Introduction | Vol. 12, No. 6 / 1 Jun 2022 / Optical Materials Express 2283

Optical Materials EXPRESS

Feature issue introduction: advanced solid-state lasers

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Abstract: This Joint Issue of *Optics Express* and *Optical Materials Express* features 36 state-of-the art articles written by authors who participated in the international conference Advanced Solid State Lasers held online from October 3-7, 2021. This review provides a summary of these articles covering a wide spectrum of topics around solid-state lasers from materials research to sources and from design innovation to applications.

ASSL (Advanced solid-state lasers) is the international conference devoted to recent advances in both materials and sources aspects of solid-state lasers. Materials encompasses 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. Coherent and high brightness radiation sources include lasers as well as pump and nonlinear devices. 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 performance.

We hope readers will enjoy this issue of 36 top-level articles that highlight the state of the art in the field. We are thankful to all authors and reviewers for their excellent contributions. We would also like to thank Carmelita Washington and Rebecca Robinson from the Optica staff for their outstanding work throughout the launch of this feature issue as well as the review and production processes.

Gain media are at the heart of solid-state lasers, and new materials and the corresponding lasers continue to be central to the conference. Yb-doped materials were at the focus of this ASSL meeting, and this particularly due to the celebratory topic around the 30-year anniversary of diode-pumped Yb-doped lasers. Advances using Yb:YAG were reported by Cvrček et al., where heatsinking to SiC was explored in the disk geometry [1]. Qi et al. also report on fabrication of yttrium aluminosilicate fibers with high Yb^{3+} doping from Yb:YAG ceramic nanopowders and its application in single-frequency fiber lasers [2]. Average power levels from Yb-doped fibers continue to increase with Wu et al. demonstrating 6.2 kW from a confined-doped Yb-fiber with an optical to optical efficiency of 82% and a beam quality factor of ~1.9 at an output power

#464524
Journal © 2022

https://doi.org/10.1364/OME.464524
Received 18 May 2022; published 24 May 2022

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of 5.07 kW. Moreover, the transverse mode instability threshold of the confined-doped fiber amplifier is ~4.74 kW [3].

Also other Yb-doped materials continue to attract research attention, in particular materials with broad bandwidths to support ultrashort pulse operation. Pan et al. reports on polarized spectroscopy and diode-pumped laser operation of disordered Yb:$Ca_3Gd_2(BO_3)_4$ crystal [4], and Sun et al. demonstrated sub-40 fs pulses from a diode-pumped SESAM mode-locked Yb:$Sr_3Y_2(BO_3)_4$ laser [5]. In addition, Lin et al. report on a Kerr-lens mode-locked Yb:$SrLaAlO_4$ laser with pulses as short as 44 fs with an average power of 277 mW at a repetition rate of 66 MHz [6]. In his invited OMEx contribution, C. Kränkel discusses rare-earth mixed doped sesquioxide materials as a potentially promising family of laser gain media with broad bandwidths for high-power ultrafast lasers [7].

Several gain materials based on other active ions emitting in other wavelength regions were also reported. Interest in materials for bulk solid-state lasers in the short-wave mid-infrared range continues to grow. Wang et al. demonstrated SESAM mode-locking of Tm,Ho:CALGO generating pulses as short at 52 fs at a central wavelength of 2015 nm. Polarized spectroscopy properties of Ho^{3+} ions and singly-doped and co-doped CALGO crystals were presented to explain the laser results [8]. Sub-100 fs pulses were reported at a central wavelength of 2010.4 nm from a mode-locked laser using Tm^{3+} doped in the disordered CLTGG crystal [9], and Loiko et al. demonstrated in-band pumping of a Tm, Ho:$LiYF_4$ planar waveguide generating 540 mW at 2051 nm with a slope efficiency of 32.6% [10]. Basyrova et al. report on power scaling and thermal lensing in mid-infrared Er:CaF_2 lasers operating on the $^4I_{11/2}\rightarrow{}^4I_{13/2}$ transition and demonstrated 0.83 W at 2800 nm [11]. Fiber lasers in this region of the spectrum continue to progress in the direction of higher powers and longer wavelengths. In his invited contribution, Jobin et al. discuss recent developments in lanthanide-doped mid-infrared fluoride fiber lasers emitting between 2.5 µm and 5.0 µm [12]. Liu et al. report on a lutetium aluminum garnet single-crystal fiber doped with Ho^{3+} (Ho:LuAG) presenting spectroscopic characterization and demonstrating 6 W at 2.09 µm [13].

Characterizing new materials and providing highly accurate material properties is an essential step in the design of future sources, and a number of contributions were dedicated to mid-IR laser and nonlinear materials. Brown et al. present spectroscopic characterization of Er-doped $Ga_2Ge_2S_{13}$ glass for mid-IR applications [14]. Additionally, new Sellmeier and thermo-optic dispersion formulas are presented for the nonlinear crystal CdSe by Miyata et al., which is essential for predicting crystal phase matching conditions to realize tunable mid-IR sources [15]. In an invited paper, Wang et al. report the recent progress on acentric $La_3Nb_{0.5}Ga_{5.5}O_{14}$ (LGN) crystals for ultrafast mid-IR laser systems showing its potential in generating both few-cycle pulses from 3 to 6 µm and terawatt-class OPCPA systems around 5 µm [16]. In the short-wave mid-IR and near-IR wavelength regions, Vařák et al. report the influence of various optical fiber fabrication processes on the fluorescence decay of rare-earth ions commonly used in fiber lasers and amplifiers, i.e., Yb^{3+}, Tm^{3+} and Ho^{3+}, which is crucial for understanding the performance of fiber lasers [17]. Wang et al. report crystal growth and polarization spectra and analyses for Pr^{3+}-doped $GdScO_3$ single crystals to show its potential as a near infrared laser gain medium originating from the Pr^{3+} $^1D_2$ transition [18]. Fabrication of the two-dimensional molecular crystal (2DMC) Sb_2O_3 and its characterization as a saturable absorber at 1 µm is also reported, which motivates the potential application of 2DMC for ultrafast photonics [19]. Sato and Taira report the linear thermal expansion coefficient of various laser host crystals with cubic symmetry by first principles calculations, which is an important parameter for power scaling crystal solid-state lasers [20].

Modal configuration of the beams is a crucial issue for many applications, such as optical manipulation, quantum optics, and optical communications. Contributions in this area are reported in the mid-infrared spectral region. Cao et al. experimentally demonstrate the direct

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generation of a stable 2 μm ultrafast vortex beam from a Tm:$CaYAlO_4$ oscillator by pattern matching of a folded-cavity resonator [21], and Gao et al. report the direct generation of mid-infrared pulsed optical vortices at ~2.7 μm by employing polycrystalline Fe:ZnSe as a saturable absorber [22]. An InAs/GaAs quantum dot laser was epitaxially grown on on-axis (001) GaAs-on-insulator (GaAsOI) substrate showing the potential to fabricate highly integrated light source on Si for photonic integrated circuits [23].

Pushing the limits of laser sources, generating new laser modalities, and developing novel laser devices to enable new applications are active areas of current research. Moon et al. report a cavity dumped, mode-locked Alexandrite laser oscillator with 100 mJ pulse energy stabilized by using a double trigger system as a means to generate high pulse energy in a single oscillator [24]. Zhu et al. used a novel gain medium structure to realize high optical to optical efficiency for an actively Q-switched Nd:YAG laser at the hundred milli-joules level [25]. Lim and Taira demonstrated a flat-convex unstable cavity Nd:YAG/Cr^{4+}:YAG ceramic air-cooled microchip laser generating a record 37.6 and 59.2 MW peak power pulses with an energy of 17.0 and 24.1 mJ and a width of 452 and 407 ps at 20 Hz by using a uniform power square and hexagon pump, respectively [26]. Wang et al. report a dual-wavelength, self-Q-switched mode-locked waveguide laser based on a Nd:LGGG cladding waveguide fabricated by femtosecond laser direct writing [27]. Their results are promising for using waveguide lasers based on mixed crystals for integrated optics. Okhrimchuk et al. report the inscription of a waveguide in Nd:YAG crystals with a cladding composed of crystalline hollow channels and demonstrate less than 0.5 dB/cm loss at 1550 nm [28]. Coherent beam combining (CBC) of multiple laser sources is a means for generating laser power beyond the single laser power limit, and Du et al. experimentally demonstrate beam combining stabilization using machine learning trained while phases drift as a path towards robust CBC [29].

Nonlinear optical processes in nonlinear crystals and fibers can be used to generate radiation in spectral regions difficult to achieve by direct lasing. A number of contributions were focused on nonlinear optics. Fuertjes et al. report a tunable, high-energy optical parametric chirped pulse amplification system with a front-end based on a femtosecond Cr:ZnS laser [30]. They generated idler pulses from an optical parametric amplifier tunable between 5.4 and 6.8 μm using ZGP with a pulse energy up to 400 μJ at 1 kHz and pulse compressed to sub-100 fs duration. Dorrer and Spilatro report a new approach for spectral and temporal shaping of spectrally incoherent pulses in the infrared and ultraviolet using closed-loop control of the spectral density and pulse shape of nanosecond spectrally incoherent pulses after optical parametric amplification [31]. Additionally, Ma et al. report on an intra-cavity diamond Raman laser at 1634 nm generating 2 W of average output power at 25 kHz with a pulse duration of 5.7 ns and near diffraction limited beam quality [32]. Kosc et al. present experiments and modeling of the angular dependence of the transverse Raman scattering in KDP and DKDP in geometries suitable for beam polarization control enabling researchers to generate optimal crystal cuts for specific applications [33]. Using twin BIBO crystals for walkoff compensation, Li et al. report the theoretical and experimental results for an intracavity frequency doubled red laser [34]. The use of walkoff compensated crystals increased the red power by 1.2 times compared to the uncompensated case and generates a nearly round beam. Using cascaded Raman conversion in phosphosilicate fiber and second harmonic generation in periodically-poled lithium niobate, Chandran et al. report >1 W at 743 nm with a corresponding pulse energy of 220 nJ at a repetition rate of 5 MHz [35]. The source displays excellent beam quality with ideal parameters for biomedical imaging applications. Sidelnikov et al. report the development of a comprehensive theory for describing the mechanism of brightness enhancement in multimode laser-diode-pumped graded-index fiber Raman lasers showing quantitative agreement with experimental results [36].

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