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Recommended Citation

Schepler, Kenneth L.; Jeong, Yoonchan; Jiang, Shibin; Gallo, Katia; Taira, Takunori; and Ilday, F. Ömer, "Focus issue introduction: Advanced Solid-State Lasers (ASSL) 2014" (2015). *Faculty Bibliography 2010s*. 6789.

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Focus issue introduction: Advanced Solid-State Lasers (ASSL) 2014

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Abstract: The editors introduce the focus issue on “Advanced Solid-State Lasers (ASSL) 2014,” which is based on the topics presented at a congress of the same name held in Shanghai, China, from October 27 to November 1, 2014. This Focus issue, jointly prepared by *Optics Express* and *Optical Materials Express*, includes 28 contributed papers (21 for *Optics Express* and 7 for *Optical Materials Express*) selected from the voluntary submissions by attendees who presented at the congress and have extended their work into complete research articles. We hope this focus issue offers a useful snapshot of the variety of topical discussions held at the congress and will contribute to the further expansion of the associated research areas.

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OCIS codes: (060.0060) Fiber optics and optical communications; (130.0130) Integrated optics; (140.0140) Lasers and laser optics; (160.0160) Materials; (190.0190) Nonlinear optics; (230.0230) Optical devices; (320.0320) Ultrafast optics.

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We are pleased to introduce the focus issue on "Advanced Solid-State Lasers (ASSL) 2014," which is based on the topics presented at a congress of the same name held in Shanghai, China, from October 27 to November 1, 2014. This is the second ASSL congress. The first ASSL congress was held in Paris, France, from October 27 to November 1, 2013. ASSL is one integrated congress, combining the three topical meetings formally known as ASSP, AIOM, and FILAS [1]. This new congress offers researchers from all over the world great opportunities for presenting and discussing, in one place, their latest significant achievements in areas of materials, sources, and applications. The single-track format offered great stimulus for close interactions and networking among attendees and colleagues. The ASSL 2014 congress also provided selections of short courses and a series of special events including a conference banquet of traditional Chinese fare and an Industry Panel Session where panelists discussed the successes and challenges encountered when commercializing research in the laser technology arena. These events and the overall informality of this congress allowed for great interaction, encouragement and refreshment to attendees.

It is worth noting that during the congress, 27 invited, 58 contributed oral, and 160 contributed poster papers were presented, together with 6 postdeadline papers.

In general, the 2014 ASSL Congress included topics categorized as follows [2]:

Materials

- Laser crystals
- Transparent ceramics
- Crystal and glass fibers
- Nonlinear crystals and processes
- Waveguides and laser patterning
- Photonic structures

Sources

- Solid State Lasers
- Fiber Lasers
- Optical Sources Based on Nonlinear Frequency Conversion Schemes
- High Power CW and Pulsed Sources
- IR, Visible and UV Sources
- Laser Beam Combining
- Short-pulse Lasers
- Frequency Combs and Frequency-stable Lasers
- Microchip and Compact Lasers
- Tunable and New Wavelength Lasers
- Optically Pumped Semiconductor Lasers
- High-Brightness Diodes

Applications

- Laser and systems for medical applications
- Laser and systems for consumer electronics manufacturing

This ASSL 2014 focus issue, jointly prepared by *Optics Express* and *Optical Materials Express*, includes 28 contributed papers (21 for *Optics Express* and 7 for *Optical Materials Express*) selected from the voluntary submissions from attendees who presented at the ASSL Congress 2014 and have extended their work into complete research articles. While they do not cover the whole range of research topics presented and discussed at the congress, readers should be able to sample the breadth and depth of the presentations and discussions given at the congress, particularly in the following areas:

Topics for Optics Express

- Ultrafast lasers (4)
- Modelocked oscillators (2)
- Q-switched lasers (1)
- Fiber lasers (8)
- Infrared lasers (2)

- Random lasers (1)
- Laser resonators (2)
- Laser beam characterization (1)
- Laser beam combining (1)
- Laser stabilization (1)
- Laser damage (1)
- Laser theory (1)
- Nonlinear sources (2)
- Nonlinear effects in fibers (2)
- Nonlinear optical materials (1)
- Free-space optical communications (1)

Topics for Optical Materials Express

- Fiber lasers (3)
- Laser materials (3)
- Infrared lasers (2)
- Modelocked oscillators (1)
- Remote sensing and sensors (1)

The numbers given in parentheses denote the number of contributed papers in the corresponding category. It was not easy to divide all the contributed papers into separate categories with no conflict, so some papers have been attributed to more than one topical focus.

Here we give brief introductions of the contributed papers. Primary foci of the papers are given in parentheses:

Optics Express

Pulsed lasers

Zhou *et al.* [3] demonstrate a new technique of coherent pulse stacking amplification, overcoming limits on achievable pulse energies from optical amplifiers, by using low-finesse Gires-Tournois interferometers. They validate the idea with experimental performances close to theoretical expectations in a single reflecting resonator, demonstrating a peak-power enhancement factor of ~ 2.5 , with 92% and 97.4% efficiency for amplified nanosecond and femtosecond pulses, respectively. Furthermore, they also show theoretically that large numbers of equal-amplitude pulses can be stacked using sequences of multiple reflecting resonators, thus providing a new path for generating very high-energy pulses from ultrashort pulse fiber amplifier systems, overcoming current limitations of solid-state amplifiers. (ultrafast lasers, laser beam combining)

Aleksandrov *et al.* [4] demonstrated passive mode-locking of a $\text{Tm, Ho:KLu(WO}_4)_2$ laser operating at 2060 nm using different designs of InGaAsSb quantum-well based semiconductor saturable absorber mirrors (SESAMs). The self-starting mode-locked laser delivered pulse durations between 4 and 8 ps at a repetition rate of 93 MHz with maximum average output power of 155 mW. Mode-locking performance of a SESAM and a single-

walled carbon nanotube saturable absorber in a Tm,Ho:KLu(WO₄)₂ laser were also compared. (modelocked oscillators)

Li *et al.* [5] investigated different pulse-shaping mechanisms experimentally and numerically in passively mode-locked thulium-doped fiber lasers. Conventional solitons were demonstrated in a passively semiconductor saturable absorber mirror mode-locked anomalous dispersion thulium-doped fiber laser. With normal dispersion fiber and spectral filter added in cavity, pulse-shaping processes were theoretically analyzed in the presence of dispersion map and dissipation in thulium-doped fiber lasers. The existence of parabolic pulse as nonlinear attraction was proved and distinct pulse intensity profiles evolution from Gaussian shape to parabolic shape was proposed in dissipative dispersion-managed thulium-doped fiber lasers. (modelocked oscillators, fiber lasers)

Chiba *et al.* [6] report a broadband Yb-doped fiber laser system with a gain-narrowing compensator comprised of multiple dielectric layers. Utilizing this filter, they obtained broadband pulses over a bandwidth of 1020–1080 nm directly from the amplifier. After the dispersion compensation, the chirped pulse amplification system delivered 65-fs pulses with energies of 100 nJ and a repetition rate of 3 MHz. (ultrafast lasers, fiber lasers)

Kim *et al.* [7] demonstrated a monolithic polarization maintaining fiber chirped pulse amplification system with 25 cm Yb³⁺-doped high efficiency media fiber that generates 62 μJ sub-400 fs pulses with 25 W at 1.03 μm. This monolithic fiber optic CPA system shows great potential of 1) reliable industrial ultrafast fiber laser owing to the absence of photodarkening and 2) high energy, ultrashort pulse laser system owing to scalability of energy per pulse. (ultrafast lasers, fiber lasers)

Ren *et al.* [8] demonstrated a passively Q-switched nanosecond pulsed erbium-doped fiber laser based on a MoS₂ saturable absorber. The high quality MoS₂ saturable absorber was prepared by pulsed laser deposition method on a broadband high-reflectivity mirror with a large modulation depth of 9%. Stable Q-switched operation was achieved with 660 ns pulse width and maximum pulse energy of 152 nJ. The experimental results verify that MoS₂ is a useful saturable absorber for stable Q-switched pulse generation at 1.5 μm. (fiber lasers, Q-switched lasers)

Fiber lasers

Xu *et al.* [9] present a 1.01 kW, all-fiberized master oscillator power amplifier structured superfluorescent source based on dual-cladding ytterbium-doped fiber. The seed source was a 0.814 W homemade amplified spontaneous emission (ASE) source. A two-stage high power fiber amplifier boosted the seed power to 1.01 kW with a beam quality of $M^2 = 1.7$. No self-pulsing or relaxation oscillation effect was observed and the power fluctuation was less than 2% in 100 seconds of continuous operation. To the best of our knowledge, this is the first demonstration of an all-fiberized superfluorescent source with output power exceeding 1kW. (superfluorescence, fiber lasers)

Wu *et al.* [10] analyzed the role of the point reflector's reflectivity in the performance of forward-pumped random fiber lasers, in both the long- and short-cavity cases. The results show that the power performance is sensitive to the small reflection added on the pump side of the fiber end, whereas both the power distribution and threshold tend to be stable when the reflectivity reaches a relatively high level (>0.4). Moreover, for the short cavity case (e.g. 500 m), the maximum achievable 1st-order random lasing output can even increase when the reflectivity decreases from 0.9 to 0.01, due to the different lasing power distributions with different reflectivity values. This work reveals a new and unique property of random fiber lasers and provides insights into their design for applications such as distributed amplification and high power sources. (fiber lasers, random lasers)

Infrared lasers

Gutty *et al.* [11] demonstrated a core-pumped Q-switched thulium-doped fiber laser system with fast tuning capability over 100 nm without any movable part. With up to 7 kW peak power in a diffraction-limited beam, this source is well adapted for pumping a frequency agile mid-IR parametric oscillator or amplifier based on quasi-phase-matched single-period crystals. (fiber lasers, infrared lasers)

Peppers *et al.* [12] spectroscopically characterized Fe:ZnSe(Cr:ZnSe) crystals under visible excitation into the charge transfer bands of transition metal ions. The excitation efficiencies of mid-IR photoluminescence between 5T_2 (5E) and 5E ($^5T^2$) states via direct relaxation to the upper laser levels and via metastable upper 3T_1 were investigated. It was demonstrated that the latter route is the dominant process for Cr^{2+} ions and could provide sufficient pump rate for mid-IR lasing. The pump efficiencies via direct relaxation to the upper laser levels were estimated to be <2% for both ions under 532 nm excitation. (infrared lasers)

Zhang *et al.* [13] grew a novel Ho^{3+}/Yb^{3+} -codoped PbF_2 mid-IR crystal. Enhanced emission at 2.86 μm ($^5I_6 \rightarrow ^5I_7$ of Ho^{3+}) was observed from the crystal under excitation at 970 nm. In comparison to Ho^{3+} -singly doped PbF_2 , the Ho^{3+}/Yb^{3+} -codoped PbF_2 crystal possessed comparable quantum efficiency (88.8%), and fluorescence branching ratio (20.52%) along with a larger calculated emission cross section ($1.90 \times 10^{-20} cm^2$). The energy transfer efficiency from Yb^{3+} to Ho^{3+} is as high as 96.7%, indicating that Yb^{3+} is an effective sensitizer for Ho^{3+} in PbF_2 crystal. (infrared lasers)

Laser components

Wetter *et al.* [14] analyze the performance of a VBG equipped diode of narrow linewidth in a side-pumped double-beam, mode-controlled resonator and demonstrate power scaling without loss of beam quality by a factor of three, when compared to previous results. 69 W of diffraction-limited laser output power at 1053 nm in a Nd:YLF lasers are demonstrated with slope efficiency of 65% and record optical-to-optical efficiency of 60%. (laser resonators)

Altmann [15] shows that the condition provided by paraxial wave optics for the resonance frequencies of the eigenmodes of an optical resonator leads to a contradiction, if the resonator is divided into subcavities. Moreover, he shows that the results obtained in this way imply a violation of energy conservation. Since for nearly plane waves, paraxial wave optics becomes exact within wave optics, this contradiction also concerns wave optics. A solution for this problem is proposed based on a consideration of the change of momentum of a photon bouncing between two equiphase surfaces with vanishing distance. This leads to a transverse force exerted on the photon. Assigning a relativistic mass to the photon leads to a Schrödinger equation describing a transverse motion of the photon. In this way the transverse modes of an optical resonator can be understood as the quantum mechanical eigenfunctions of a single photon. (laser theory, laser resonators)

L. Huang *et al.* [16] implemented the first experimental investigation of a real-time mode decomposition technique for few-mode fibers based on a stochastic parallel gradient descent algorithm, which could reduce the cost and complexity of mode decomposition systems. They were able to decompose the mode spectra as well as calculate the beam quality factor at a monitoring rate of about 9 Hz, achieving good agreement between the measured and reconstructed intensity profiles in each frame. The mode decomposition technique proposed in this paper provides a compact way to further look into the dynamics of fiber lasers. (laser beam characterization)

Wang *et al.* [17] developed an improved model to analyze the defect density distribution and assess the damage performance of high-reflective coatings. Two kinds of high-reflective coatings deposited by e-beam evaporation (EBE) and ion beam sputtering (IBS) techniques were analyzed. The lower overall damage threshold is the major feature for the coatings

deposited by IBS method according to the defect parameters extracted from the model. The defect analysis model improved here is suitable for high-reflective coatings. (laser damage)

Y. Huang *et al.* [18] demonstrated a multi-pass pumping scheme for thin disk lasers consisting of dual parabolic mirrors with conjugated relationship. The sensitivity to disturbances such as misalignment was analyzed by ray tracing methods. Both theory and experiment showed that disturbances in this system will not lead to a misalignment of each pumping spot; only the position of the superposed pumping spot on the disk crystal will be changed. Compared with the multi-pass pumping scheme consisting of parabolic mirror and folding prisms, this pumping scheme has a better anti-disturbance ability. (laser stabilization)

Nonlinear optics

Chen *et al.* [19] demonstrated a high-power narrow-linewidth photonic bandgap fiber amplifier. In order to suppress stimulated Brillouin scattering, the seed linewidth was broadened by applying a random phase noise with an electro-optical modulator. A factor of 15 in terms of Brillouin gain suppression can be theoretically expected. Output power of 87 W, linearly-polarized (11 dB polarization extinction ratio) and narrow-linewidth (780 MHz FWHM) output were obtained. (nonlinear effects in fibers)

Harish *et al.* [20] investigated the use of an arbitrary waveform generator to phase-modulate a laser source and externally broaden its linewidth. Through nonlinear optimization in a computer, they found modulation signals that produced top-hat-shaped optical spectra of discrete lines with highest total power within a limited bandwidth and limited peak spectral power density. The required modulation bandwidth was comparable to the targeted optical bandwidth. Such spectra are attractive for suppressing stimulated Brillouin scattering in optical fiber. (nonlinear effects in fibers)

Beutler *et al.* [21] employed AgGaSe₂ for difference-frequency generation between signal and idler of synchronously-pumped picosecond /femtosecond OPOs at 80 / 53 MHz. Continuous tuning in the picosecond regime was achieved in the 5-18 μm range with average power of 140 mW at 6 μm . In the femtosecond regime the tunability extends from 5 to 17 μm with average power of 69 mW at 6 μm . Maximum single pulse energies of >1 nJ in both cases represent the highest values at such high repetition rates. (harmonic generation and mixing, nonlinear optical materials)

Cheng *et al.* [22] observed dissipative soliton resonance phenomena in a graphene oxide mode-locked Yb-doped fiber laser, which delivered square-shaped 0.52 ns~60.8 ns pulses and single pulse energies up to 159.4 nJ at 1064.9 nm. The 3dB bandwidth of the Lorentz-shaped spectrum was 0.19 nm. They verified that reverse saturable absorption played a major role in generating square-shaped or flat-top pulses with modeling using a scalar generalized nonlinear Schrodinger equation. (nonlinear optical materials, fiber lasers)

Applications

Yu *et al.* [23] investigated far-field correlation of bidirectional tracking beams in inter-satellite optical communication links. The correlation of the bidirectional tracking beams changes in the far-field as a result of wave-front deformation. A far-field correlation model shows that deformation pointing-tracking errors and far-field correlation factor δ depend on RMS of deformation error rms, which decline with an increasing rms including Tilt and Coma. The principle of adjusting far-field correlation factor with wave-front deformation to compensate deformation pointing-tracking errors has been given, through which the deformation pointing-tracking error is reduced. This work possesses significant reference value on optimization design in inter-satellite optical communication. (free-space optical communications)

Optical Materials Express

Fiber lasers

Wang *et al.* [24] fabricated a single-mode 15- μm core diameter ytterbium-doped phosphate photonic crystal fiber with all solid structure. A 45 cm long fiber produced 8.2 W of output power with 29% slope efficiency. (fiber lasers)

Lee *et al.* [25] demonstrated high gain in a heavily Tm-doped silicate fiber. A single-mode double-clad Tm³⁺-doped silicate fiber with ion concentration of 7 wt% ($8.35 \times 10^{20}/\text{cm}^3$) produced a gain of 5.8 dB/cm at 1945 nm pumped with 647.6 mW at 1567 nm. Furthermore, they experimentally demonstrated efficient cm-long fiber lasers and watt-level cladding pumped Tm³⁺-doped silicate fiber amplifiers. (fiber lasers)

Laser materials

Röser *et al.* [26] report on the fabrication, optical properties and lasing characteristics of Yb-doped fused silica in bulk volume. The glass rods were manufactured by sintering of Yb-doped fused silica granulates and subsequent homogenization. The glass shows a high optical quality with refractive index variations in the 10 ppm range. They successfully demonstrated quasi-cw lasing with a maximum optical to optical efficiency of 60% and slope efficiencies of about 70% with respect to absorbed pump power for all samples. The laser cavity was tuned in a wavelength range of 100 nm. (laser materials)

Martinez *et al.* [27] investigated the effect of Co⁶⁰ γ irradiation on the rate of post-growth thermal diffusion of iron into ZnSe and ZnS. Samples had thin films of iron deposited on one facet and were annealed at 950°C for 14 days in the presence of γ radiation and diffusion lengths were compared to those of traditional post-growth thermal diffusion in the absence of γ irradiation. Samples of Fe:ZnSe and Fe:ZnS annealed under 44R/s γ irradiation showed increases in diffusion rate of 14% and 50%, respectively. This technique shows promise for production of materials doped with more uniform dopant concentrations, larger crystal size or increased concentrations of dopants. (infrared lasers, laser materials)

Yoon *et al.* [28] present measurements of the concentration dependence of the energy transfer upconversion (ETU) macro-parameter in Nd:YAG obtained via the Z-scan technique. The ETU coefficient is found to increase from $27 \times 10^{-18} \text{ cm}^3/\text{s}$ to $75 \times 10^{-18} \text{ cm}^3/\text{s}$ when the concentration increases from 0.3 at.% to 1.1 at.%. The Z-scan technique offers a simple and sensitive measurement of the ETU parameter. The information presented in this paper will allow laser designers to consider the effects of upconversion on their systems. (laser materials)

Infrared lasers

Singh *et al.* [29] present 2- μm laser development from early research to current state-of-the-art instrumentation and projected future NASA Langley Research Center space missions. This applies to both global wind and carbon dioxide active remote sensing. Discussions cover fundamental spectroscopy research, theoretical prediction of new materials, laser demonstration and engineering of lidar systems spanning around two decades. A brief historical perspective of Tm:Ho work by early researchers is also given. (infrared lasers, remote sensing and sensors)

Modelocked oscillators

Kang *et al.* [30] demonstrated passively mode-locked ytterbium and erbium doped fiber lasers operating at 1039 and 1560 nm by using a saturable absorber film consisting of common gold nanorods mixed with sodium carboxymethylcellulose. The film had broadband longitudinal surface plasmon resonance absorption from 800 to 1800 nm. Stable passively mode-locked laser operation at 1039 or 1560 nm was achieved for a threshold pump power of ~ 100 or ~ 70 mW, respectively. The pulse width, the output power, and the repetition rate of the 1039 nm

mode-locked laser were 460 ps, 1.47 mW, and 43.5 MHz for a pump power of ~110 mW, respectively. The corresponding output parameters of the 1560 nm mode-locked laser were 2.91 ps, 2 mW, and 35.6 MHz for a pump power of ~74 mW, respectively. (modelocked oscillators, fiber laser)

In conclusion, the ASSL Congress 2014 was quite successful as the only international, integrated event regarding solid-state lasers running single-track technical sessions for presenting and discussing materials, sources, and applications. We believe that joining in this exciting meeting in the future would offer great opportunities for seeing the utmost recent advances in solid-state laser science. We hope this focus issue offers a good snapshot of a variety of topical discussions held at the ASSL Congress 2014 and will contribute to the further expansion of the associated research areas. Finally, we invite you to join the upcoming ASSL Congress 2015 that is to be held in Berlin, Germany on October 4–8, 2015.

Acknowledgments

The editors would like to give sincere thanks to all the authors who have contributed to this Focus issue and to all the peer reviewers for their invaluable time and genuine efforts. We would also like to give special thanks to Prof. Andrew Weiner, Editor-in-Chief of *Optics Express* and Prof. David Hagan, Editor-in-Chief of *Optical Materials Express*, for their support on this Focus issue, and to the OSA journal staff: Ms. Carmelita Washington, Mr. Dan McDonold, Mr. Marco Dizon and Mr. Keith Jackson for their hard work and kind coordination throughout the whole review and production process.