Introduction
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Feature issue introduction: Advanced Solid-State Lasers 2017

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Abstract: The Advanced Solid State Lasers 2017 Conference (ASSL) was held from October 1 to 5, 2017. It was an extraordinary conference at the Nagoya Congress Center in Nagoya, Japan. ASSL 2017 again suggested an impressive platform where miscellaneous perceptions with a variety of approaches to optics, photonics, sensing, laser technology, laser systems, and solid state lasers were presented. This international meeting was highly selective, leading to high level contributions through one plenary conference, 17 invited presentations, 70 regular talks, and 121 posters. The present joint issue of *Optics Express* and *Optical Materials Express* features 27 articles written by ASSL 2017 authors and covering the spectrum of solid-state lasers from materials research to sources, and from design innovation to applications.

OCIS codes: (140.3380) Laser materials; (140.3530) Lasers, neodymium; (140.3280) Laser amplifiers; (140.3070) Infrared and far-infrared lasers; (140.3500) Lasers, erbium; (060.2280) Fiber design and fabrication; (140.3615) Lasers, ytterbium; (060.3510) Lasers, fiber; (060.2320) Fiber optics amplifiers and oscillators; (230.7390) Waveguides, planar; (140.3480) Lasers, diode-pumped; (190.4400) Nonlinear optics, materials; (190.4970) Parametric oscillators and amplifiers; (140.3515) Lasers, frequency doubled; (140.3550) Lasers, Raman; (190.4370) Nonlinear optics, fibers; (140.4050) Mode-locked lasers; (140.7090) Ultrafast lasers; (190.5650) Raman effect; (140.3298) Laser beam combining; (140.3580) Lasers, solid-state; (140.5680) Rare earth and transition metal solid-state lasers; (060.2270) Fiber characterization; (060.2390) Fiber optics, infrared; (160.2290) Fiber materials; (320.6629) Supercontinuum generation.

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ASSL 2017 as always highlights new sources, advanced technologies, components and system design to extend the operation and application of solid-state lasers. Materials are the basis for the technology covered by ASSL, and the meeting encompassed advances in optics, materials science, condensed matter physics and chemistry relevant to the development, characterization and applications of new materials for lasers and photonics. These include crystals, glasses and ceramics, as well as functionalized composite materials, from fibers and waveguides to engineered structures with pre-assigned optical properties. Materials used for fabrication of basic laser components were also a core part of the conference. Coherent and high brightness radiation sources include lasers as well as pump and nonlinear devices. All laser regimes have been investigated from ultrafast lasers to cw operation, from Raman to high-power sources. Emphasis is on advances in science and technology, for improved power, efficiency, brightness, stability, wavelength coverage, pulse width, cost, environmental impact or other application-specific attribute.

We hope that readers will enjoy this special issue and that it will inspire them to participate in the next edition of ASSL, which will be held in Boston from November 4 to 8, 2018. We are also thankful to all of the authors and reviewers for their nice contributions. And we thank very much Carmelita Washington, Sharon Jeffress, and Sarah Walker from the OSA staff for their outstanding work throughout the review and production processes

B. Zhao *et al.* [1] report on the crystal growth, structure, Raman and optical spectroscopy of novel "mixed" tetragonal vanadates, $Yb:Lu_{1-x-y}Y_xLa_yVO_4$. Optical absorption, stimulated emission, and gain cross-section spectra of Yb^{3+} are determined for π and σ polarizations. For a $Yb:Lu_{0.74}Y_{0.23}La_{0.01}VO_4$ crystal, the absorption bandwidth is >10 nm, the σ_{SE} is 1.1×10^{-20} cm^2 at 1013 nm, the gain bandwidth is > 40 nm (for π-polarization), and the radiative lifetime of the $2F_{5/2}$ state is ~305 µs. The Stark splitting of the Yb^{3+} multiplets is determined using low-temperature (6 K) spectroscopy. A diode-pumped *a*-cut 2 at.% $Yb:Lu_{0.74}Y_{0.23}La_{0.01}VO_4$ laser generated 5.0 W at 1044 nm with a slope efficiency of 43%. The developed materials are promising for sub-100 fs mode-locked lasers at ~1 µm. The Energy Transfer Upconversion (ETU) macroparameter is measured by S. Cante *et al.* [2] for Nd-doped $GdVO_4$ and YVO_4 samples at temperatures ranging from Room Temperature (RT) to 450K, by means of a simple and automated z-scan technique. Furthermore, the ground state absorption cross section into the $^2H_{9/2}$ + $^4F_{5/2}$ energy levels is characterised for both crystals over the same range of temperatures.

J. Huynh *et al.* [3] present a femtosecond regenerative Yb:YGAG ($Y_3Ga_2Al_3O_{12}$) ceramic slab amplifier delivering 405 fs pulses at a wavelength of 1030 nm with a bandwidth limit of 306 fs, 1.1 W of average power, 8 µJ of pulse energy, and a repetition rate of 100 kHz. The amplifier is seeded by 9 pJ pulses generated by a Yb-doped fiber ring oscillator with extracavity spectral shaping to minimize gain narrowing. The net-gain of the pulses is 60 dB, the spectral bandwidth is 4.1 nm (FWHM), and the M^2 beam quality factor is < 1.2. Due to similar optical and thermo-mechanical properties to Yb:YAG, the Yb:YGAG gain medium is a promising alternative for upgrading the existing Yb:YAG picosecond disk amplifiers to the femtosecond regime. H. Uehara *et al.* [4] have demonstrated the continuous-wave operation of a highly efficient 2.8 µm Er-doped Lu_2O_3 ceramic laser at room temperature. An $Er:Lu_2O_3$ ceramic with a doping concentration of 11 at.% demonstrated a slope efficiency of 29% and an output power of 2.3 W with pumping at 10 W. These are the highest slope efficiency and output power obtained to date for an $Er:Lu_2O_3$ ceramic laser at 2.8 µm. In addition, they prepared ceramics with various doping concentrations and determined their emission cross sections by fluorescence lifetime measurements and emission spectroscopy. S. Bigotta *et al.* [5] report for the first time laser action in resonantly-pumped transparent polycrystalline Er^{3+}:YAG ceramic developed through a 2-step approach combining spark plasma sintering and HIP post treatment. Microstructural and spectroscopic properties, as well as the laser performance of large scale 0.5at.% Er:YAG transparent polycrystalline ceramic are discussed. A maximum slope efficiency of 31% and optical-optical efficiency of 20% was measured.

The adiabaticity criterion of the thermally-guided very-large-mode-area (TG VLMA) fiber is presented by W. Liu *et al.* [6] based on the mode-coupling theory. The requirement for the adiabatic propagation of fundamental mode is discussed systematically. It is revealed that the pump absorption plays the most important role and the adiabaticity criterion can be met as long as it is small enough. Then, the effects of the configuration parameters of TG VLMA fiber on the up-limitation of pump absorption for the adiabaticity criterion are investigated. It is found that for the straight TG VLMA fiber, reducing the initial refraction index and inner-cladding diameter and utilizing the bidirectional pumping scheme are beneficial to the adiabatic propagation of fundamental mode. The bent TG VLMA fiber is also studied. It is

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found that the bent fiber is much more difficult to meet the adiabaticity criterion than the straight one. The results show that even with the 100-cm bend radius, the pump absorption should be smaller than 1 dB/m to meet the adiabaticity criterion. It is suggested that enlarging the core-to-cladding ratio can be helpful for loosening the adiabaticity criterion of bent TG VLMA fiber. These pertinent results can provide significant guidance for understanding and designing the TG VLMA fiber and pertinent lasers and amplifiers. Theoretical and experimental evaluation of the photodarkening effect as a heat source in ytterbium doped fibers is presented by P. Šušnjar *et al.* [7]. An additional non-radiative decay channel that opens after photodarkening the fiber is identified via fluorescence lifetime reduction and as an additional heat source proportional to inversion. It is included in the heat source model which was tested on a core-pumped fiber amplifiers. High temperature elevation at low pump powers shows potential heat-related problems in high inversion systems that are more susceptible to photodarkening. M. Dubinskii *et al.* [8] report the latest progress in fabrication and laser performance of the fully crystalline double-clad 'Yb:YAG-core/undoped-YAG-clad' fibers grown by the hybrid crystal growth method. The single-crystalline ytterbium (Yb) doped yttrium aluminum garnet (YAG) fiber cores were grown by the laser heated pedestal growth (LHPG) method, and the single-crystalline undoped YAG claddings were grown by the liquid phase epitaxy (LPE) technique, in which the single-crystalline Yb:YAG cores were used as the growth seeds. The key parameters of the hybrid-grown 'crystalline core/crystalline clad' (C4) fibers, including material composition, crystal structure, and fiber propagation loss, were characterized. The results confirmed that the grown C4 fibers, indeed, have both the single-crystalline fiber core and single-crystalline fiber clad. By utilizing a double-clad low-loss C4 fiber as a diodecladding- pumped laser gain medium, we realized a fiber laser with the optical-to-optical conversion efficiency of 68.7% versus the incident pump power.

E. Kifle *et al.* [9] report on a Tm^{3+} monoclinic double tungstate planar waveguide laser that is passively Q-switched (PQS) by a saturable absorber (SA) based on single-walled carbon nanotubes (SWCNTs) randomly oriented in a polymer film. The laser is based on a 18 µm-thick 5 at.% $Tm:KY_{1-x-y}Gd_xLu_y(WO_4)_2$ active layer grown on an undoped (010)-oriented $KY(WO_4)_2$ substrate by liquid phase epitaxy with determined propagation losses 0.7 ± 0.2 dB/cm. The PQS laser generated a maximum average output power of 45.6 mW at 1.8354 µm with a slope efficiency of 22.5%. Stable 83-ns-long laser pulses with an energy of 33 nJ were achieved at a repetition rate of 1.39 MHz. The use of SWCNTs as SA is promising for generation of sub-100 ns pulses in such waveguide lasers at ~2 µm. V. Fromzel *et al.* [10] demonstrated continuous wave operation of an in-band pumped Er:YAG planar waveguide laser with the output of 75 W at 1645 nm and a slope efficiency of 64% with respect to the absorbed pump power at 1532 nm.

Thin (~250 µm) crystalline layers of monoclinic Ho^{3+}-doped $KY(WO_4)_2$ grown by the liquid phase epitaxy method on (010)-oriented undoped $KY(WO_4)_2$ substrates are promising for the development of thin-disk lasers at ~2.1 µm, as shown by X. Mateos *et al.* [11]. Using a single-bounce pump geometry, 3 at.% and 5 at.% $Ho:KY(WO_4)_2$ thin-disk lasers delivering output powers of >1 W at 2056 nm and 2073 nm are demonstrated. For the 3 at.% Ho^{3+}-doped thin-disk, the thermal lens is negative (the sensitivity factors for the two principal meridional planes, MA(B), are −1.7 and −0.7 m^{-1}/W) and astigmatic. For higher Ho^{3+} doping (5-10 at.%), the effect of upconversion and end-bulging of the disk enhances the thermo-optic aberrations leading to a deteriorated laser performance. J. Wei *et al.* [12] present a detailed characterization of the optical properties of the recently developed nonlinear material, orientation-patterned gallium phosphide (OP-GaP), by performing difference-frequency-generation experiments in the 2548-2782 nm wavelength range in the mid-infrared (mid-IR). Temperature and spectral acceptance bandwidth measurements have been performed to study the phase-matching characteristics of OP-GaP, and the dependence of nonlinear gain on the polarization of input incident fields has been investigated. The transmission of the OP-GaP

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crystal at the pump and signal wavelengths has been studied and found to be dependent on polarization as well as temperature. Further, they have observed a polarization-dependent spatial shift in the transmitted pump beam through the OP-GaP sample. They have also measured the damage threshold of the OP-GaP crystal to be 0.84 J/cm^2 at 1064 nm.

F. Guo *et al.* [13] directly measured the phase-matching angles of second-harmonic generation and difference-frequency generation up to 6.5 μm in the Langanate crystal $La_3Ga_{5.5}Nb_{0.5}O_{14}$ (LGN). They also determined the nonlinear coefficient and damage threshold. They refined the Sellmeier equations of the ordinary and extraordinary principal refractive indices, and calculated the conditions of supercontinuum generation. Intracavity difference-frequency generation (DFG) between signal and idler pulses is investigated by A. A. Boyko *et al.* [14] in orientation-patterned GaAs inside the cavity of a ~1 µm pumped nanosecond optical parametric oscillator (OPO). Using two different samples and temperature tuning in the non-critical configuration, tunability between 7 and 9.2 µm is demonstrated. The superior thermo-mechanical properties of OPGaAs enabled also for the first time operation of this cascaded scheme at kilohertz (1-3 kHz) repetition rates reaching average powers ~10 mW in the mid-IR. T. H. Runcorn *et al.* [15] demonstrate a nanosecond 560 nm pulse source based on the frequency-doubling of the output of a combined Yb-Raman fiber amplifier, achieving a pulse energy of 2.0 µJ with a conversion efficiency of 32% from the 976 nm pump light. By introducing a continuous-wave 1120 nm signal before the cladding pumped amplifier of a pulsed Yb:fiber master oscillator power amplifier system operating at 1064 nm, efficient conversion to 1120 nm occurs within the fiber amplifier due to stimulated Raman scattering. The output of the combined Yb-Raman amplifier is frequency-doubled to 560 nm using a periodically poled lithium tantalate crystal with a conversion efficiency of 47%, resulting in an average power of 3.0 W at a repetition rate of 1.5 MHz. The 560 nm pulse duration of 1.7 ns and the near diffraction-limited beam quality (M^2~1.18) make this source ideally suited to biomedical imaging applications such as optical-resolution photoacoustic microscopy and stimulated emission depletion microscopy.

W. Tian *et al.* [16] report on a Kerr-lens mode-locked Yb:YSO lasers for the first time. Pumped by a single-mode fiber laser with high brightness and linear polarization, the Yb:YSO laser can deliver as high as 2 W average power with as short as 95 fs pulse duration at the repetition rate of 137.2 MHz, resulting in the single pulse energy of 14.8 nJ and the peak power of 155.7 kW. This work proves the potential on generation of sub-100 fs pulses with multi-watt level average power with the Yb doped oxyorthosilicates crystals. S. Aparanji *et al.* [17] present a technique for simultaneous power-combining and wavelength conversion of multiple fiber lasers into a single, longer wavelength in a different band through Raman-based, nonlinear power combining. They illustrate this by power combining of two independent Ytterbium lasers into a single wavelength around 1.5 microns with high output powers of upto 99 W. A high conversion efficiency of ~64% of the quantum efficiency and a high level of wavelength conversion with > 85% of the output power in the final wavelength are demonstrated. The proposed method enables power-scaling in various wavelength bands where conventional fiber lasers are unavailable or limited in power. 3 at.% $Er:SrF_2$ laser crystals with high optical quality were successfully grown using the temperature gradient technique (TGT). The intense mid-infrared emission was observed around 2.7 µm with excitation by a 970 nm LD by L. Su *et al.* [18]. Based on the Judd–Ofelt theory, the emission cross-sections of the $^4I_{13/2}$-$^4I_{11/2}$ transition were calculated by using the Fuchtbauer-Ladenburg (FL) method. Efficient continuous-wave laser operation at 2.8 µm was achieved with the lightly-doped 3 at.% $Er:SrF_2$ crystal pumped by a 970 nm laser diode. The laser output power reached up to 1.06 W with a maximum slope efficiency of 26%. High brightness compact microchip-seeded MOPA system was realized by V. Yahia *et al.* [19]. Implementing a microchip preamplifier stage acting as gain aperture element lead to excellent output beam quality with M^2 = 1.4. At maximum amplification level, 235 mJ (0.4 GW) of output energy (power) was measured. Analysis of the effect of the preamplifier showed that this element

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increases the available beam intensity by two orders of magnitude without significant increase in system footprint. Final beam brightness was 18 PW/sr.cm^2.

M. R. Oermann *et al.* [20] present the coherent beam combination of four 2100 nm holmium amplifiers with their phase controlled through acousto-optic modulators driven by the RF output of direct digital synthesizer chips. Phase alignment was achieved through the use of a field programmable gate array based stochastic parallel gradient descent algorithm. The influence of the Kramers-Kronig phase is demonstrated by W. Minster *et al.* [21] in a coherently combined fiber laser where other passive phasing mechanisms such as wavelength tuning have been suppressed. A mathematical model is developed to predict the lasing supermode and is supported by experimental measurements of the gain, phase, and power. The results show that the difference in Kramers-Kronig phase arising from a difference in gain between the two arms partially compensates for an externally applied phase error.

S. Arun *et al.* [22] demonstrate a simple module for octave spanning continuous-wave supercontinuum generation using standard telecom fiber. This module can accept any high power ytterbium-doped fiber laser as input. The input light is transferred into the anomalous dispersion region of the telecom fiber through a cascade of Raman shifts. A recently proposed Raman laser architecture with distributed feedback efficiently performs these Raman conversions. A spectrum spanning over 1000nm (>1 octave) from 880 to 1900nm is demonstrated. The average power from the supercontinuum is ~34W with a high conversion efficiency of 44%. Input wavelength agility is demonstrated with similar supercontinua over a wide input wavelength range. Mechanically robust and low loss single-mode arsenic sulfide fibers are used by A. Sincore *et al.* [23] to deliver high power mid-infrared sources. Anti-reflection coatings were deposited on the fiber facets, enabling 90% transmission through 20 cm length fibers. 10.3 W was transmitted through an anti-reflection coated fiber at 2053 nm, and uncoated fibers sustained 12 MW/cm^2 intensities on the facet without failure. A Cr:ZnSe laser transmitted >1 W at 2520 nm, and a Fe:ZnSe laser transmitted 0.5 W at 4102 nm. These results indicate that by improving the anti-reflection coatings and using a high beam quality mid-infrared source, chalcogenide fibers can reliably deliver ~10 W in a single mode, potentially out to 6.5 μm. S. Liang *et al.* [24] report a gain-switched diode-seeded thulium doped fiber master oscillator power amplifier (MOPA) producing up to 295-kW picosecond pulses (35 ps) at a repetition rate of 1 MHz with a good beam quality (M^2 ~1.3). A narrow-band, grating-based filter was incorporated within the amplifier chain to restrict the accumulation of nonlinear spectral broadening and counter-pumping of a short length of large-mode-area (LMA) fiber was used in the final stage amplifier to further reduce nonlinear effects. Finally, they generated watt-level >2.5-octave supercontinuum spanning from 750 nm to 5000 nm by using the MOPA output to pump an indium fluoride fiber.

J. C. Coyle *et al.* [25] report a broadly wavelength-tunable femtosecond diode-pumped Ti:sapphire laser, passively mode-locked using both semiconductor saturable absorber mirror (SESAM) and Kerr-lens mode-locking (KLM) techniques. Using two pump laser diodes (operating at 450 nm), an average output power as high as 433 mW is generated during mode-locking with the SESAM. A tunability range of 37 nm (788-825 nm) was achieved with the shortest pulse duration of 62 fs at 812 nm. In the KLM regime, an average output power as high as 382 mW, pulses as short as 54 fs, and a tunability of 120 nm (755-875 nm) are demonstrated. W. Wang *et al.* [26] conceived a Tm-doped mixed sesquioxide ceramic laser that is mode-locked near 2 μm using InGaAsSb quantum-well semiconductor saturable absorber and chirped mirrors for dispersion compensation. Maximum average output power of 175 mW is achieved for a pulse duration of 230 fs at a repetition rate of 78.9 MHz with a 3% output coupler. Applying a 0.2% output coupler pulses as short as 63 fs are generated at 2.057 μm. Y. Yu *et al.* [27] demonstrate highly stable mode-locked Yb-doped fiber oscillators using nonlinear amplifying loop mirror, delivering linearly polarized laser pulses with high energy at low repetition rate of several MHz. These lasers are composed of polarization-maintaining fibers and fiber-based components without intra-cavity dispersion compensation.

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Spectral bandwidth of 31 nm is realized in the case of 6 MHz repetition rate, and the pulse energy reaches 10 nJ. A pair of gratings compresses the output pulse to 93 fs. RMS power stability is as low as 0.04% in 10 hours, which shows excellent stability.