speed on a continuously moving substrate. Industrial laser processing tools for the micro-patterning of photovoltaic and flat panel display devices are becoming widely used on production lines. For the fabrication of micro-structures with high precision and high accuracy over large area substrates laser processing provides significant advantages over conventional processing techniques, including removing the need for complex and expensive lithography processes.

6459-21, Session 5

The promise of solar energy: applications and opportunities for laser processing in the manufacturing of solar cells

C. M. Dunsky, Coherent, Inc.

Photovoltaics, while not a new technology, has in the last five years enjoyed unprecedented growth and acceptance as part of the worldwide energy mix. The industry has recently experienced exponential growth in manufacturing capacity and installed base, with Germany and Japan leading the way and the U.S. market ramping up quickly as well, particularly in California. With the help of government cost incentives, traditional wafered-silicon PV technology today can provide electrical power at a cost approaching that of peak-demand grid-supplied power. Innovations in both wafered silicon and various thin-film PV technologies planned for the next 5-10 years promise to lower the cost of PV power to parity with that supplied by the grid. When that occurs, the growth of the industry will be pulled even more strongly by market demand. A barrier to meeting this growth on the supply side will be the availability of automated production equipment that can streamline the manufacturing process, evolving it to a true lights-out, high-volume global manufacturing base. Laser processing offers the potential to provide several facets of that high-volume manufacturing solution. This paper discusses current laser processes for PV manufacturing and highlights some of the challenges for laser technology and systems that must be met to fulfill this promise.

6459-22, Session 5

Mechanisms of femtosecond laser nanomachining of dielectric surfaces

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Nano-craters formed by single femtosecond laser shots undergo a shift with increasing laser intensity, from dominated by a deep central cavity, to a smooth and shallow crater containing a deeper central cavity. The structure of the nano-crater structures, formed in quartz and glass surfaces using 0.53 micrometer or 1.05 micrometer femtosecond laser radiation, suggests two ablation regimes in which distinct damage mechanisms dominate. Shallow craters are ascribed to thermo-mechanical spallation of a surface molten layer during propagation of a thermoacoustic tensile wave. Formation of deep craters at higher intensities may be related to laser plasma-assisted ablation via radiative energy transfer in the form of highly-penetrating short-wavelength radiation from laser-induced surface plasma to bulk materials. This interpretation of laser fabrication mechanisms for shallow and deep nano-craters on dielectric surfaces is supported by theoretical modeling of ionization dynamics, laser energy deposition and energy transport processes in these materials.

6459-23, Session 5

Laser micromachining of the ceramics: can lasers match the performance of diamond saws?

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We have studied the feasibility of laser cutting the ceramic Al2O3-TiC composite (referred to as N58 hereafter) that is widely used for manufacture sliders carrying the magnetic read/write heads for the hard disk drives (Ref.1). The current process uses thin diamond saws to cut rows of sliders into individual sliders. The diamond saw process while very successful, is difficult to maintain and sometime leads to chipped edges of sliders due to mechanical stress.

Our samples were N58 rows of sliders, 230 micron thick and 1 mm wide; one side of the strip contained deposited metal head features embedded in sputtered alumina overcoat. The process requires cutting through all of these materials uniformly, resulting in a very smooth "side wall". We tried a variety of lasers ranging from q-switched CO2 laser at 9250 nm to excimer laser at 193 nm. Laser pulse widths ranged from several tens of nsec down to 130 fsec. Picosecond and femtosecond lasers with very high peak powers performed the best among those tested in terms of the cut surface quality, slag deposition, wall angle, as well as exhibiting more uniform etch rates between the N58 and alumina than longer-pulse lasers.

The observed cut surface quality and cutting speed of the laser processes were still much lower than those offered by today's diamond saws. More fundamental understanding of the laser cutting of ceramics will be helpful. As the limits of saw technology are reached, lasers may yet offer an alternative.

Ref.1: Review of laser-based applications advancing magnetic-recording hard-disk-drive technology; Gurinder P. Singh, Peter Baumgart, Eric Baugh, Chie Poon, and Timothy Strand. Proc. SPIE Int. Soc. Opt. Eng. 5713, 417 (2005).

6459-24, Session 5

Laser MicroJet: an agile micromachining tool

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High power lasers have a large field of machining applications for which they are particularly suited. Although a laser-based technology, the Laser MicroJet (LMJ) is much different from a conventional laser. It is an agile tool for many micro-machining applications, such as cutting of MEMS substrates and ferrous/non-ferrous materials. Using a low-pressure, ultra-thin water jet as a waveguide for conveying the laser onto the work piece, the Laser MicroJet does not generate thermal or mechanical damage and contamination is greatly reduced. This paper will present tests performed with this innovative technology on a wide range of materials, including gallium arsenide (GaAs) and silicon wafers, steel, tantalum, ceramic packaging (alumina) and kapton. An infrared Nd:YAG laser (wavelength: 1064 nm) and a frequency-doubled (green) laser (wavelength: 532 nm) were employed for the machining of materials.

6459-25, Session 6

Laser-induced formation of photocatalytic TiO2 micronetworks on a UV-absorbing glass surface

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Laser-induced formation of functional materials from glasses has a great potential for creation of monolithic and high-performance glass-based devices, such as optical circuit and micro-TAS.

We have recently developed a laser-induced formation technique of photocatalytic TiO2 on a UV-absorbing Na2O-TiO2-SiO2 glass surface by excimer laser irradiation under a specific condition. The laser-induced TiO2 has a peculiar structure like micro-sized network after accumulating laser pulses, which we call TiO2 micronetwork. The TiO2 micronetwork had the rutile crystalline phase and exhibited photocatalytic ability. Utilizing this technique, we were able to form a range of TiO2 micronetworks in an array of 20 micrometer-holes and a channel modified with TiO2 on its bottom surface. This flexible laser-induced formation of photocatalytic TiO2 onto a glass surface without any heat-treatments and/or adhesives allows us a new route to make a monolithic glass device like micro-fluidics with light-catalyzed reactions.

6459-26, Session 6

Laser modification of ceramic surfaces with micro- and nanoparticles

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Laser supported processes can be used to modify the electrical and thermal properties of ceramic substrates locally. These processes are characterised by a strong thermal interaction between the laser beam and the ceramic surface which leads to localised melting. During the dynamic melting process metal particles are introduced into the melt pool in order to modify the physical properties.

Different alumina samples were treated with metal powders of tungsten, copper, and oxides of these metals. The interface between the metal and the ceramic can be designed by using selected combinations of metal- and metal-oxide-powders and also by a thermal post-processing. The application of nano-particles during the laser-dispersing process resulted in completely different characteristics of the micro-structure and the electrical properties compared to the conventional metal powders with an average grain size of 5 - 15 microns. The micron sized metal particles are embedded within the ceramic matrix as particle agglomerates or as distinct metal phase the nano-particle phase covers the grain boundaries of the ceramics leading to network of nano-scaled electrically conducting “wires”.

The resulting resistance of the laser tracks can be adjusted from semiconducting to metallic behavior with a resistivity down to 2•10-6W/m. The modified ceramic can be used for heating elements working at operation temperatures of up to 1000°C, high current resistances which can be loaded with currents of up to 100 A.

6459-27, Session 6

Fabrication of back-gated SWNT field-effect transistors using laser chemical vapor deposition

J. Shi, Y. S. Zhou, Y. Lu, Y. S. Lin, S. Liou, Univ. of Nebraska/Lincoln

Due to the recent advances in the synthesis and manipulation of single-walled carbon nanotubes (SWNTs), there have been increasing interests in the development of CNT-based devices for nanoelectronics and nanoelectromechanical systems (NEMS). Conventional fabrication technique is thermal chemical vapor deposition (CVD), in which substrates as well as chamber wall are globally heated to sufficiently-high reaction temperatures. In this study, we demonstrated a process for position-controlled fabrication of SWNT- field-effect transistors (FETs) by bridging the SWNTs across pre-defined electrodes using the laser chemical vapor deposition (LCVD) technique. The SWNT-FETs were back-gate modulated, showing p-type semiconducting characteristics. The process is fast and can be conducted using either far-infrared CO2 laser (10.6 μm) or near-infrared Nd:YAG laser (1064 nm). We have also demonstrated localized synthesis of SWNTs by a focused laser beam. Due to the unique advantages of the LCVD process, such as fast and local heating, as well as its potential to select chiralities during the grow, it may provide new capabilities and versatilities in device fabrication.

6459-28, Session 6

Nanoscale characterization with tip-enhanced near-field Raman spectroscopy

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Raman spectroscopy provides valuable information about physical and chemical properties such as molecule and electronic structures of materials due to the interaction between the incident photons and molecule vibrations. However, the resolution of conventional micro-Raman spectroscopy is constrained in a sub-micro range due to the optical diffraction limit. Fortunately, a sharp metal tip with a diameter at nanoscale (several tens of nanometers) under a laser irradiation is capable of localizing the incident light at the apex of the tip, where the electrical field intensity is significantly enhanced by near-field effects. In this paper, we report a home-made tip-enhanced Raman spectroscopic system with a resolution of around 20 nm operating in the 180° back-scattering mode. The optical enhancement by various tips with different geometries was simulated with the OptiWave(tm) software. Sharp metal tips were made by tungsten wire through electrochemical etching. The resolution of the constructed nano-Raman spectrometer was demonstrated to be up to 20 nm. The nano-Raman spectrometer was used to characterize single-wall carbon nanotubes (SWCNTs). The SWCNTs were grown between two electrodes on a silicon substrate using laser-assisted chemical vapor deposition (LCVD). Strong RBM mode and clear Raman image of the SWCNTs were observed. The nano-Raman spectroscopy based on tip-enhanced near-field optics has potential applications in next-generation microelectronics to enable nanoscale stress and defect characterization for integrated circuits with continuing shrinking size.

6459-29, Session 6

Precision laser bending of thin precious metal alloys

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Lasers are capable of delivering energy to a metal to induce stresses from the thermal gradient through the material. Under the right conditions these stresses can cause the metal to bend. Experiments were conducted to produce bending in a homogenous metal and that same metal with a titanium coating on one side. Transient heating of a one and two layer thin cantilever beam was modeled to support the experimental results using a thermo mechanical finite element model. In the experiments, both upward and downward bending was observed. The titanium coated samples showed potential to be more controllable than the uncoated samples.

6459-30, Session 7

Laser-assisted maskless fabrication of flexible electronics

C. P. Grigoropoulos, S. H. Ko, H. Pan, Univ. of California/ Berkeley; D. Poulikakos, ETH Zürich (Switzerland)

A new paradigm will be presented for the low temperature fabrication of passive (conductor, capacitor) and active (field effect transistor) electrical components on flexible polymer substrates. A drop-on-demand (DOD) ink-jetting system was used to print gold nano-particles suspended in carrier solvents, insulating polymer material and a semiconductor polymer to fabricate passive and active electrical components on flexible polymer substrates. Low power, short-pulsed laser ablative material removal enabled finer electrical components to overcome the resolution limitation of inkjet deposition. Temporally modulated laser irradiation was utilized to locally evaporate the carrier solvent as well as sinter gold nano-particles, thereby yielding conductors of resistivity just slightly higher than bulk gold. Highly selective multi-layered gold nanoparticle film processing was demonstrated using the SPLA-DAT (selective pulsed laser ablation by differential ablation threshold) scheme. This approach enabled definition of narrow channels for FETs (field effect transistors). High performance OFETs (organic field effect transistors) were demonstrated after the final step of semiconductor polymer deposition.

6459-31, Session 7

Laser deposition and laser structuring of laser active planar waveguides of Er:ZBLAN, Nd:YAG and Nd:GGG for integrated waveguide lasers

J. Gottmann, RWTH Aachen (Germany)

Laser radiation is used both for the deposition of the laser active thin films and for the micro structuring to define wave guiding structures for the fabrication of waveguide lasers. Thin films of Er:ZBLAN (a glass consisting of ZrF4, BaF2, LaF3, AlF3, NaF, ErF3) for green up-conversion lasers (545 nm), Nd:YAG (Y3Al5O12) and Nd:GGG (Gd3Ga5O12) for infrared lasers (1064 nm) are produced. Fabrication of the laser active waveguides by micro-structuring is done using fs laser ablation of the deposited films. The structural and optical properties of the films and the extinction losses of the structured waveguides are determined in view of the design and the fabrication of compact and efficient diode pumped waveguide lasers. The resulting waveguides are polished, provided with resonator mirrors, pumped using diode lasers and characterised view of the fabrication of compact and efficient waveguide lasers.

Pulsed laser deposition with ArF is used to grow transparent erbium doped ZBLAN thin films on MgF2 single crystals in a Ne/F2 processing gas atmosphere. The substrate temperatures during deposition are varied in the range of 20 - 300 degrees Celsius. Pulsed laser deposition with KrF is used to grow transparent Nd:YAG and Nd:GGG thin films on YAG and Saphire single crystals in an oxygen processing gas atmosphere. The substrate temperatures during deposition are varied in the range of 400 - 900 degrees Celsius and the influence of a post annealing in the range of 1000-1500 degrees Celsius on the fluorescence properties is investigated.

Visible emissions from Er:ZBLAN film due to up-conversion luminescence (528, 548 and 660 nm) and infrared emission (1,54 μm) under excitation by diode lasers in the spectral range 970 - 980 nm are investigated using time resolved spectroscopy. Nd:YAG and Nd:GGG films are pumped with 808 nm diode lasers and the emission in the infrared spectral range is investigated. Conversion efficiencies and life times of the levels are investigated as a function of the dopand concentration and the growth related structural film properties. The damping of the light in the planar waveguides is determined by detection of the scattered light.

The thin films are micro machined to form optical wave guiding structures using Ti:sapphire fs laser radiation. The fluence, the scanning velocity and the orientation of the polarisation in respect to the scanning direction are varied. The resulting structures are characterised using optical microscopy, atomic force microscopy and scanning electron microscopy. Optical wave guiding properties like damping and guided modes are studied in the visible and infrared spectral range and compared to simulations using the beam propagation method.

The polished waveguides are provided with external resonator mirrors, pumped using diode lasers and out coupled light is characterised view of the fabrication of compact and efficient waveguide lasers.

6459-32, Session 7

Deposition of functionalized nanoparticles in multilayer thin-film structures by resonant infrared laser ablation

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We report the successful deposition of functionalized nanoparticles in vacuum, using resonant infrared laser-assisted nanoparticle transfer (RIRLANT) from bulk frozen targets. In one set of experiments, monodisperse 170 nm silica spheres were synthesized with a rhodamine dye in the core of the nanoparticle and a fluorescein dye on the surface. The silica nanoparticles were dispersed in a solvent, and several milliliters of the suspension were pipetted into a target well and frozen. Once the target was mounted in vacuum, infrared light tuned to a solvent vibrational mode was focused through a barium fluoride window and rastered across the target, which was also rotated to insure uniform ablation. Post-deposition photoluminescence measurements showed no significant alteration of the emission spectra of either dye, suggesting that no damage occurred to either the encapsulated or surface-bound dye during ablation. The selection of an infrared laser wavelength is critical to producing a uniform coating of material and preserving nanoparticle functionality. However, after initial experiments with a tunable infrared free-electron laser, a conventional Er:YAG laser was found to achieve comparable results for solvents with absorption bands around 3 μm. A variety of nano- and microscale materials were subsequently deposited in this way, and multilayered structures were created by resonant infrared pulsed laser deposition of appropriate polymers. in a manner not possible with solvent-based deposition techniques. Deposition through shadow masks turned out to be straightforward, suggesting the potential utility of RIRLANT in preparing designer sensor structures using functionalized nanoparticles.

6459-33, Session 7

CO2 laser-assisted combustion-flame deposition of diamond films

H. Ling, Y. Han, Y. Lu, Univ. of Nebraska/Lincoln

Diamond films deposited by combustion-flame method at various temperatures have been investigated during the past years. The quality of the

diamond crystals is strongly dependent on the substrate temperature, which is usually controlled at 750 - 1050 °C in most experiments. In combustion-flame deposition process, the effective deposition area is limited. In this study, a CO2 laser was used to irradiate the growth point on tungsten carbide (WC) substrate surfaces in order to maintain required temperature in the growth region area while keep the rest of the substrate at low temperature. The power of the laser beam was adjusted between 200 - 400 W. Scanning electron microscopy (SEM) and Raman spectroscopy of the deposited diamond films showed that the CO2 laser irradiation during combustion-flame deposition improved the crystallization of the diamond films. Based on the experimental results, the CO2 laser-assisted combustion-flame deposition can be a promising method for local heating during diamond film growth.

6459-34, Session 7

Synthesis of diamond on WC-Co substrates using a KrF excimer laser in combination with a combustion flame

Y. Han, H. Ling, Y. Lu, Univ. of Nebraska/Lincoln

A KrF excimer laser was used in combination with the combustion-flame method to deposit diamond films on cemented tungsten carbide (WC-Co) substrates. The laser has a wavelength of 248 nm, a pulse width of 23 ns, a pulse energy range of 84~450 mJ, and a repetition rate up to 50 Hz. During the experiments, the laser fluence and repetition rate were varied. The surface morphology of the deposited diamond films were examined using scanning electron microscopy (SEM). The composition and bonding structures in the deposited films were be studied by energy dispersive X-ray analysis (EDX) and Raman spectroscopy, respectively. The effects of the KrF excimer laser irradiation in the combustion-flame deposition of diamond were analyzed.

6459-35, Poster Session

CNT-BLU fabrication by laser-induced local material transfer

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Compared to conventional backlight technologies such as CCFF and LED, Carbon Nano-Tube Backlight Unit (CNT-BLU) have a number of key advantages, including a flatter design, a lower power consumption, no optical films (i.e. reflectors or diffuser films), and a reduced cost.

DTC/ITRI has developed a novel planar reflective CNT-BLU using a screen-printing method. The term “planar” here indicates that the cathode and the gate are horizontal with respect to the anode plane, in marked departure from the conventional “vertical” structure, in which the cathode and the gate are vertical with respect to the anode plane.

The planar reflective design keeps higher transmittance for luminescence and reduces the thickness of the backlight unit, and hence renders it suitable for use as the backlight unit of LCD-TVs. Although screen printing is a low cost manufacturing technique, its resolution and uniformity are poor. Therefore, this study presents a novel non-contact method, designated as “laser induced local material transfer” (LILMT) for patterning the CNT emitter. The LILMT method makes possible the manufacturing of large-scale substrates with a high resolution.

In the LILMT technique, a laser beam is passed through a transparent support and focused on a thin film composed of the desired transfer material, i.e. CNT in the current case. The pulsed laser output causes the CNT to be evaporated, transferred, and deposited precisely on a cathode positioned parallel to the support (see Fig. 1). The displacement of the transparent support and the cathode with respect to the laser beam creates a CNT emitter formation. This study presents the preliminary results obtained for the field emission using square-type CNT emitters with dimensions of 1x1 mm2. The emission characteristic is shown in Fig. 2. The results show that the turn-on electric field is approximately 2V/μm (400V, anode-to cathode voltage for 200μm gap).

6459-36, Poster Session

Microstructure devices generation by selective laser melting

J. J. Brandner, E. Anurjew, E. Hansjosten, W. Pfleging, K. Schubert, Forschungszentrum Karlsruhe (Germany)

Selective Laser Melting (SLM) is a generative manufacturing procedure mainly known for the application with metal powders. From these, metallic structures are produced in a layer-by-layer way. This layer-related procedure is comparable to the stereolithographic manufacturing of polymer devices. On a base plate, a thin layer of metal powder is spread. The powder is locally completely melted by the application of a focused laser beam. The base plate is then lowered by a value defined by the thickness of the metal layer, metal powder is spread again, and the local melting process is re-initiated. The complete procedure is continued as described, until the device is manufactured in the defined way. Commercially available metal powder can be used as base material.

In principle, the SLM process should be suitable for the generation of metallic microstructures. The main precondition for the generation of microstructures by SLM is that the spatial resolution of the laser focus is small and precise enough to generate microstructure walls of around 100μm thickness in a reproducible way by melting metal powder. The walls should be gas- and leak-tight.

In this publication, experimental results of the generation of metallic microstructure devices by SLM will be given. The process will be described in details. Process parameters for the generation of stainless steel devices having wall thicknesses in the range of about 100μm will be given. Examples for microstructure devices made by SLM will be shown. The devices can be manufactured in a reproducible way.

Moreover, very first preliminary results on the use of ceramic powder as base material will be presented.

6459-37, Poster Session

Femtosecond laser writing of Bragg gratings using a single-pulse processing

C. K. Min, Information and Communications Univ. (South Korea)

We report microfabrication of periodic photonic band gap structures in transparent materials using a single pulse femtosecond laser processing. This technique has the potential to generate line and dot patterns with ultrahigh processing speed of 1 kbit/s. We create the line patterns with a slit, which is applicable to fabricate a Bragg grating. The pulse width was 100 fs, the wavelength was 800 nm, and the repetition rate was 1 kHz. The laser beam was guided into a microscope and focused by a 50x objective (NA, 0.42) into the core. The sample was placed on a computer-controlled stage. The average power of the laser beam was controlled by neutral density filters inserted between the laser and the microscope objective. The laser pulse-induced refractive index change is 0.006-0.01. The refractive-index changes were estimated by coupling light from an He:Ne laser into the waveguides and measurement of the numerical aperture (NA) of the waveguides

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6460-01, Session 1

Laser scissors in cell biology: then and now

M. W. Berns, Univ. of California/Irvine

No abstract available

6460-02, Session 1

Probing cell mechanics with femtosecond laser pulses

I. Z. Maxwell, Harvard Univ.; A. Heisterkamp, Laser Zentrum Hannover e.V. (Germany); E. Mazur, Harvard Univ.

We use femtosecond laser pulses to selectively disrupt the cytoskeleton of a living cell and probe its mechanical properties. Our nanosurgery setup is based on a home-built fluorescence microscope with an integrated femtosecond laser. We severed single actin bundles inside live cells to probe the local dynamics of the cytoskeleton and correlate it to global changes in cell shape. Simultaneous cutting and imaging allows us to study immediate cellular response with several hundred-nanometer spatial and less than 500-ms time resolution. The targeted actin bundle retracts rapidly after laser cutting due to prestressed tension stored in the actin filaments. We show that actin bundles in living cells can be modeled as viscoelastic elements. Using this nanosurgery technique we can further understand and model the stress distribution in the actin filaments and elucidate its contribution to cell shape and function.

We also studied the threshold pulse energy for nanosurgery as a function of the repetition rate of the laser. Previous work on femtosecond laser micromachining in glasses shows that at high laser repetition rates there is a marked accumulation effect that defines the morphology of the structure written in the glass. An equivalent effect is observed in biological cells, where pulse energy threshold and irradiation time necessary for nanosurgery is dependent on the laser repetition rate.

6460-03, Session 1

Attenuation of molecular function by multiphoton excitation-evoked chromophore-assisted laser inactivation (MP-CALI) using green fluorescent protein

T. Takamatsu, Kyoto Prefectural Univ. of Medicine (Japan)

Noninvasive and straightforward methods to inactivate selected proteins in the living cell with high spatiotemporal resolution are eagerly awaited for elucidation of protein function in the post-genome-mapping era. Chromophore-assisted laser inactivation (CALI) facilitates inactivation of proteins by photochemically generated reactive oxygen species (ROS), but CALI using single-photon excitation thus far has presented several drawbacks, including complex procedure, low efficiencies of inactivation with a certain chromophore, and photodamage effects. We here show that by application of multiphoton excitation to CALI using near-infrared femtosecond laser, enhanced green fluorescent protein (EGFP) can work as an effective chromophore for inactivation of a protein's function without nonspecific photodamage in the living cell. We found that 80% reductions of gap junctional currents between HeLa cell pairs expressing connexin43 (Cx43) tagged with EGFP but not between HeLa cell pairs expressing Cx43 tagged with monomeric red fluorescent protein (mRFP) were elicited by brief laser irradiation (< 500 ms) at 850-nm wavelength of the gap junctional plaque.

6460-04, Session 1

Femtosecond laser synthesis and size control of colloidal nanoparticles for biomedical applications

S. Besner, P. M. Boyer, D. Rioux, A. V. Kabashin, M. Meunier, École Polytechnique de Montréal (Canada)

Femtosecond laser ablation in liquid has been used to produce colloidal solutions of nanoparticles of different types. Using this method, we have been able to produce plasmonic (Au, Ag) and magnetic (Co, SmCo, Gd) nanoparticles as well as quantum dot (Si, GaAs) of different size and oxidation degree. The control over the laser parameters and the chemical environment allows to modify the final size distribution as well as the chemical composition of the resulting nanoparticles. Nanoparticles with a mean size between a few nanometers and a few tenths of nanometers were produced. Also, using different additives during the fabrication process, functionalization of nanomaterials by appropriate capping ligands in a single step is possible. The femtosecond laser-based irradiation may also be used to finely control the size characteristics and stability of colloidal nanoparticles in a liquid environment. The method uses the plasma of the laser-induced liquid breakdown and multiphoton absorption to fragment large, strongly size-dispersed and agglomerated nanoparticles into smaller and low-dispersed nanoparticles. The size of the nanoparticles after the laser treatment is independent of initial characteristics of the colloids but depends on the laser condition and on the chemical environments. In some cases, this treatment also leads to a net increase of the solution stability. All those nanoparticles are of significance importance in view of their potential biological applications.

6460-05, Session 1

A compact ultrafast laser microscope for imaging and processing of biological samples

A. Heisterkamp, J. Baumgart, Laser Zentrum Hannover e.V. (Germany); A. Ngezahayo, Univ. Hannover (Germany); H. Lubatschowski, Laser Zentrum Hannover e.V. (Germany)

We developed a compact and easy to handle microscope system for precise imaging and manipulation of single cells. Using an ultrashort laser with an emission wavelength of 720-950nm at pulse durations of 100fs we converted a commercial Zeiss microscope into a two-photon microscope, with the opportunity of performing plasma-mediated ablation in different biological samples. The microscope is handled by a custom built software to control the ablation and imaging process. In first studies using this system, we investigated several side effects of the fs-laser at different repetition rates for both, imaging and processing of cellular samples. The results were used to build a pulse picker system into the microscope setup to achieve minimum collateral damage in possible applications in cell biology.

6460-06, Session 2

Laser microtome: all optical preparation of thin tissue samples

F. G. Will, Rowiak GmbH (Germany); H. Lubatschowski, Laser Zentrum Hannover e.V. (Germany); T. Block, P. Menne, Rowiak GmbH (Germany)

The laser microtome, developed by Rowiak GmbH, is a device which sections biological tissue and other material into thin slices. In contrast to a conventional microtome, no mechanical forces are applied to the sample.

Therefore native tissue can be processed and does not need to be frozen or embedded in resin or paraffin. This means, tissue preparation can be performed as a one step procedure. In particular, the cutting area can be shaped even three dimensional and sectioning of hard tissue such as bone or teeth is possible without decalcification.

The cutting process is done by a 10 MHz fs-oscillator with a wavelength of about 1030nm. The ultra short laser pulses are focused inside the target tissue. So cutting is performed below the surface of the tissue.

The minimum and maximum thickness of the sections depends on the material properties. Up to now slices of 10 - 100 μm has been performed. Thinner sections are more difficult to handle, but a thickness of 5 μm is feasible.

We will present the operation principle of the device with technical and application-dependent aspects. Furthermore we will present sectioning results of different tissues, such as cartilage, cornea, kidney and others. A preview of the next device generation with an embedded 3D-imaging system realized by optical coherence tomography is given, too. With this new seeing laser microtome preparation of 3D-tissue samples is possible.

6460-07, Session 2

Protein crystallization and processing using femtosecond laser and all solid state 193 nm laser

Y. Mori, K. Takano, H. Adachi, T. Inoue, Graduate School of Engineering (Japan) and CREST JST (Japan) and SOSHO Inc. (Japan); S. Murakami, The Institute of Scientific and Industrial Research (Japan) and CREST JST (Japan) and SOSHO Inc. (Japan); H. Matsumura, Graduate School of Engineering (Japan) and CREST JST (Japan) and SOSHO Inc. (Japan); M. Kashii, Graduate School of Medicine (Japan); H. Y. Yoshikawa, S. Maki, T. Kitatani, CREST JST (Japan); S. Okada, SOSHO Inc. (Japan); T. Sasaki, Graduate School of Engineering (Japan) and SOSHO Inc. (Japan)

We have discovered that the crystallization of proteins can be induced even in the low supersaturated solution by using the femto-second laser irradiation(1). This method is useful for producing high quality protein crystals in a short nucleation times. The forced nucleation in a low supersaturated solution followed with crystal growth in stirred solution is very effective to produce crystals with high X-ray diffraction (XRD) resolution(2). We have also developed laser process technology in order to cut out high-quality single crystal part from polycrystalline and/or partially defective proteins by using all solid-state 193 nm laser and femto-second laser(3-5). The proceeded crystals can be detached from the wall of a capillary and well using femtosecond laser with less damage, and mounted on XRD measurement position easily. These processing and manipulation could improve the XRD data of protein crystals. The precise structural information of proteins is important for designing and developing novel drugs.

With this new technology, we have succeeded to crystallize various proteins with high XRD resolution, such as, membrane protein AcrB (2.3A) (6), orotidine 5'-monophosphate decarboxylase (2.7A) (7), the translocon-associated membrane protein (SecDF) (3.7A) 8), the tRNA thiolation enzyme MnmA from Escherichia coli complexed with tRNA Glu (3.1A)(9), Human Triosephosphate Isomerase (1.2A)(10), SHPS-1(receptor-type transmembrane protein) (2.8A)(11). Based on these new technologies, we have also started the Protein Crystallization Company “SOSHO, Inc.”(12)

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6460-08, Session 2

Structuring of fused silica glass by means of femtosecond laser pulses for biochips applications

R. Osellame, V. A. Maselli, R. Martinez, R. Ramponi, P. Laporta, G. Cerullo, Politecnico di Milano (Italy)

A biochip is a device that squeezes onto a single substrate the functionalities of a biological laboratory, by incorporating on it a network of microfluidic channels, reservoirs, valves, pumps, and microsensors. This concept is undergoing an exponential development and promises dramatic advances both in basic research and in clinical applications as a low-cost diagnostic tool. Glass is a very interesting substrate material for biochips, because it provides high transparency, low fluorescence, and biologically benign surfaces. Femtosecond laser processing of surfaces and bulk of a dielectric material is a very flexible and simple method to produce several kinds of devices, from photonic to microfluidic ones. We report on the use of femtosecond laser pulses for different structuring activities on fused silica: surface laser ablation, laser irradiation followed by selective chemical etching and optical waveguide writing. All these aspects of laser-material interaction will be combined aiming at the implementation of bio-photonic devices. In particular, we'll show that suitable surface structuring can influence a cellular culture. We'll demonstrate that laser irradiation followed by chemical etching can provide buried hollow channels with a circular cross-section and 1.5-mm length. We'll prove the possibility to integrate hollow channels and optical waveguides to implement photonic functionalities in biochips, like on-chip optical detection by means of laser induced fluorescence.

6460-09, Session 2

Femtosecond laser-induced nanocavitation

N. Linz, S. Freidank, Univ. zu Lübeck (Germany); G. Paltauf, Karl-Franzens-Univ. Graz (Austria); A. Vogel, Univ. zu Lübeck (Germany)

We showed recently that femtosecond-laser-induced nanocavitation is the working mechanism of cell surgery with fs laser pulses at low and moderate repetition rates up to 1 MHz. At the same time, it is the most important mechanism for collateral damage.

In the present study we present breakdown thresholds for 315-fs laser pulses with wavelengths of 1040 nm, 520 nm and 347 nm using bubble formation in water as breakdown criterion. Unlike previous data, these threshold values are neither influenced by nonlinear propagation artifacts (because they were obtained at large NA) nor are they distorted by optical aberrations (because the pulses were focused through UV-VIS-IR water immersions microscope objectives built into the cuvette wall).

Investigation of fs-laser-induced optical breakdown thresholds in water at large NA is challenging, because the breakdown threshold energies are only a few nanojoules and the size of the transient laser-produced bubbles is well below the optical resolution limit. Therefore, we developed a probe beam scattering method in which the bubble size is inferred from the bubble oscillation time. We were able to detect bubbles with a maximum radius as small as 150 nm and an oscillation time of 15 ns and investigated also the dependence of bubble size on the laser pulse energy. We found that this dependence is considerably weaker for UV wavelengths than for IR wavelengths, as expected from previous numerical calculations on plasma formation.

Close to threshold, we identified a regime with very small conversion efficiency of laser pulse energy into bubble energy, ranging from 0,0002 % up to about 0,01 %. This regime, which is broadest for UV-wavelengths, is very suitable for cellular nanosurgery. The mechanism of bubble formation is thermoelastic rupture of the liquid at temperatures below the critical point. The agreement between theoretically predicted and experimentally determined bubble sizes is excellent. With increasing pulse energy, we found a steep increase of the conversion efficiency into bubble energy, indicating a similarly steep increase of the plasma energy density.

6460-10, Session 3

Novel oral applications of ultra-short laser pulses

E. Wintner, Technische Univ. Wien (Austria)

Ultra-short laser pulses potentially allow ablation free of collateral damage which could allow pain-free treatment of teeth. In this context, an overview of different scanners to be integrated in a handpiece for the practical application of ultra-short laser pulses is presented. Furthermore, for the case of 330 fs pulses, novel data on ablation thresholds for dental hard tissue (enamel, dentine; human and bovine), for a number of dental restoration materials, as well as for different types of bovine bone are reported. Finally, a preliminary investigation is presented on the applicability of ultra-short pulses with mentioned duration for the gentle cleaning of titanium implants focusing on the preservation of the special plasma-sprayed biocompatible implant surface.

6460-11, Session 3

Generation of smooth continuum centered at 1.15 um for ultrahigh resolution OCT

H. Wang, A. M. Rollins, Case Western Reserve Univ.

In ultrahigh-axial resolution OCT imaging (2-3 um), resolution is reduced with depth due to the absorption and dispersion of the sample. To balance the trade-off between resolution degradation and light penetration (due to scattering) a broadband OCT light source centered around 1.2 um is optimal. For high quality OCT imaging, the light source should have low intensity noise and sufficient average power and the spectrum should be smooth. Here, we demonstrate a novel light source which provides this performance using. A novel convex-dispersion photonic crystal fiber (PCF) with no zero-dispersion wavelength (ZDW) is pumped by a compact, turn-key Nd:glass fs laser centered at 1.05 um. A continuum is generated in the fiber by self-phase modulation that extends from 0.8 um to 1.3 um. By spectral filtering, a smooth and near-Gaussian shape spectrum is generated with a bandwidth of 200 nm (full width at half-maximum) centered at 1.15 um with an average power above 50 mW. Because the PCF has no ZDW, the noise amplification which occurs with continuum generation in PCF with one ZDW is avoided. This light source enables high quality OCT imaging with axial resolution of about 2.1 um in tissue. The continuum spectrum can be extended even broader by using higher peak-power pulses. Thus, a broad-band continuum which covers the entire range of 1-1.4 um centered at 1.2 um is feasible by pumping with the appropriate fs laser. The utility of 1 um fs lasers for OCT imaging may be greatly enhanced by use of this pumping scheme.

6460-12, Session 3

Femtosecond laser pulse processing of transparent corneal-like material

D. Yu, V. Kohli, A. Y. Elezzabi, Univ. of Alberta (Canada)

Laser-assisted ablation has received wide attention for its use in ophthalmology. With the advent of femtosecond lasers, considerable emphasis has been placed on the applicability of using ultrahsort laser pulses as scalpel tool for performing non-invasive corneal surgery. Herein, we investigate the interaction mechanism of multi-shot ablation on Hydroxy Ethyl Methacrylate (HEMA) using a sub-100 femtosecond laser system operating at few KHz and 80 MHz. The ablation efficiency between the two operating repetition rates were compared, using a range of pulse energies from a few nanojoules to hundreds of microjoules, and a beam dwell time of milliseconds to one second. Volume of ablated material was measured, and within the microjoule energy and repetition regime, ablation craters were formed without the creation of cavitation bubbles and scaring. At higher repetition rates with nanojoule pulse energies, ablation volumes were much smaller and were often formed with the presence of cavitation bubbles. Furthermore, the ablation rates as function of the number of incident pulses and pulse train interval have been studied. These results are important for future advancements in laser ophthalmology where critical care must taken to determine the optimal laser parameters for corneal surgery while minimizing collateral damage.

6460-13, Session 3

New developments in femtosecond laser corneal refractive surgery

R. Le Harzic, Fraunhofer-Institut für Biomedizinische Technik (Germany); C. Wullner, D. Christoph, Wavelight Laser Technologie AG (Germany); K. König, Fraunhofer-Institut für Biomedizinische Technik (Germany)

Studies on corneal surgery and flap processing on enucleated porcine eyes have been performed using a dedicated femtosecond laser source based on Ytterbium technology. The influence of several laser parameters such as wavelength, energy, repetition rate and numerical aperture has been studied. Best parameters for ocular femtosecond laser surgery are discussed in terms of process efficiency and safety aspects.

6460-14, Session 3

Characterization of the extent of damage in tissue ablation

F. Bourgeois, A. Crawley, A. Ben-Yakar, The Univ. of Texas/ Austin

Ultrashort laser pulses have increasingly been used to ablate subcellular structures inside living cells and multi-cellular organisms. We recently demonstrated nano-axotomy in the nematode Caenorhabditis elegans and observed nerve regeneration of the severed axons. Post-surgery biological phenomena can be impaired by the amount of collateral damage. Such damage is due to expansion of the thermoelastic stress-induced cavitation bubbles and the shock-waves beyond the focal volume of the laser beam. This study presents a systematic characterization of the extent of damage in C. elegans created by 100 femtosecond laser pulses at 1 kHz repetition rate with energies varying from 2 nJ to 20 nJ per pulse and number of pulses from 1 to 1000. To image the extent of damage in the surrounding area of the severed axons, we used worms that have GFP labeled muscles underneath the GFP labeled axons. The laser-exposed regions that lose fluorescence signal indicate the extent of both photo-damage and photobleaching. The results show that for each energy level, the extent of total damage reaches a plateau after a certain amount of delivered pulses. The minimum energy required for ablation greatly depends on the number of pulses. While a single shot of 21 nJ can severe an axon, the threshold drops to 8 nJ for 25 pulses, to 5.5 nJ for 100 pulses and to 3.8 nJ for 1000 pulses. However, 25 pulses at 7 nJ only photobleaches the axon and fluorescence is restored within two seconds.

6460-15, Session 4

Development of industrial Ti:sapphire femtosecond lasers and its industrial micro/ nano machining

K. Takasago, T. Sumiyoshi, T. Imahoko, N. Inoue, K. Yoshida, M. Kamata, H. Sekita, Cyber Laser Inc. (Japan)

For the industrial applications of femtosecond laser micromachining, development of long operational life, stable femtosecond lasers are one of the technically urgent issues. For this purpose fiber femtosecond lasers and thin disk femtosecond lasers have been extensively studied by many groups. However it is still difficult to extract a large amount of pulse energy from femtosecond fiber lasers and there is no reliable pump source for thin disk femtosecond lasers in viewpoint of industrial use. For this reason we choose a Ti:sapphire crystal to develop industrial femtosecond lasers because it is one of the most technically proven laser medium for the ultrashort laser system.

In this paper, we will present our recent progress of the development of long operational life, stable femtosecond lasers that generate 1 mJ, 800 nm with a 1 kpps repetition rate. In 2004 we already achieved a 10 k hour maintenance free operation of the femtosecond laser system. Additionally we have introduced an auto power management system (APMS) to the femtosecond lasers in order to compensate for unavoidable degradation of the optical components used in the system during the long term operation. The APMS consists of an auto power control (APC) system for the pump laser, the regenerative amplifier, and an auto timing adjustment system (ATS) for optimal extraction of the laser pulses from the amplifier. Our femtosecond lasers will be able to exceed a stable operational time of 30 k hours without any manual adjustment. The developed femtosecond lasers also exhibited temperature-independent operational performance of both laser output power and pointing stability between 293 and 303 K.

We will also present recent excellent examples of femtosecond laser micromachining of advanced materials, which is actually valuable in industrial micro/nano machining.

6460-16, Session 4

High-energy, high-repetition rate diode-pumped femtosecond amplifier

E. P. Mottay, C. Hönninger, A. Courjaud, Amplitude Systemes (France); I. B. Manek-Hönninger, M. Delaigue, Univ. Bordeaux I (France)

Precision micro machining in an industrial environment demands stable and high performance femtosecond lasers. Up to now most femtosecond amplified systems delivering mJ pulse energies are based on Ti:sapphire as gain medium which require rather complex pump lasers.

We demonstrate a directly diode-pumped femtosecond laser amplifier milliJoulr pulse energy and pulse repetition rates up to 100 kHz. Chirped pulse amplification is applied in order to eliminate nonlinear effects and to avoid damage of optical components during the amplification process. The seed pulses of 20-nJ pulse energy and 200 fs pulse duration are temporally stretched using a grating stretcher, amplified inside a regenerative amplifier cavity, and temporally compressed by a pair of diffraction gratings. The use of highly efficient transmission gratings led to an overall compressor transmission of 80%. The amplifier medium was Yb:KYW.

We extracted up to 1.25 mJ at a pulse repetition rate of 2 kHz and 0.88 mJ at a pulse repetition rate of 5 kHz. The compressed pulse duration was 480 fs. The beam quality has been measured and gave an M^2 value of < 1.2. Pulse energy was 50 microJoule at a repetition rate of 100 Khz.

6460-17, Session 4

MicroJoule level diode-pumped femtosecond oscillator

E. P. Mottay, C. Hönninger, Amplitude Systemes (France)

High energy femtosecond oscillators at high pulse repetition rate have a great potential for many applications such as micro- and nano-machining and structuring, waveguide writing in dielectric media, or nonlinear frequency conversion. Up to now most femtosecond oscillators operating at pulse repetition rates higher than 1 MHz were limited at pulse energies far below the microjoule level.

We demonstrate a directly diode-pumped Yb:KYW laser oscillator delivering pulse energies up to 1 μJ and pulse durations down to 430 fs, thus pulse peak powers exceeding the MW level. The pulse repetition rate is 9 MHz and the average power is on the 10-W-level. The laser setup is compact and fits in a 60 x 40 cm footprint, and does not use cavity dumping.

We externally compressed the pulse duration of this laser down to about 60fs by focusing the laser into a large mode area micro-structured fiber followed by a compressor module containing a pair of parallel aligned dispersive mirrors. The good coupling efficiency and the high-reflecting dispersive mirrors resulted in an overall compressor transmission of 80%. For a maximum injected pulse energy of 0.53 μJ we obtained up to 0.42 μJ pulse energy after the compressor which corresponds to a peak power of 7 MW.

6460-18, Session 4

High average power cryo-cooled ultrafast lasers

S. Backus, Kapteyn-Murnane Labs., Inc.

In this talk, we will discuss our recent work in developing cryogenically ultrafast laser-amplifier systems with average powers > 30 Watts, for use in coherent EUV and soft x-ray light sources, military applications, and for industrial applications such as micromachining.

Ultrafast laser systems with average powers of 10-30 Watts, and pulse durations <30 fs and at pulse repetition rates of >1 kHz are made possible by the use of cryogenically-cooled ti:sapphire amplifier systems. These systems can take advantage of efficient, high-power diode-pumped Nd:YAG/Nd:YLF lasers as their energy source, efficiently converting the highly-multimode, 200 ns duration 532/527 nm pulses from these lasers into near diffraction-limited femtosecond pulses. Cryogenic cooling of the laser medium dramatically reduces thermal lensing, simplifying the optical configuration of the laser and allowing for the generation of high-quality pulses with unprecedented short duration. Cryo-cooling also enables the flexibility of running the system in either high peak power, mode or high average power mode, without reconfiguring the amplifier layout or optics.

Currently, we have demonstrated average powers >30 watts, at 5 kHz in a commercially-available system. We have also demonstrated a 7 W, 20 kHz laser system which is used for eye surgery research. We are also developing a DPA system which will allow for a > 90% efficient compressor, and thus an increase of >20% in the output of our systems.

Further improvements in this field should allow powers of 40-50 Watts at repetition rates from 40-100 kHz in the near future.

6460-19, Session 5

New methods of characterization and control of femtosecond pulses focused with high numerical aperture objectives

J. A. Squier, W. Amir, C. G. Durfee III, J. Field, R. Huff, Colorado School of Mines; S. Kane, HORIBA Jobin Yvon Inc.; T. Planchon, D. Schaffer, Colorado School of Mines

Optimization of nonlinear imaging requires control of the generation, delivery and focusing of ultrashort pulses. In this talk we describe new innovations along this entire pathway. New broad-band, efficient grisms have resulted in a dramatic simplification of 35 fs chirped pulse amplification systems (generation). Further, these new dispersion-compensation devices make it possible to compensate second and third order dispersion from meters of fiber in a convenient, compact geometry (delivery). For active phase shaping within the microscope (control), we have developed a new efficient pulse shaper - 85% throughput with over 4000 individually controllable elements. A new collinear, background-free, fringe-free method for fully characterizing the pulse intensity and phase at the focus of the microscope objective has been created to match this application. Finally, to ensure efficient, high-resolution imaging the coupling of spatial aberrations to temporal distortions needs to be measured and quantified (focusing). We present linear, single-shot methods for the characterization of spatial-temporal distortions of femtosecond pulses focused with

multi-element, microscope objectives. We have incorporated these methods to characterize objectives used in conjunction with femtosecond pulses from the blue (400 nm) to the infrared (>1.0 μm).

6460-20, Session 5

High-speed characterization for optical telecommunication signals

C. Dorrer, Lucent Technologies

Optical telecommunication systems constantly evolve toward higher bit-rates requiring the modulation and detection of optical waves with finer temporal resolution. 40 Gb/s systems are now commercially available, and research and development is targeting higher bit-rates for which optical pulses with duration in the picosecond range are used. Chromatic dispersion, nonlinearities and amplified spontaneous emission from optical amplifiers are sources of transmission impairments that must be characterized and mitigated. Advanced modulation formats rely on the modulation of not only the amplitude of an optical wave (e.g. on-off-keying), but also its phase (e.g. phase-shift-keying) in order to optimize the transmission capabilities. The importance of the characterization of the properties of optical sources and components will be emphasized. Various diagnostics developed to measure the electric field of optical sources in the telecommunication environment will be described, and it will be shown that they provide relevant information not accessible by conventional means such as direct photodetection, which is usually limited to intensity-only measurements with insufficient bandwidth. Sampling diagnostics capable of measuring eye diagrams and constellation diagrams of data-encoded sources will be presented. Various optical pulse characterization techniques based on concepts identical to those used in ultrafast optics have also been developed in order to meet the sensitivity requirements imposed by the telecommunication environment.

6460-21, Session 5

Autonomous, flexible and reliable ultra-short pulse laser at 1552 nm

L. Vaissie, Raydiance, Inc.; K. Kim, College of Optics & Photonics/Univ. of Central Florida; J. F. Brennan III, M. M. Mielke, Raydiance, Inc.

Despite the growing number of biomedical and micromachining applications enabled by ultra-short pulse lasers in laboratory environments, real-world applications remain scarce due to the lack of robust, affordable and flexible laser sources with meaningful energy and average power specifications.

In this presentation, we will describe a laser source developed at the eye-safe wavelength of 1552 nm around a software architecture that enables complete autonomous control of the system, fast warm-up and flexible operation. Such remote software control over energy per pulse, pulse repetition rate, pulse train format and pulse width provide an unprecedented set of tools to optimize parameters for multiple applications in a single compact system without any add-ons.

The hardware architecture was designed for robust operation using volume scalable components, mostly fiber-based, and one-time-alignment opto-mechanical design. Our current desktop ultrashort pulse laser system offers specifications (1-5 microJ at 500 kHz, 800 fs-3 ps pulse width, variable repetition rate from 25 kHz to 500 kHz) that are meaningful for many applications ranging from medical to micromachining. We will present an overview of applications that benefit from the range of parameters provided by our desktop platform.

Finally, we will present a novel scalable approach for fiber delivery of high peak power pulses using a hollow core Bragg fiber recently developed for the first time by Raydiance and the Massachusetts Institute of Technology for operation around 1550 nm. We will demonstrate that this fiber supports single mode operation for core sizes up to 100 micron, low dispersion and low nonlinearities with acceptable losses. This fiber is a great candidate for flexible delivery of our laser pulses in applications such as minimally accessible surgery or remote detection.

6460-22, Session 5

High-power, ultra-short pulses from fiber laser pumped optical parametric amplifier

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In this contribution we report a high repetition rate optical parametric amplifier (OPA) pumped by a chirped pulse fiber amplifier system. The fiber CPA system permits power scaling and enables OPA at repetition rates in the 100 kHz-10MHz range. The OPA stage is seeded by a continuum generated in a Sapphire plate and more than 50 nm bandwidth is efficiently amplified, resulting in recompressed 3 μJ, 30 fs pulses.

Several applications rely on high repetition rate (and therefore high average power) and ultra-intense ultra-short pulse laser systems. If one considers the properties of ytterbium-doped short pulse fiber lasers [1] and ultrafast optical parametric amplification systems [2] one easily realizes the well matched compatibility of those techniques to achieve these challenging parameters. It is well known that fiber laser systems are average power scalable due to the fiber design itself, parametric amplifiers are inherently immune against thermo-optical problems due to the fulfilled energy conservation during the nonlinear amplification. The generation of ultra-short energetic pulses in rare-earth-doped fibers is restricted by the limited amplification bandwidth (~5 THz in the case of Ytterbium doped fibers) and pulse distortion due to nonlinearity in the fiber core. On the other hand parametric amplification offers an enormous amplification bandwidth (~ 200 THz in noncollinear configuration (NOPA)), furthermore, a gain of 106 or even 108 can be achieved in just few millimeter long crystals, therefore, the B-integral (accumulated nonlinear phase) is typical negligible. So far parametric amplification suffers from the lack of a high energy high repetition rate pump laser source, whose parameters potentially can be transferred into pulse durations in the sub-10 fs range using the parametric process. High performance short-pulse fiber laser have the potential to fill this gap.

6460-23, Session 5

High-average-power ps-UV-lasers for advanced micromachining

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Picosecond laser pulses are used to micro-machine virtually any material with highest precision and minimal thermal impact. The use of UV pulses can provide additional benefits in higher throughput and improved edge quality for materials like glass or ceramics.

The appropriate laser design for this application employs power scaling of IR-pulses by Nd:YVO4-oscillator-amplifier (MOPA) systems and efficient harmonic generation to the UV (355 nm).

We report on a new IR-MOPA with a wide range of pulse repetition frequencies (PRF) from single pulses (with energies > 200 μJ) to 1 MHz (with average powers over 10 W).

Conversion efficiencies > 50% from IR to UV were achieved at 100 kHz, generating a UV pulse energy > 30 μJ with an excellent beam quality (M^2) < 1.1). The pointing stability is superior to other ultra-fast laser sources. The average power of more than 3 W enables fast and efficient processing. The advantages of this laser source are demonstrated by high-end micro-machining samples on sapphire, zirconium ceramics, and metals like molybdenum.

6460-24, Session 6

Strong field physics using mid-infrared lasers

G. Doumy, C. Blaga, F. Catoire, R. Chirla, P. Colosimo, I. M. Lachko, A. March, E. F. Sistrunk, J. Tate, J. Wheeler, L. F. DiMauro, P. Agostini, The Ohio State Univ.

Atoms irradiated by intense laser light emit electrons and attosecond photons bursts. The aim of this talk is to discuss the influence of the laser wavelength on the characteristics of these emissions and to present some preliminary results and the prospects of high harmonic generation using mid-infrared wavelengths. The strong field ionization theory(1) and the quasi-classical approach of high harmonics(2) predict that the photoelectrons maximum kinetic energy and the photon bandwidth are proportional to the ponderomotive energy UP (with UP I 2). Since strong field ionization photoelectron spectra extend to 10 UP and the high harmonic cutoff reaches Ip + 3.2 UP,(3) long wavelengths produce, at the same intensity, more energetic electrons and photons. We show that photoelectron energies in the range of keV can easily be produced using 2 or 4 micron wavelengths.

Another theoretical advantage of the long wavelength fundamental radiation is that the attochirp, or group delay dispersion of the attosecond pulse, is reduced as (I due to the spreading of the electron wavepacket(4). This attochirp can be measured by the RABBITT method four or an all-optical method recently demonstrated(5). However, on the other hand, the yield is predicted to drop as We will briefly review the current theoretical predictions(6).

Experimental results on high harmonic generation using the 2-micron source at OSU are then presented and discussed. They include measurements of the cutoff and preliminary investigations of the harmonic spectral phase. The advantage of the reduction of the attochirp is evaluated in the perspective of pulse durations approaching the atomic unit of time (24 as).

1 Keldysh Sov. Phys. JETP 20, 1307 (1965) ; F. H. Faisal Journ. Phys. B 6, L89 (1973) ; H. R. Reiss Phys. Rev. A 22, 1786 (1980).

2 M. Lewenstein et al. Phys. Rev A 49, 2117 (1994).

3 K. Schafer et al. Phys. Rev. Lett. 70, 1599 (1993).

4 Y. Mairesse et al. Science 302, 1540 (2003).

5 N. Dudovich et al, Nature Physics, 2(11), 781 (2006).

6 J. Tate et al, Phys. Rev. Lett. (2006).

6460-25, Session 6

Characterization of attosecond pulse trains

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We report the direct observation of a train of attosecond pulses by mean of autocorrelation method using nonresonant two photon processes in atoms and molecules in the xuv region.

6460-26, Session 6

Attosecond pulses generated by two color laser fields

T. Ruchon, E. Gustafsson, J. Mauritsson, P. Johnsson, Lunds Univ. (Sweden); M. Swoboda, Lunds Univ. (Germany); T. Remetter, Lunds Univ. (Sweden); R. López-Martens, P. Balcou, École Nationale Supérieure de Techniques Avancées (France); A. L'Huillier, Lunds Univ. (France)

Focusing an intense infrared laser field in gas medium, one can generate high order harmonics spanning from the ultraviolet to the soft X-ray region, providing the bandwidth required for getting attosecond pulses. However, the different frequency components in the harmonic spectrum are not naturally synchronized and the bursts obtained are usually not short.

In this communication, we will report on progress in controlling the chirp of the harmonics over a broad spectrum using metallic filters. Previous experiments allowed us to observe 170 as pulses centred at 30 eV using harmonics generated in a static argon cell along with Al filters . We have extended this technique to harmonics generated in a neon cell flowed by a kHz pulsed valve, along with aluminium, silicium or zirconium filters. We obtained pulse durations down to 130 as, centered at 80 eV.

Attosecond pulses have been used to study photoionization by XUV radiation in presence of a strong IR field. When using long IR pulses for the generation (35 fs), attosecond pulse trains with two pulses per cycle are obtained, and consecutive electron wave packets get different momentum shifts from the IR field . Recently, adding a small portion of doubled frequency light to the generation IR field, we have shaped attosecond pulse trains in order to get only one burst per laser period . Now, photoionization takes place in the same IR field for all bursts in the train, thus increasing the counting statistics compared to a single event. Recent results and movies recorded with this "stroboscope" will be presented.

Th. Remetter et al., Nature Physics 2, 323 (2006)

J. Mauritsson et al.,Phys. Rev. Lett. 97, 013001 (2006)

6460-27, Session 7

Attosecond pulses in atoms and molecules

H. Merdji, CEA (France)

High order harmonics generation (HHG) offers the unique opportunity of generating attosecond pulses. The condition for the production of short pulses critically depends on the spectral phase of the XUV radiation. In the HHG process the laser field that induces the tunnelling ionization drives the electron wave packet into the continuum. When the wave packet recombines with its parent ion attosecond burst of light are emitted. Measuring the spectral phase of the radiation reveal the dynamics of the electron wave packet. This is done using the RABITT technique [Paul et al., Science 292, 1689 (2001)]. First I will show the dependence of the electron dynamics in the process of high order harmonic generation in an atom as a function of the XUV frequency (i.e. the harmonic order) and the intensity [Mairesse et al., Science 302, 1540 (2003)]. Theses measurements allow us to optimize the attosecond pulses that we produce [Mairesse, et al. PRL 96, 163901 (2004)].

Finally, I will present our last attosecond measurements in molecules. Our motivation was driven by recent number of papers that have demonstrated the interest of high-order harmonic generation (HHG) from aligned molecules [Itatani et al. (Nature 432, 867 (2004)); Kanai et al. (Nature 435, 470 (2005))]. In a recent experiment, we have measured, up to high order, the harmonic amplitude and relative phase for aligned molecules (N2 and CO2). The position and the behavior of the jump in CO2 coincides with the dip in the harmonic spectrum measured at harmonic 23 by Kanai et al.. We also investigated the case of aligned nitrogen molecules. We observed a phase jump at harmonic 25, but this jump is independent of the angle of alignment. The origin of this interference would thus be different from that observed in CO2 and is not consistent with the two-center interference model used by Kanai et al.

6460-28, Session 7

Metrology and applications of isolated XUV attosecond pulses

E. Goulielmakis, R. Kienberger, M. Uiberacker, Max-Planck-Institut für Quantenoptik (Germany); A. Baltuska, Max-Planck-Institut für Quantenoptik (Germany) and Technische Univ. Wien (Austria); M. Drescher, Univ. Hamburg (Germany)

Over the last forty years, developments on laser science have allowed the increase of the spatial and temporal resolution for observing the microcosm to unprecedented levels. By the end of the millennium, this resolution, has allowed real time observations of the atomic motion inside molecules, solids, biological complexes and has opened a new era for physics chemistry and biology[1].

Attoscience is a new field of physics devoted to the study of phenomena pertinent to the electronic motion. The key tool of attoscience is pulsed electromagnetic radiation that last merely a few hundred of attoseconds (1 as =10 -18 seconds) [2].

To demonstrate the potential of these new tools to track ultrafast processes, we employ an attosecond pulse as a sampler to trace for the first time what would be considered only a few years ago immeasurably fast, namely: the oscillations of light waves [3]. We discuss the possibilities of exploiting the new tools for advancing the metrology of light fields and enabling the synthesis of optical monocycles and subcycles.

[1] A. Zewail, Nobel lecture, 1999

[2] R. Kienberger et al. Nature 427, 817 (2004)

[3] E. Goulielmakis et al. Science 305, 1267 (2004)

6460-29, Session 7

Applications with attosecond pulses

G. G. Paulus, Max-Planck-Institut für Quantenoptik (Germany)

Taking advantage of the unique properties of phase-controlled few-cycle pulses, a close analogue of the double-slit scheme has been realized in the time domain. An unprecedented degree of control of which-way information and the briefness of the temporal slits suggest applications for studying fundamental aspects of quantum theory and attosecond science.

6460-30, Session 8

Coupling management of fs laser written waveguides

A. Szameit, F. Dreisow, S. Nolte, Friedrich-Schiller-Univ. Jena (Germany); A. Tuennermann, Fraunhofer Institut für Angewandte Optik und Feinmechanik (Germany)

Arrays of evanescently coupled waveguides are an excellent model for discrete systems and exhibit unique propagation properties which are in some extend in strong contrast to the evolution of light in isotropic media. A crucial parameter for all application is the strength of the coupling between the single waveguides itself, whether being highly homogeneous or, in contrast, vary with specifically defined values.

In this talk we introduce a method to determine the coupling between fs laser written waveguides, using a system of two evanescently coupled waveguides. One can derive a simple analytical solution for the light evolution in such systems and, therefore, it is possible to determine the coupling constant directly from the measurement of the resulting output patterns of the waveguides. These measurements, performed for elliptical and cylindrical waveguides, reveal absolute values of the coupling as a function of wavelength, waveguide separation and angle of direction, which is fundamental for the design of one- and two-dimensional array of special geometries requiring specifically defined coupling. Since for elliptical waveguides the coupling is anisotropic, this can be used as an additional degree of freedom to tune the coupling in an array only by choosing the orientation of the waveguides. This allows in particular studying the influence of the diagonal coupling in cubic waveguide arrays.

We believe this work to be of great interest for the design and fabrication of fs laser written integrated optical devices requiring specifically defined evanescent coupling.

6460-31, Session 8

Optical and structural properties of waveguides in LiNbO3 fabricated by ultrashort laser pulses

J. Burghoff, H. Hartung, S. Nolte, Friedrich-Schiller-Univ. Jena (Germany); A. Tünnermann, Fraunhofer Institut für Angewandte Optik und Feinmechanik (Germany)

The use of ultrashort laser pulses has found widespread attention in the microstructuring of transparent materials. Specifically, the origin of refractive index changes in glasses and crystalline materials was extensively investigated. In LiNbO3, which is an important material for nonlinear optical applications, the possibility of waveguide fabrication with fs laser pulses was also shown. Recently, two distinct types of waveguides were discovered in LiNbO3 which show different thermal stability and optical properties. In one type, we demonstrated frequency doubling of 1064-nm radiation. Here, we discuss the different origins of the two waveguide types and present results of thermal annealing experiments. Furthermore, the influence of the processing parameters and the focusing on the properties of the waveguides is investigated. The electro-optic coefficient of the waveguide was measured and gives evidence that the nonlinear properties of the crystal are little effected by the laser structuring.

6460-32, Session 8

Deep-subsurface waveguides with circular-mode symmetry by direct laser writing with astigmatically shaped beams at low-numerical aperture

J. Siegel, V. Diez-Blanco, J. Solis, Consejo Superior de Investigaciones Científicas (Spain)

Bulk modification of transparent materials with Femtosecond (fs) laser pulses is a promising tool for the fabrication of 3-D photonic elements. However, in spite of its successful application to the production of waveguides and other elements its use is still hampered by problems related to the control of energy deposition inside the material. In particular, spherical aberration strongly reduces the maximum power density achievable and increases the depth of focus as a function of the focusing depth, thus effectively limiting the processing depth and resolution. In this work, the combined use of small numerical aperture focusing lens (in order to minimize spherical aberration effects) and astigmatic beam shaping has been investigated as a route for producing waveguides with symmetric profiles at large processing depths by direct laser writing with fs laser pulses. The laser source used is a commercial fs-amplifier operating at 800 nm and providing 100 fs laser pulses at 1 KHz repetition. rate. We have used both SiO2 and Er:Yb-doped phosphate glass (Kigre MM2) as materials for the study. A variable slit has been used to produce the astigmatic beam that was focused inside the sample with a 0,26 NA long working distance microscope lens. In all cases, the samples have been scanned perpendicularly to the irradiation beam at speeds in the 100 micrometer/s range. The effect of the pulse energy, the slit width and the scanning speed on the characteristics of the waveguides produced has been analyzed. By adjusting the experimental parameters we have been able to produce waveguides with low losses (<1 dB/cm in non-doped samples) and circular mode symmetry at depths as large as 8 mm.

6460-33, Session 9

Type II ultrafast-laser writing of Bragg grating waveguides in bulk glass

H. Zhang, S. M. Eaton, S. Ho, M. L. Ng, J. Li, P. R. Herman, Univ. of Toronto (Canada)

A novel type II photosensitivity mechanism has been exploited in ultrafast laser interactions to simultaneously write Bragg gratings and buried optical waveguides in bulk borosilicate glass (Corning EAGLE2000). The Bragg grating waveguides are defined by an array of refractive index voxels that provide single-mode guiding and narrow Bragg resonances (0.08 nm) across a broad 1200 - 1600 nm spectrum, encompassing both telecom bands. The arrays were formed by transverse scanning of an 800-nm femtosecond laser with a NA = 0.25 aspherical lens and focal position ~200-um below the sample surface. The combination of 1-kHz repetition rate and variable scan speeds of 0.4 to 2 mm/s offered simple means for changing the voxel periodicity (0.4 to 2 um) and freely tuning the 1st, 2nd, and 3rd order Bragg resonances in the infrared spectrum. Low-loss guid-

ing with moderately strong Bragg resonances were available only in a narrow processing window defined by 2 to 5 uJ pulse energy and demonstrating high sensitivity to pulse duration over an examined 80-fs to 2-ps range. The lowest propagation loss of 0.3 dB/cm was demonstrated at 200 fs whereas the strongest Bragg grating response of >10 dB (in transmission) was found at 320 fs. Near-symmetric mode sizes (1/e2 diameter) of 11 um x 14 um closely match the modes in standard telecom fiber. Cascaded Bragg grating waveguide systems will be presented together with prospects for fabricating novel three-dimensional optical sensor systems.

6460-34, Session 9

Inscribing fiber Bragg gratings using IR-fs pulses and a phase-mask scanning technique: potential and applications

E. Wikszak, J. Thomas, S. Nolte, Friedrich-Schiller-Univ. Jena (Germany); A. Tuennermann, Fraunhofer Institut für Angewandte Optik und Feinmechanik (Germany)

Over the last decade, Fiber Bragg Gratings (FBG) have become key components for optical telecommunication systems and sensor applications due to their low losses and narrow bandwidth filtering.

Using conventional writing techniques based on UV absorption requires the use of photosensitive fiber material. However, this is problematic in active fibers and, therefore, causes problems when applying this technique to fiber lasers and amplifiers. In the last years, an alternative method based on the non-linear absorption of focused femtosecond pulses allowed the inscription of FBG into non-photosensitive fibers. We report here on the inscription of such gratings using IR femtosecond pulses and a phase-mask scanning technique to produce high reflectivity gratings in various non-photosensitive fibers. The specific issues associated with the femtosecond inscription like appropriate focusing and positioning techniques necessary for high quality phase-mask scanning will be discussed. We will also give some application examples like fiber lasers in rare-earth doped fibers with integrated Bragg reflectors and chirped Bragg gratings for dispersion control.

6460-35, Session 10

Modeling of ultrashort pulse propagation and nonlinear plasma formation in transparent Kerr media using realistic initial conditions

C. L. Arnold, Laser Zentrum Hannover e.V. (Germany); W. Ertmer, Univ. Hannover (Germany); H. Lubatschowski, Laser Zentrum Hannover e.V. (Germany)

Detailed Understanding of the nonlinear interaction of ultrashort laser pulses with materials is crucial for modern applications of ultrashort pulses, such as micromachining of materials, waveguide writing, or refractive surgery. In order to manipulate material by the controlled generation of damage or alteration, pulse energy is deposited on the surface or within the bulk of materials by tightly focusing of ultrashort pulses. Nonlinear interactions such as plasma generation, self-focusing and plasma defocusing are the main processes involved. Laser energy is stored in the focal region by means of kinetic energy of free electrons in the plasma. The size and the density of the generated plasma determine the achievable precision.

A theoretical understanding of the plasma formation and the pulses interaction with the self-generated plasma is given by the work presented. A numerical model including linear and nonlinear pulse propagation effects and nonlinear ionization is introduced. Nonlinear ionization is numerically treated by using a multi rate equation model for dielectrics recently published by Rethfeld. It keeps track of the temporal evolution of the energy distribution of generated free electrons in the conduction band and hence is more powerful than common Drude models that are often used. Using a Drude approach the importance of cascade ionization versus multiphoton ionization was often overestimated.

Based on the above model numerical calculations are performed to understand nonlinear side-effects, such as streak formation, occurring in addition to ultrashort laser pulse induced optical breakdown. Special attention is paid to the shape, size, and density of generated breakdown plasmas. These characteristics determine the intensity of the mechanical, thermal or chemical interaction involved. To push the simulations closer to reality, complex spatial shapes for the incident pulses are assumed. Using diffraction integral techniques, initial conditions such as the diffraction pattern of focused truncated gaussian beams or focused uniform plane waves are calculated. Time dependent diffraction integrals enable us to even consider temporal effects that only occur at the use of ultrashort pulses, such as pulse front distortions induced by e.g. imperfect focusing optics. These initial conditions are more realistic than perfect gaussian beams that have often been used before.

The calculations can be performed for any transparent Kerr-medium of known optical parameters such as water or fused silica.

6460-36, Session 10

Luminescent high-energy density femtosecond plasmas in bulk materials

A. Vogel, N. Linz, S. Freidank, Univ. zu Lübeck (Germany); G. Paltauf, Karl-Franzens-Univ. Graz (Austria)

Fs laser pulses focused at large NA into nominally transparent materials are used for cellular nanosurgery and for nanomorphing of solid dielectrics but can also produce well localized effects of considerably larger extent when the laser pulse energy is increased. This differs strongly from fs breakdown at small NAs for which an increase of the pulse energy leads to an ever more delocalized energy deposition owing to nonlinear beam propagation effects including plasma defocusing and filamentation that limit the maximum possible plasma energy density.

We characterized fs breakdown in water at large NA by measuring the energy dependence of plasma transmission T and cavitation bubble size Rmax. For E/Eth 3 7 (Eth = bubble formation threshold), we observed plasma luminescence on photographs of the focal region that allowed to determine the plasma size. From plasma absorption A = 1-T and plasma volume V we determined the energy density e = Eabs / V. Knowledge of e, the equation of state of water, and the Grüneisen coefficient allows to assess the temperature T after equilibration of electron and ion temperatures and the resulting thermoelastic pressure. The data on plasma volume (= initial cavitation bubble volume) and maximum bubble radius Rmax were implemented into the Gilmore model of cavitation bubble dynamics and used to calculate the initial plasma pressure averaged over the period of stress confinement and the time after relaxation of the thermoelastic stress.

We found that for large NAs and well above the breakdown threshold both energy density (>>20 kJ cm-3) and equilibrium temperature in fs plasmas are comparable to those of ns plasmas. However, owing to stress confinement, the peak pressure is for a sub-nanosecond time period much larger in fs plasmas although the resulting ultrashort thermoelastic stress wave will be rapidly damped. Moreover, the number density r and possibly also the average kinetic energy Ekin (“temperature”) of the free electrons are considerably larger in fs plasmas because only one set of free electrons is produced by a fs pulse whereas a dynamic equilibrium between free electron generation and recombination evolves during a ns pulse which results in a given energy density at much lower values of r and Ekin. This outcome raises interesting questions about the laser plasma coupling in fs breakdown because it is not consistent with the common view that plasma becomes completely reflective at a critical free electron density of >>1021 cm-3.

Thus, fs optical breakdown phenomena in bulk media at large NA span a large range: from nanocavitation induced by a temperature rise of less than 200 degrees Celsius for energies at the bubble formation threshold to laser plasma coupling features similar to those in laser fusion when energies well above the breakdown threshold are employed.

6460-37, Session 11

Femtosecond laser nanomachining of silicon wafers and two-photon nanolithography

K. König, F. Bauerfeld, D. Sauer, H. Schuck, T. Velten, S. Schenkl, Fraunhofer-Institut für Biomedizinische Technik (Germany); R. LeHarzic, JenLab GmbH (Germany)

We explored the feasibility of nJ NIR MHz femtosecond laser pulses for nano- and microprocessing of non-biological materials, such as silicon wafers, metal films, and polymers based on multiphoton ablation as well as two-photon polymerization.

We report on sub100nm-nanostructering based on multiphoton ablation of silicon wafers and nanostructured single cell microcaontainers produced by two-photon polymerization using a compact laser scanning microscope with fast galvoscanners.

6460-38, Session 11

Femtosecond lasers: combining 5-D microscopy and 3-D nanoprocessing

J. Li, P. R. Herman, H. Zhang, S. M. Eaton, A. H. Nejadmalayeri, A. Hosseini, Univ. of Toronto (Canada)

An ultrafast-laser based optical system has been developed that combines nano-scale machining at high pulse energy (~1 uJ) with 5-dimensional (3 spatial dimensions + time + wavelength spectrum) optical microscopy at low pulse energy (~1 nJ) to enable on-the-fly diagnostic feedback for target alignment and optimizing femtosecond laser interactions. The fundamental and frequency-doubled output of a fiber laser (1045 nm, 450 fs, 0.1-5 MHz) and a Ti:Sapphire laser (800 nm, 40 fs, 1 kHz) system served as dual nanoprocessing and spectroscopic excitation sources. A precision optical delivery system was integrated with a time-gated intensified CCD (ICCD) camera, an imaging spectrometer, and single-photon-counting avalanche photodiodes to offer high optical sensitivity for monitoring various laser interactions, including multi-photon fluorescence, plasma luminescence, heat accumulation effects, and second-harmonic and third-harmonic generation (SHG and THG). Spatial (~100 nm), temporal (~50ps) and spectral (~0.1 nm) resolution has been demonstrated in various modes of operation. By simply toggling the laser fluence above and below the material ablation threshold, the system permitted prompt in-situ characterization of laser-formed structures for assessing material modification thresholds, photochemical changes, and laser-interaction volume as well as for directing focal alignment and controlling exposure for device trimming applications. This paper describes the ultrafast system and presents several application directions, including: aluminum foil assays by laser-induced breakdown spectroscopy; 3-D visualization of heat accumulation effects during high-repetition rate (>300 kHz) laser interactions in bulk glasses, and 3-D profiling of nonlinear responses (THG) induced in laser-formed buried optical waveguides.

6460-39, Session 11

Ultrafast pulsed laser ablation for synthesis of nanocrystals

B. Liu, Y. Che, Z. Hu, IMRA America, Inc.; Y. Chen, X. Pan, Univ. of Michigan

Fiber-based near infrared (1μm) ultrafast laser is used to ablate metal targets in vacuum. By confining the laser fluence above the fundamental ablation threshold and below the threshold of strong atomization and ionization, crystalline nanoparticles are found to be abundant in the ablated mass. At higher fluences, droplet-like large particles appear as a result of splashing by the strong recoil force, and the fraction of particle in the ablated mass quickly drops. Using metal nickel as a sample material, we have produced Ni/NiO core/shell nano-spheres and NiO nano-cubes. This study provides evidence that ultrafast laser ablation can be a simple physical method for generating nanoparticles with a narrow particle size distribution, a high particle yield, and versatile structural forms and chemical compositions.

6460-40, Session 11

An ultrashort pulse laser lathe for axisymmetric micromachining of explosives

J. A. Palmer, E. J. Welle, Sandia National Labs.

Engineers at Sandia National Laboratories have devised a novel ultra short pulse laser lathe system for bulk micro machining of axisymmetric features in energetic material samples with three-dimensional cylindrical geometry. 120 femtosecond pulses from a 800-nm Ti:sapphire laser were utilized to machine hexanitrostilbene (HNS) rods with diameters less than 200 micrometers and greater than 5:1 aspect ratio without detonation or deflagration. To date, this work represents the smallest energetic material rod structures fabricated by this technology. Results indicate that surface roughness is dependent upon rotation speed and feed rate. Valuable explosive nano particles were collected, and analyzed as a byproduct of fabrication and show promise for future nano-engineered energetic material systems.

6460-41, Session 11

Welding of transparent materials with high-repetition-rate femtosecond lasers

J. M. Bovatsek, Spectra-Physics; J. Nguyen, B. Chen, Cornell Univ.; F. Yoshino, IMRA America, Inc.; L. Bonassar, Cornell Univ.; A. Y. Arai, IMRA America, Inc.; C. B. Schaffer, Cornell Univ.

When a femtosecond laser pulse is tightly focused into the bulk of a transparent material, energy can be deposited into the sample at the focal volume through nonlinear absorption. At high repetition rate, where the pulse-to-pulse separation is shorter than the thermal diffusion time, there is an accumulation of thermal energy in the beam focus when multiple pulses irradiate one spot in the sample. Here, we use a high repetition rate femtosecond laser tightly focused at the interface between two pieces of glass to weld the glass together. The use of the multiple pulse heat accumulation effect allows for very precise control of the heat deposited at the glass interface, and therefore to the penetration of the weld into the two glass samples. We achieved penetration depths of a couple of micrometers up to about 50 μm. Because higher penetration welds are stronger, this control allows us to trade off small weld size for stronger weld strength to suit the application. The use of high repetition rate lasers also facilitates high speed welding, with weld lines formed at up to 2 cm/s. This paper expands on our previously presented preliminary results to examine the optical and structural characteristics of the glass welds.

6460-42, Session 11

Joining of transparent materials by femtosecond laser pulses

W. Watanabe, National Institute of Advanced Industrial Science and Technology (Japan); S. Onda, T. Tamaki, K. Itoh, Osaka Univ. (Japan)

When a femtosecond laser pulse is focused at the interface of two substrates, localized melting and quenching of the two substrates occur around the focal volume. The substrates can then be joined by resolidification of the materials due to nonlinear absorption of focused femtosecond laser pulses. We demonstrate the joining of similar and dissimilar transparent materials.

6460-43, Poster Session

Laser microwelding of silicon and borosilicate glass using nonlinear absorption effect induced by 1558-nm femtosecond fiber laser pulses

T. Tamaki, Osaka Univ. (Japan); W. Watanabe, National Institute of Advanced Industrial Science and Technology (Japan); K. Itoh, Osaka Univ. (Japan)

The micro-welding technique based on the nonlinear absorption of focused femtosecond laser pulses is useful for joining transparent materials without introducing a light-absorbing intermediate layer. In fact, it has been successful to weld a wide variety of glass materials using 800-nm or 1045-nm pulses. In this paper, we show that this technique can be extended to semiconductor materials, which are opaque in the above wavelength regions, by demonstrating the welding of silicon and borosilicate glass. The key is the use of long-wavelength pulses. We used 1558-nm, 947-fs, 0.8-μJ, 500-kHz pulses from an amplified femtosecond Er-fiber laser (IMRA America, FCPA μJewel B-250). We also used a 20x objective lens with a numerical aperture of 0.40 to focus the pulses at the interface of silicon and borosilicate glass, which were mounted on a two-dimensional translation stage. By translating the stage perpendicular to the optical axis in the two-dimensional plane at 200 μm/sec, we produced a 3 x 3 array that consists of welding areas of 100 μm x 100 μm. After welding, we performed a simple tensile test. The joint strength was found to be 3.74 MPa, which was on the same order as that between borosilicate glasses (9.87 MPa). Although the welding between silicon substrates is currently hindered by the difficulty of observing focal point with visible light, our result is an important step toward the welding of semiconductor materials, which may have various applications such as three-dimensional stack of electronic devices and fabrication of micro-electro-mechanical systems.

6460-44, Poster Session

Femtosecond laser nanostructured substrates for surface-enhanced Raman scattering

E. D. Diebold, E. Mazur, Harvard Univ.

We present a new substrate for efficient surface enhanced Raman scattering (SERS). Using a train of focused frequency-doubled femtosecond laser pulses from a regeneratively amplified Ti:Sapphire laser, we fabricate submicron surface structures on a silicon wafer. After irradiating the silicon wafer with 400nm, 100fs laser pulses in a cuvette of water, we observe the formation of an array of spikes, each approximately 500nm tall and 200nm wide. The wafer is scanned across the beam to structure an arbitrarily sized area. When covered with a thin film of a noble metal, the structured surface exhibits a strong enhancement of the Raman signal as measured using micro-Raman spectroscopy. To quantify the surface enhancement factor of the device, we cover the surface with a self-assembled monolayer of benzenethiol. The Raman surface enhancement factor of the structured area is measured to be approximately 10^6. These inexpensive, reproducible, and efficient SERS substrates show great promise for use in chemical and biological sensing, as well as demonstrate yet another application for ultrafast laser technology.

6460-45, Poster Session

Plasmonics mediated nanohole fabrication on various substrates with femtosecond laser excitation

T. Miyanishi, N. N. Nedyalkov, M. Obara, Keio Univ. (Japan)

Nanohole formation on silicon, fused quartz, and gold substrates mediated by near-electromagnetic field enhancement with gold nanoparticles is experimentally and theoretically investigated. Gold nanoparticles with diameters of 20, 40, 80 or 200 nm are spin-coated on the substrates. The used laser is an 820 nm, 150 fs Ti: sapphire laser system. The morphological changes of the surface and the fabricated nanostructures are analyzed by scanning electron microscope (SEM) and atomic force microscope (AFM). The distribution of the near-electric field is also analyzed by the FDTD (Finite Difference Time Domain) simulation code to compare to the experimental results. In addition, the optical properties of the gold nanoparticles are analyzed on the basis of the Mie's theory in order to explain the observed dependences.

The electric near-field distribution on the surface obtained by FDTD code is found dependent on the laser polarization, wavelengths used, and it is related to the excitation of different plasmon modes. The properties of the produced morphological changes on the substrates are found to depend strongly on the polarization and the fluence of the laser pulse. When the laser pulse is linearly polarized the produced nanohole shape is elongated in the direction of the polarization. The shape of the hole becomes symmetrical when the laser radiation is circularly polarized.

The largest field enhancement calculated by the FDTD method in the case of particle diameter of 200 nm is about 25. The diameter of the field enhanced area is theoretically scaled as 1/3.5 of the gold particle diameter.

6460-46, Poster Session

Femtosecond-laser microstructuring of silicon for novel photovoltaic devices

B. R. Tull, M. T. Winkler, E. Mazur, Harvard Univ.

Silicon is an abundant, stable, and efficient material for use in photovoltaic devices. However, it is costly to process, and is transparent at wavelengths longer than 1100nm, a spectral region containing 25% of solar energy. The limitations of silicon have spurred significant research into complex heterostructures that capture a greater fraction of sun's energy. Engineering silicon to extend its effective spectral range, however, might offer a simpler way to increase the efficiency and decrease the cost of silicon-based photovoltaics.

We report the creation of a thin, highly absorbing layer on silicon surfaces using the intense conditions at the focus of a high-intensity, femtosecond laser pulse. Irradiation of a silicon surface with 100-femtosecond laser pulses in the presence of a sulfur-containing gas creates a highly doped layer of nanocrystalline silicon in the top several hundred nanometers. The incorporation of this thin layer results in near unity absorption of light from the near-ultraviolet (250 nm) to the near-infrared (2500 nm), including wavelengths normally invisible to silicon (> 1100 nm). After thermal annealing, a photovoltaic responsive junction is formed between the nanocrystalline layer and the underlying silicon.

We have previously shown that this process can be used to make viable silicon-based visible and infrared photodetectors. Here we report details on the photovoltaic properties of femtosecond-laser microstructured silicon using dopants in addition to sulfur, such as tellurium and selenium. We discuss the observed changes in optical and electrical properties under different annealing conditions and correlate these changes with dopant diffusion in the nanocrystalline layer.

6460-47, Poster Session

Visualization of light propagation in fs written waveguide arrays

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For various applications it is interesting to directly visualize the propagation of light in waveguides. For this purpose, we used special fused silica glasses with a high content of OH. This leads to the formation of color centers when waveguides are written with fs laser pulses. When light is launched into the waveguides the color centers are excited and the fluorescence can be directly observed. This is especially interesting in waveguide arrays for the visualization of the evanescent coupling, since the discrete light evolution exhibits many features which are in strong contrast to propagation in common isotropic media.

As an example for the visualization we will discuss here for the first time the possibility to excite a completely incoherent propagation within the waveguide array although the sources are fully coherent. When multiple waveguides are excited, the light evolution in the array can be described as a superposition of the single propagating amplitudes. The formula for the resulting intensity contains an interference term. One can explicitly show that this interference term vanishes for certain excitation patterns. When for instance two adjacent waveguides are excited the light propagates as there was no interference term, which is equivalent of the simple sum of the two intensities of the single amplitudes. This suggests the term “quasi-incoherent” for this new kind of propagation effect. In contrast a coherent superposition including the interference term is obtained for an excitation of two waveguides when there is one waveguide located between the two excited ones.

6460-48, Poster Session

Hollow waveguide for femtosecond pump-probe experiments in the gas phase

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A method to increase the sensitivity of femtosecond pump-probe experiments in the gas phase is demonstrated by implementation of a hollow-glass waveguide, increasing the probe signal. We study intramolecular vibrational redistribution in polyatomic molecules.

One central aspect of statistical reaction theories is the rapid redistribution of vibrational energy within a molecule with the assumption that redistribution proceeds faster than reaction so that microcanonical intramolecular equilibrium is reached prior to reaction(1,2). This question has been investigated in the past by means of chemical activation experiments in bulk and in molecular beams (see 3,4 for reviews) and also by high resolution molecular spectroscopy of highly exited molecules followed by quantum dynamical analysis (see5,6,7 for reviews). In recent work in our group we have used femtosecond pump-probe techniques of polyatomic alkyliodides(8), related to previous and parallel work also in other research groups(9,10). In our time resolved pump-probe experiments the intramolecular vibrational energy redistribution (IVR) in the gas phase is investigated8. The transfer of energy from a well defined vibrational state to other closely coupled states in the absence of collisions or other interactions with the environment is investigated. Both, the pump and the probe pulses are focused on the same spot of the sample. The pump pulse (near-IR 1700 nm, 150 fs pulse length) populates the first overtone of the CH-stretching vibration of CH3I or an other sample molecule. With the probe pulse (UV 310-340 nm, 150 fs pulse length) the IVR process is detected by spectral changes of the S0 → S1 absorption spectrum of the sample molecule (see the scheme of Fig.1).

Fig.1. Experimental scheme of probing intramolecular energy redistribution (tIV R) and intermolecular energy transfer (ttransfer) after CH-overtone excitation by the UV-absorption technique (after reference8).

Due to the small absorption cross-section in the near-IR the fraction of molecules excited by the pump pulse is only around 10-3 or even smaller and for low vapor pressures it is difficult to obtain a satisfactory signal-to-noise ratio. Also decreasing the focus spot is impossible due to an occurrence of optical breakdown. An additional possibility of increasing the effective interaction volume is to use a hollow waveguide filled with the gas under investigation. We studied this possibility in the present work in some detail.

The optimal conditions of coupling a Gaussian laser beam into a hollow cylindrical waveguide11,12 (fused silica) were determined theoretically and experimentally. The radiation of a cw laser (□ = 633 nm) and a 150-fs pulsed laser (□ = 1700 nm and 320 nm) were used to investigate the waveguide coupling conditions and its losses with a parallel and conical waveguides entrance. The optimal condition is reached when the ratio of beam waist to the waveguide inner radius is close to 0.64. Under this condition only one fundamental mode exists inside the waveguide with a well defined beam profile. The conical waveguide entrance showed an improved shift tolerance. It was shown that the beam characteristics of the pump and the probe beam are not changed substantially after propagation through the gas filled hollow waveguide. Fig.2 shows a scheme of experimental setup.

Fig. 2. Scheme of experimental setup (L1-3 - lenses, DM - dichroic mirror, 1 - cell, 2 - capillary, P - prism, DNIR, UV - detectors)

An experiment with a hollow waveguide of 500 mm length and 450 μm inner diameter demonstrated an increased output signal by factor of 5.5 and improved signal-to-noise ratio by factor of almost 2. The experimental results are in good agreement with model calculations. Preliminary investigations showed that the use of a hollow waveguide of 500 mm length and 200 μm inner diameter is able to increase the useful absorption signal at least by factor of 10. Investigations of IVR in CH3I showed promising results with this method. Fig. 3 presents some preliminary results.

Fig. 3. Measured relaxation curves with capillary (solid curve, scale to the left) and coaxial focused geometry (dots, scale to the right). Cell length 600 mm; capillary length 500 mm, inner diameter 450 μm.

*Figures not available in abstract (please see manuscript for full text and figures)

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Conference 6461: Laser Cooling of Solids

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6461-01, Session 1

Anti-Stokes laser cooling in erbium-doped low-phonon materials

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Solid-state cooling by anti-Stokes emission (CASE) first demonstrated by Epstein [1] and coworkers in 1995 in an ytterbium-doped heavy-metal fluoride glass promoted huge efforts by the scientific community to improve this process and to develop other different materials doped with rare-earths ions. However, in spite of the important results obtained by the Epstein group and other researchers, only a reduced number of Yb3+-doped glasses and crystal matrices [2] were able to produce CASE and among rare-earth ions only a Tm3+-doped heavy-metal fluoride glass was reported to be an efficient cooler [3].

Here we report the first evidences of anti-Stokes laser-induced cooling in two different low phonon erbium-doped matrices [4] (a KPb2Cl5 crystal and a fluorochloride glass). The local cooling was detected by using a photothermal deflection technique whereas the bulk cooling was detected by means of a calibrated thermal sensitive camera. The studies were carried out by exciting the samples with a tunable Ti: sapphire laser. The Er3+ ion was excited in the 4I9/2 manifold. It is worthwhile to mention that the cooling was observed in the spectral region where some upconversion processes starting at the pumped level occur. Moreover, the spectral region where cooling is efficient can be easily reached by conventional laser diodes which renders these systems very convenient for applications such as compact solid-state optical cryocoolers or radiation-balanced lasers [5].

A short discussion on the experimental and grounds of the cooling process is presented.

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6461-02, Session 1

Ultrapure ZBLAN glass for optical refrigerators

M. P. Hehlen, R. I. Epstein, Los Alamos National Lab.

The efficiency of optical refrigeration in rare-earth-doped solids is very sensitive to the concentration of impurities. Transition-metal and hydroxyl ion impurity concentrations in ytterbium-doped ZBLAN glass, for example, have to be reduced to 10-100 ppb for a practical laser cooler to reach operating temperatures of 100-150 K. Achieving this level of purity requires targeted purification of the ZBLAN glass precursor materials. We will report on progress toward a synthesis method for ultra-pure ZBLAN that implements individual aqueous purification and drying/fluorination in HF gas of the fluoride precursors.

6461-03, Session 1

Laser cooling using cavity enhanced pump absorption

D. V. Seletskiy, M. P. Hasselbeck, M. Sheik-Bahae, The Univ. of New Mexico; R. I. Epstein, Los Alamos National Lab.

It is understood that laser cooling is most efficient if absorption of the pump laser is maximized. Based on this, we devised a new method to resonantly trap laser pump light in an optical cavity with a cooling element inside. Our approach is based on a Gires-Tournois cavity which consists of two dielectric mirrors: input coupler and a back mirror with a nearly unity reflectivity. By matching established resonant conditions, nearly all power can be absorbed by the intra-cavity absorber. Those conditions are: 1) the reflectivity of the input coupler is matched to the power loss per cavity round-trip and 2) the cavity is on resonance.

In our experimental setup pump light is generated in a Yb:YAG disk laser at =1030 nm.

The intra-cavity cooling element is a 2% ytterbium doped glass sample (Yb:ZBLAN). According to first resonant condition, reflectivity of the input coupler is matched to the measured single pass absorption length of the sample (αL). The back mirror of our Gires-Tournois cavity is a dielectric stack deposited directly on the polished face of the doped glass sample. The intra-cavity face of the cooling element is anti-reflection coated.

To satisfy second resonant condition above, input coupler holder is axially piezo-driven, which allows to scan the cavity length for maximum absorption condition and hold that resonance by completing the feedback loop.

Our current experimental trapping efficiency, defined as a ratio of absorbed per incident power is 85%, which equates to 11 fold increase in absorbed power compared to double-pass geometry.

6461-04, Session 1

Differential luminescence thermometry applied to laser cooling of Yb-ZBLAN

S. R. Greenfield, J. Thiede, R. I. Epstein, Los Alamos National Lab.

We have used Differential Luminescence Thermometry (DLT) to measure very small temperature changes due to laser radiation in a rare earth doped glass. Luminescence from the absorbing chromophore, Yb3+, induces a temperature change by optical refrigeration. The luminescence is detected by a spectrophotometer. The spectral changes upon cooling - primarily narrowing of the spectral features - are used to determine temperature changes. Repeated averaging for several minutes allows us to measure temperature changes as small as 5 mK. This method is used to screen Yb-ZBLAN glass samples by finding the lowest temperature at which they undergo local cooling.

6461-05, Session 2

Observation of photoluminescence upconversion

Y. J. Ding, Lehigh Univ.

For the specific layer thicknesses of type-II InAs/GaSb quantum wells, we have observed photoluminescence upconversion. Indeed, at a fixed temperature the photoluminescence peak wavelength is slightly blue-shifted as the pump intensity is increased. At the relatively high pump intensities, there is a new photoluminescence peak centered at a much shorter wavelength. On the other hand, for the fixed pump intensity the photoluminescence peak intensity decreases with increasing the temperature at relatively low temperatures. At relatively high temperatures, however, a new photoluminescence peak centered at a much shorter wavelength has also appeared. This new transition peak is due to the recombination of electrons and holes in InAs and GaSb layers of the type-II quantum wells. Furthermore, the integrated photoluminescence intensity has a minimum value at an elevated temperature. Our analysis indicates that the photoluminescence upconversion observed by us is assisted by longitudinal-optical phonons. In the other words, we have evi-

denced phonon-assisted up-transfer of electrons in the type-II structure. The presence of native defect states in the GaSb barrier layers plays an essential role in the observation of the photoluminescence upconversion. We will also provide an overview on whether it is feasible to achieve photoluminescence upconversion in a dot-in-a-well structure. We will discuss the possibility of using these structures to achieve laser-induced cooling.

6461-06, Session 2

Effect of high carrier density in laser cooling of semiconductors

M. P. Hasselbeck, M. Sheik-Bahae, The Univ. of New Mexico; R. I. Epstein, Los Alamos National Lab.

We re-examine the previous work of Finkeissen et al (APL, 75, 1258, 1999) in which local cooling of a GaAs quantum well structure was reported. When a complete account of all the pump laser power is made, we find that heating of the substrate will overwhelm any laser cooling that may occur in the quantum wells. Changes in magneto-exciton peaks appearing in the luminescence spectra were claimed to be the signature of a cooling lattice. We argue that such behavior may be alternatively explained by screening of the exciton Coulomb binding potential that results with increasing photocarrier density injected by the pump laser. The density-dependent luminescence of three-dimensional excitons in GaAs is calculated with the Banyai-Koch theory to show that such an explanation is plausible. The arrangement of Finkeissen et al illustrates the difficulty of using the pump laser as a non-contact optical probe of the sample temperature in a laser cooling experiment. We have resolved this problem by use of a second, weak cw probe laser. The probe laser weakly perturbs the sample to provide an independent measure of temperature with, for example, differential luminescence thermometry.

6461-07, Session 2

Phase fluorometry for semiconductor lifetime measurement

A. R. Albrecht, R. B. Laghumavarapu, Ctr. for High Technology Materials; B. Imangholi, M. Sheik-Bahae, The Univ. of New Mexico; K. J. Malloy, Ctr. for High Technology Materials

Understanding and quantifying non-radiative recombination is a critical factor for the successful laser cooling of semiconductors. The usual approach is to measure the non-radiative lifetime with pulsed photoexcitation and then monitor the luminescence decay via time-resolved photon counting. We present an alternative approach that employs phase fluorometry with a lock-in amplifier. A sinusoidally modulated diode laser is used for excitation. Lifetime data are extracted from the frequency dependent phase shift and amplitude response of the photoluminescence signal, detected by a photo multiplier tube. Samples studied include high quality GaAs/AlGaAs and GaAs/GaInP heterostructures, grown by MBE and MOCVD. Data over a temperature range from 10 to 300K is compared with results obtained in time-domain measurements.

6461-08, Session 2

Investigations of surface defects on semiconductor fluorescence lifetime

D. A. Bender, M. P. Hasselbeck, M. Sheik-Bahae, The Univ. of New Mexico

Using near-field scanning optical microscopy (NSOM) we investigate the role of surface defects on fluorescence lifetime in GaAs. Through the use of high spatial resolution near-field apertures we are able to probe the surface of candidate GaAs semiconductor samples for laser cooling. Defects on the surface of GaAs samples can serve as recombination centers reducing the non-radiative lifetime. As the non-radiative lifetime decreases, more of the excitation energy is converted to heat. Spatially resolving lifetimes allows us to select regions of a semiconductor that produce less heat under excitation and are therefore more likely to exhibit laser cooling. A conventional far-field optical microscope is used for global excitation and the near-field aperture is employed to collect fluorescence locally. We find that lifetimes measured on oval surface defects of GaAs samples are roughly 1/10th of the lifetime measured in defect free regions. Atomic force microscopes (AFM) scans were also performed to characterize the size of the oval defects. A detailed update will be presented on our current effort to produce a fluorescence lifetime image (FLIM) with our NSOM.

6461-09, Session 3

Ultralow-loss ion beam sputtered optical coatings on highly polished ZBLAN for laser cooling applications

R. P. Shimshock, L. Lling, MLD Technologies, LLC

Using an Ion Beam Sputtering (IBS) Process and metal oxide coating materials, optical coatings with the lowest optical absorption in the one micron wavelength region can be produced. When these coating coatings are applied to highly polished optical surfaces, the dense, bulk like properties of the IBS deposited films also yield very low scatter losses. These Ultra Low Loss IBS High Reflectance (HR) coatings can be applied to highly polished, high purity ZBLAN substrates for use in solid state laser cooling applications. This paper reviews coating and polishing results necessary to implement a laser cooling module.

6461-10, Session 3

Differential luminescence thermometry in laser cooling of solids

W. M. Patterson, E. Soto, M. Fleharty, M. Sheik-Bahae, The Univ. of New Mexico

In laser cooling experiments, the use of contact temperature sensors such as a thermocouple is undesirable because the element can absorb anti-Stokes luminescence, creating unwanted heat. We have developed a non-contact, spectroscopic technique to measure the temperature change of rare earth doped glasses and crystals with very high precision. The approach makes use of the temperature dependence of the spectral line shape.

A weak cw probe laser (Stocker Yale, 660 nm, 35 mW) excites the sample in vacuum. The luminescence spectrum is captured in a single-shot collected by a 600 μm fiber assembly and routed to an Ocean Optics, HR4000 high resolution spectrometer. Excellent temperature resolution has been demonstrated with Tm:BaY2F8 using custom software we have developed to collect, display and manipulate the spectra in real time. Spectra are normalized and subtraction of two spectra determines whether the material is heating or cooling and by how much. By making use of temperature dependent broadening of various peaks in luminescence spectra, we obtain excellent differential temperature accuracy, enabling us to use this non-contact technique to measure laser cooling in glasses and crystals.

6461-11, Session 3

Electron-lattice interactions of severely localized electrons and solid state optical cooling

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Electron-lattice interactions for severely localized electronic states are typically very strong. Effects of electron-lattice interactions then can be treated semi-classically except at temperatures well below the characteristic phonon temperature. Here this semi-classical approach is used to discuss scenarios in which electron-lattice interactions of severely localized electronic states drive optical cooling of solids. First, a two-level model for a self-trapped exciton is considered. After photon-excitation in

the low-energy tail of the exciton absorption, the exciton relaxes to its minimum-energy atomic configuration. The photon emitted from this relaxed configuration can be of higher energy than that of the absorbed photon. As such, this up-conversion produces cooling. Second, a three-level model for excitation of a severely localized f-electron between crystal-field levels is discussed. For simplicity, only the middle level of this three-level system is taken to have a significant electron-lattice interaction. In this case, atomic relaxation follows photo-induced promotion of a ground-state electron to the middle level. Due to its Stokes shift, photon emission from this relaxed state contributes to heating. However, phonon-excitation can promote the electron from this relaxed state to the uppermost crystal-field state. Since the energy of a photon emitted from this state exceeds that of the absorbed phonon such emission contributes to cooling. The phonon-excitation rate is critical to cooling. This excitation rate depends upon the second level's Stokes shift (a measure of its electron-lattice coupling), the energy of the uppermost crystal-field level, and the temperature. This semi-classical model is analyzed to obtain the conditions for optimal optical cooling.

6461-12, Session 3

Optical cooling of Raman lasers using CARS

N. Vermeulen, C. Debaes, H. Thienpont, Vrije Univ. Brussel (Belgium)

A well known practical problem when designing lasers is the unwanted heat generation inside these light sources. Also Raman lasers, the lasing mechanism of which is based on Stimulated Stokes Raman Scattering (SSRS) in a Raman medium, suffer from this drawback. Indeed, during the SSRS-process, an incoming pump photon scatters onto e.g. a molecular vibration in the Raman medium, and this scattering event results both in the generation of a lower energy Stokes photon and in the creation of a phonon or heat.

In this paper, we present a novel method to efficiently reduce the heat generation in Raman lasers. This so-called 'Raman cooling method' relies on Coherent Anti-Stokes Raman Scattering (CARS), a four wave mixing process where two pump photons are converted into a lower energy Stokes photon and a higher energy anti-Stokes photon. Important hereby is that, in contrast to the purely Stokes generating SSRS-process, CARS is not accompanied by the creation of phonons. Thus, the idea behind Raman cooling is to drastically increase the efficiency of CARS in comparison with the SSRS-efficiency, so that less heat generation takes place inside the Raman medium. Besides numerically demonstrating this novel cooling concept, we also illustrate the potentialities of this cooling technique. Our first numerical results indicate that for Raman lasers based on silicon-on-insulator waveguides - a category of media in which (quasi)perfect phase matching can be established for the CARS-process - one can obtain under certain pumping conditions a reduction of the heat dissipation of more than 30% by the use of Raman cooling.

6461-13, Session 3

Single fluoride crystals as materials for laser cooling applications

S. Bigotta, Univ. di Pisa (Italy); A. Di Lieto, Scuola Normale Superiore di Pisa (Italy) and Univ. di Pisa (Italy); L. Bonelli, Univ. di Pisa (Italy); D. Parisi, Univ. di Pisa (Italy) and Scuola Normale Superiore di Pisa (Italy); A. Toncelli, M. Tonelli, Univ. di Pisa (Italy)

We report the successful growth and the laser cooling results of Yb3+-doped single fluoride crystals.

Up to now, almost the totality of the works on laser cooling of solids have been devoted to the optimization of the cooling process, with only short descriptions of the investigated material. Indeed, the most used materials for laser cooling are still the fluorozirconate glasses ZBLAN and ZBLANP. This does not necessarily mean that these glasses are the best choice, and the reason for their success can be found in the difficulties that occur in growing materials with the high optical quality required for laser cooling. In fact, several authors have tried to observe anti-Stokes cooling in different materials, but available samples often lack the sufficient purity in order to show net cooling or to make them serious competitor of ZBLAN in laser cooling application.

By investigating the mechanical and thermal properties of Yb-doped BaY2F8, LiYF4, and LiLuF4 crystals, and using the spectroscopic data we collected from our samples, the theoretical and experimental cooling efficiency of fluoride crystals are evaluated and compared with respect to those of ZBLAN. Two different methods, a thermocamera and a fluorescence intensity ratio technique, have been used to monitor the temperature change of the samples. The temperature change is clearly exponential, as expected from theory, and the temperature drops are of the order of 5 K in single-pass configuration, corresponding to a cooling efficiency of about 3%. This value is larger than that observed in Yb-ZBLAN in similar experimental condition.

6461-14, Session 4

Improving the light extraction efficiency for optical refrigeration of solids

J. B. Khurgin, Johns Hopkins Univ.

Laser refrigeration of solids is a promising technology capable of remotely removing heat from a small active device with minimum expended energy. The most critical factor limiting performance of laser cooler is trapping of fluorescence inside the cooling volume due to total internal reflection. This issue becomes especially pressing in semiconductors due to their large refractive index. Recent advances in nanofabrication offer an opportunity to overcome the restrictions imposed by light trapping by artificially structuring the material.

In this talk I will analyze various schemes for improving the light extraction from semiconductors and compare their relative merits. The schemes include random and ordered surface gratings, nanowires, photonic crystals, multilayer coatings, surface plasmons and metamaterials.

6461-15, Session 4

Heterostructure design optimization for laser cooling of GaAs

B. Imangholi, M. Fleharty, C. Wang, D. A. Bender, The Univ. of New Mexico; N. Nuntawong, Ctr. for High Technology Materials; M. P. Hasselbeck, M. Sheik-Bahae, The Univ. of New Mexico; R. I. Epstein, Los Alamos National Lab.

External quantum efficiency (EQE) quantifies the performance of a semiconductor optical device. For laser cooling, EQE incorporates two key performance factors: luminescence outcoupling and the predominance of radiative to non-radiative recombination of excited electron-hole pairs. Calculations indicate that an EQE of greater than 98% is required to achieve net cooling of GaAs. Surface passivation with GaInP dramatically reduces non-radiative recombination to give an EQE of 96% at 300 K and 99% at 100 K. In this study, the quality of the GaAs/GaInP interface is systematically investigated by: i) doping the passivating layer as n- or p-type and ii) changing the doping density. These effects are assessed quantitatively by measuring the non-radiative recombination coefficient and the EQE. A detailed experimental understanding is obtained with different pump laser intensities and with a range of sample temperatures.

6461-16, Session 4

Nanogap experiments in laser cooling

R. P. Martin, K. J. Malloy, A. Stintz, CHTM/The Univ. of New Mexico; R. I. Epstein, Los Alamos National Lab.; M. Sheik-Bahae, M. P. Hasselbeck, B. Imangholi, The Univ. of New Mexico

One of the challenges of laser cooling a semiconductor is the typically high index of refraction (greater than 3), which limits efficient light output

of the unconverted photon. This challenge is proposed to be met with a novel concept of coupling the photon out via a thin, thermally insulating vacuum gap that allows light to pass efficiently by frustrated total internal reflection. The applications of such a structure will go beyond laser cooling: advanced microelectronic assemblies will also need to support high temperature differences between closely-spaced devices and structures. This study has the goal of producing a test structure that allows investigation of heat transport across a "nanogap" consisting of a thin film supported over a substrate by an array of nanometer-sized posts. Beginning with a crystalline silicon substrate covered by a thin layer (100nm) of thermal silicon oxide, electron beam resist is spun onto the surface. To pattern the posts in the resist, a scanning electron microscope (SEM) is utilized as an e-beam writer. After development, the holes are etched down to the substrate. Utilizing plasma enhanced chemical vapor deposition (PECVD), an amorphous silicon film is deposited in the holes and on the surface. After thin film deposition, the a-Si is annealed at 700 degrees Celsius and trenches in the area of the pattern are created using an Inductively Coupled Plasma Etch in order to provide a pathway for the etchant. Finally, the sacrificial silicon oxide layer is removed using a selective wet etching process. Demonstration of this final step by successfully undercutting the a-Si upper layer due to the hydrophobic nature of silicon and the slow etch rate of buffered oxide etch in the small gap has proved to be problematic. Arriving at a feasible solution to this conundrum is the current objective of this project in order to begin investigating the thermal conductivity properties of the structure.

6461-17, Session 4

The relation between light absorption and luminescence in laser cooling of two-dimensional semiconductor systems

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In efforts underway to achieve laser cooling of semiconductors, an electron-hole population is generated in the sample and maintained in a steady state. The analysis of light absorption by and luminescence from this population is basic to the understanding of feasibility and efficiency issues of the cooling process. It is commonly understood that, when this electron-hole plasma is in quasi-thermal equilibrium (equilibrium at a fixed density), the KMS (Kubo-Martin-Schwinger) relation holds between its luminescence and absorption spectra: their ratio is proportional to the Bose distribution function characterized by the temperature and chemical potential of the plasma. The proportionality factor, which affects the total luminescence rate, may generally depend on the dimensionality and geometry of the system. In this Contribution, as a preliminary step to extend our theoretical analysis of semiconductor cooling to quantum well systems, we discuss the application of the KMS relation to their spectra. In particular, we derive and discuss the geometrical proportionality factor in the KMS relation for quantum wells and compare it to its counterpart for bulk semiconductors.

6461-18, Session 5

Semiconductor electroluminescence refrigeration

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This talk will report the latest theoretical and experimental study of the potential electroluminescence refrigeration in semiconductor light emitting diodes. It will cover detailed theoretical considerations in choosing semiconductor materials and heterostructure designs by taking into account material parameters such as bandgaps, band offsets, and Auger coefficients. Fabrication processes and monolithic integration of a specially designed high efficiency light extraction lens structure with LED will be presented. Test results of such structures and a study of the materials internal quantum efficiency will also be discussed.

6461-19, Session 5

Thermally assisted electroluminescence: a viable means to generate electricity from solar or waste heat?

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It has been proposed recently that thermally assisted electro-luminescence could in principle provide an alternative means to convert solar or waste heat into electricity. The basic concept is to use an intermediate active emitter between a heat source and a photovoltaic (PV) cell. The active emitter would be a light emitting diode operating at a forward bias less than the bandgap energy, such that the average emitted photon energy is larger than the average energy that is required to create charge carriers. The basic requirement for this conversion mechanism is that the emitter can act as an optical refrigerator. Thus, rather than maximizing the spectral match between the PV cell and the sun, this method relies on converting broadband into narrowband radiation, which would allow efficient conversion into a photocurrent with a single stage PV cell with matching bandgap energy. In order to make such a process efficient, however, several materials challenges will need to be addressed and overcome. Here, we analyze the practical requirements of the emitter in terms of efficiency and conversion power density, and in particular the role of bandgap energy and operating temperature.

6461-20, Session 5

Determination of internal quantum efficiency in semiconductors suitable for luminescence refrigeration

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Semiconductor based luminescent refrigerators are attractive for applications in the area of the integration of coolers with other semiconductor devices, such as infrared sensors and low-noise electronic circuits. However, since near unity internal quantum efficiency is critical for the achievement of luminescence refrigeration, it is necessary to have routine, straightforward, and accurate measurement techniques for internal quantum efficiency. Although substantial efforts have been devoted to such measurements, there are few straightforward methods that offer reliable data. In this paper, a simple experimental approach is used to determine the internal quantum efficiency of a set of specially designed GaAs-based samples. Excitation pumping power dependent photoluminescence measurements are performed at 300, 230, 100 and 50 K. The resulting integrated photoluminescence intensities are fit to a model by assuming 1) the fraction of pumping laser power absorbed to generate the carriers in the active region is independent of the pumping power; 2) the luminescence extraction and loss due to the collection system and spectrometer are independent of the pumping power; 3) the Shockley-Read-Hall, radiative, and Auger recombination coefficients are independent of the pumping power. When the pump laser power density is around 40 W/cm2, the internal quantum efficiency is determined to be 0.987 +/- 0.008 at 50 K and 0.806 +/- 0.008 at 300 K for bulk GaAs. Further details of this approach and additional experimental results will be presented.

6461-21, Session 5

Growth and characterization of GaAs/InGaP heterostructure for semiconductor laser cooling

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We present the growth technique and characterization of high quality semiconductor laser cooling material. The structure consists of GaAs passivated by InGaP which has been reported to have a longest surface re-

combination lifetime. GaAs was grown on 10 degree miscut GaAs substrate and sandwiched between lattice matched In0.51Ga0.49P. This structure was grown by a low-pressure metal organic chemical vapor deposition (MOCVD) system. The material was grown in the temperature range of 550 to 700 degree C at a pressure of 60.8 Torr. The InGaP quality was improved by the growth on 10 degrees mis-oriented substrate along <110> direction, and is confirmed by X-ray diffraction (XRD). The non-interruption growth technique was applied to prevent the indium segregation and P/As intermixing at the interface between InGaP and GaAs. The effects of V/III ratio, growth temperature and material precursors on material impurities were also studied. The carrier lifetimes were measured using the time resolved photo luminescence technique at cryogenic temperatures. Our experimental results also indicate that Arsine (AsH3) can be replaced with tertiarybutylarsine (TBA) to achieve longer carrier lifetimes. The experimental results show that the carrier lifetime was increased by an order with the use of TBA. Recent results show a highest room temperature carrier lifetime of 2 mSec. The results of the experiments in progress will be presented at the conference.

6461-22, Session 5

Competing physical effects in semiconductor laser cooling: from excitonic correlations to parasitic absorptions

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We present a comprehensive theoretical analysis of optical refrigeration of semiconductors, which is based on luminescence upconversion. The central question to be addressed is this: at a given temperature, what are the most dominant physical processes governing the limitations and efficiency of the optical refrigeration procces? We concentrate on the cooling of bulk GaAs in the quasi-thermodynamic equilibrium regime, for which we had previously laid the foundation with a comprehensive theoretical framework. Our theory includes a fully microscopic description of the absorption and luminescence characteristics of the optically excited semiconductor (including Coulomb correlation effects such as excitonic correlations and excitation-induced line broadenings), and it combines this description with a stationary cooling analysis that is able to account for a variety of physical effects competing with the cooling process (including Auger recombination, parasitic background absorption). We are able to study a wide spectrum of temperatures, ranging from those above room temperature all the way down to the few-Kelvin regime. Computing the smallest non-radiative recombination time needed in a given experiment for cooling to be possible as a suitable figure of merit, we find that different physical processes govern the cooling condition and its limitations at different temperatures.

6461-23, Session 5

Optimal bandgap energy for optical refrigeration in semiconductors

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When realized, optical refrigeration in semiconductors will offer net device cooling since heat can be transported out of the device via photons. Thermodynamically, optical refrigeration is attainable in light emitting semiconductors by establishing an electron-hole population with a quasi Fermi level separation that is less than the average emitted photon energy. The luminescence cooling power has a local maxima, for a given bandgap energy and conversion efficiency (work input into quasi Fermi level separation); a result of competition between the spontaneous emission rate (which increases with input) and the heat absorbed per electron-hole pair (which decreases with input). Furthermore, there is an optimal bandgap energy (for a given conversion efficiency) where the cooling power reaches a global maximum. The conversion efficiency depends on carrier transport and injection efficiency, light extraction efficiency, and internal or material quantum efficiency. Material quantum efficiency improves as the radiative coefficient increases with dimensionless bandgap energy. Large bandgap materials exhibit better conversion efficiencies, since the material quantum efficiency asymptotically approaches unity as the bandgap gets arbitrary large. These large bandgaps occur in semiconductors such as GaAs when they are cooled below room temperature. Temperature dependent photoluminescence and electroluminescence from GaAs and InGaAs active materials is being studied to establish the predicted asymptotic behavior of the material quantum efficiency. These results and the importance of bandgap energy and input conversion efficiency for the development of optical refrigeration will be presented.