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Tiny integrated lasers and their application to industrial laser technologies: feature issue introduction

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Abstract: This issue of Optics Express features 18 papers, prepared primarily by authors who participated in the 10th Tiny Integrated Laser and Laser Ignition Conference 2024 (TILA-LIC 2024), held on 24–26 April 2024 in Pacifico Yokohama, Yokohama, Japan, as part of the Optics and Photonics International Congress 2024; contributions from other authors related to the topic of tiny integrated lasers were welcomed. This review summarizes these articles, covering results in the fields of lasers and laser optics, nonlinear optics, optical fibers, optical materials, and spectroscopy. Innovations in photonics, also called giant micro-photonics, have allowed the creation of ubiquitous lasers that can operate in diverse fields and conditions, thus opening the door to new applications and discoveries that advance humanity.

The Tiny Integrated Laser and Laser Ignition Conference (TILA-LIC) is an international meeting, organized by the Micro Solid-State Photonics Association, Japan within the Optics and Photonics International Congress, which is held annually, usually in April, at the Pacifico Yokohama Center, Yokohama, Japan. First organized in 2013, then called the Laser Ignition Conference (LIC 2013), the conference reached its 10th edition in 2024. The conference is a forum for discussing various aspects related to ubiquitous laser sources and phenomena associated with high-intense laser pulses. Key topics areas covered by TILA-LIC include the advances in optical materials for tiny integrated laser (development and spectroscopic characterization of crystals, glasses and ceramic laser materials; nonlinear crystals; bonding technologies and composite materials for laser applications); development of tiny integrated lasers (modelling, design, realization and characterization; power-scalable laser architectures; solid-state micro-chip lasers; laser resonators, thermal management and beam quality control); discussion of various phenomena induced by powerful miniature lasers (laser induced breakdown; laser ignition; laser acceleration); as well as industrial applications of tiny integrated lasers (laser peening; ultrafast laser processing; laser ignition for green generation, or THz generation and applications).

A total of 45 communications were delivered at the TILA-LIC 2024 conference, consisting of one plenary talk, one keynote speech, one tutorial, 11 invited talks and 31 contributed papers. The presentations were organized into 10 thematic sessions, primarily focused on laser materials, laser system development, and their applications. Additionally, a poster session was held to

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complement the oral presentations. Researchers from 10 different countries contributed to the conference (Fig. 1). A dedicated session, featuring enterprises from Japan, was held to discuss the transfer of laser technology to societal applications.

Fig. 1. Participants at the 10th Tiny Integrated Laser and Laser Ignition Conference, 24 - 26 April 2024, Pacifico Yokohama, Yokohama, Japan.

A brief summary of the articles published in this feature issue of Optics Express is presented below.

Laser sources with emission in the 1.4 µm to 1.8 µm spectral range are eye-safe, because the radiation is absorbed by the vitreous body before reaching the retina. Also, lasers with a wavelength of 1.5 µm are of interest in various applications, such as optical communications, remote sensing, or range finding. Chen et al. have developed a high-peak-power, narrow-pulse-width acousto-optic Q-switched Nd:YVO_4/YVO_4 eye-safe Raman laser at 1525 nm [1]. They designed a compact laser cavity and showed that the cavity dumping effect leads to a considerable narrowing of the pulse width. The use of a YVO_4 Raman crystal with a dichroic coating led to a reduction of the scattering and absorption losses for the Stokes wave, resulting in good-quality laser beams (M^2 factor below 3.0). An average power exceeding 4.2 W was achieved at repetition rates ranging from 50 kHz to 150 kHz with maximum peak powers of 53 kW and 25 kW, respectively. These values are reported to be nearly an order of magnitude higher than previously published results for Nd:YVO_4/YVO_4 eye-safe Q-switched lasers.

In human health, accurate measurement of carboxyhemoglobin (HbCO) in blood, which is induced by CO exposure, is important for the safety of packed red blood cells transfusion. In addition, HbCO levels allow the assessment of CO-poisoning in forensic medicine. A compact dual-wavelength laser that emits at 555 nm and 579.5 nm and that can be used to measure HbCO levels in blood is reported by Chen et al. [2]. The design uses a Nd:YVO_4/KGW/LBO structure, in which intracavity stimulated Raman scattering of an N_p-cut KGW crystal produces the Stokes wave at 1159 nm from the fundamental wave at 1064 nm of the Nd:YVO_4 crystal. The second harmonic generation of the Stokes wave with a LiB_3O_5 (LBO) nonlinear crystal generates laser radiation at 579.5 nm. A second LBO crystal is used to obtain laser radiation at 555 nm, through the sum frequency generation of the Stokes and fundamental waves. By controlling the temperature of the second LBO crystal, equal powers of 5.5 W were achieved at both wavelengths of 555 nm and 579.5 nm.

Gallium compounds possess good thermal properties and spectroscopic characteristics, making them well-suited for the development of solid-state lasers emitting in the 2 µm range. Slimi et al.

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obtained a Ho:$Y_3Ga_5O_{12}$ (Ho:YGG) laser crystal through the optical floating zone technique in an oxygen-rich atmosphere [3]. The investigation of the spectroscopic properties concluded that, compared to Ho:YAG, the Ho:YGG medium presents stronger homogeneous line broadening in the absorption and stimulated-emission spectra around 2 µm, thus having a broader gain bandwidth; in addition, Ho:YGG has a smoother gain cross-section and a longer luminescence lifetime of the upper $^5I_7$ laser manifold. Optical pumping of a 2.86-at.% Ho:YGG crystal by a Tm-fiber laser at 1908nm allowed continuous-wave operation with a power of 976 mW at 2085nm and 2109 nm. The slope efficiency (with respect to the absorbed pump power) was 50.1%. Further research will aim to improve the laser performances and explore the possibility of achieving ultrashort pulse generation at ~2 µm.

Achieving thermal stability in 2-µm emitting single-doped Tm^{3+} lasers present a significant challenge due to photon de-excitation caused by the ground-state reabsorption (GSRA) effect. To precisely quantify the thermal power within a gain medium, Li et al. developed a thermal conversion coefficient model by incorporating GSRA into the rate equations [4]. Theoretical modeling has demonstrated that GSRA leads to a reduction in the pump power range within which the laser can operate. To validate the model's applicability, extensive experiments were conducted on a Tm:YAP laser pumped at 795 nm using a fiber-coupled semiconductor laser. This model is expected to contribute to the design of resonators that enhance laser performance at 2 µm while improving thermal stability.

Waveguide lasers allow for high (near unit) mode-matching between the laser and pump beams, resulting in laser emission at a low threshold and good slope of efficiency; this geometry allows for very compact laser resonators. Using direct writing with femtosecond (fs) laser beams, a technique intensively applied in recent years, different waveguide geometries can be realized in a wide variety of laser active media. A paper by Kim et al. discusses the fabrication of a double-track waveguide in Yb:CaF_2 using direct writing with a fs-laser beam [5]. The successful operation of this waveguide is demonstrated in both Q-switched mode-locked (QSML) and continuous-wave mode-locked (CWML) regimes. The pump is done with a tapered diode amplifier, with an emission at 979.4 nm for good absorption in the waveguide. A semiconductor saturable absorber output coupler was used for mode-locking. QSWL operating regime at 1047 nm with 65 kHz repetition rate and pulse duration of 3 µs was obtained. Furthermore, in the CWML regime, the device yielded pulses at 1036 nm with 979 fs duration at 298 MHz repetition rate. Maximum output power was 51 mW in both operation modes.

Using the fs-laser direct writing method, Sun et al. have realized in Nd:YAG a semi-tapered depressed-cladding waveguide of tubular shape [6]. A Sb_2Te_3 thin film as a saturable absorber was used to develop a stable Q-switch vortex laser. Depending on the pump power level (which was done at 808 nm with a Ti:sapphire laser), laser pulses with durations between 54.7 ns and 18.9 ns were obtained, the repetition rate increasing from 21.7 kHz to 103.6 kHz. This method of generating vortex laser beams may lead to the realization of on-chip integrated pulsed lasers.

The characteristics of the first deep-red europium planar waveguide laser were described by Baillard et al. [7]. Liquid phase epitaxy was employed to obtain 100-µm thick heavily-doped 11.5-at.% Eu:$KY(WO_4)_2$ layers on undoped bulk $KY(WO_4)_2$ substrates, using $K_2W_2O_7$ as a solvent; by polishing at laser-grade quality, the thickness of the layer has been reduced to 30 µm. The principal refractive indices of both the undoped substrate and Eu^{3+}-doped epitaxial layer were measured. Confocal laser microscopy was employed to investigate the layer morphology. Polarized absorption spectra in the blue-green spectral range and luminescence spectra in the visible spectral range of Eu^{3+} ions in the grown epitaxial layers were determined. The Eu waveguide was pumped at 532 nm and delivered a maximum output power of 7 mW at 704.7 nm for an absorbed pump power of around 100 mW; the slope efficiency was 9.5%, while the threshold absorbed pump power amounted to 21 mW. The measurements indicated low propagation losses (0.05 dB/cm) in the deep-red spectrum (at 704.7 nm) of the waveguide. Power

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scaling and improvement of the efficiency for this kind of waveguide as well as the manufacturing of ridge-type waveguides, through high-precision mechanical processing, are objectives that will be considered in future investigations.

Kifle et al. have achieved a significant milestone in the advancement of visible fluoride fiber lasers through the use of a Pr:ZBLAN fluoride double-clad fiber [8]. Specifically, a 0.8 mol% PrF_3-doped ZBLAN fiber, featuring a 7.5-μm core diameter and a length of 4.7 m, was pumped using a high-power fiber-coupled GaN laser module emitting at 442 nm. The Pr-fiber laser system demonstrated an output power of 9.1 W at 635 nm in continuous-wave (CW) operation for a launched pump power of 35.9 W, yielding an overall optical-to-optical efficiency of 25.3% and a slope efficiency of 27%. When operating the pump diode in quasi-CW mode (with a duty cycle of 1:2), the system achieved a peak output power of 10.32 W at 635 nm for a launched pump power of 41.3 W, resulting in an overall efficiency of 25.0%; the slope efficiency amounted to 26.2%. A temperature-dependent spectroscopic analysis of Pr^{3+} ions in ZBLAN was conducted, demonstrating the capability of these glasses to maintain their spectroscopic properties up to 200°C, thereby enabling low-threshold laser operation. Additionally, strategies for further power scaling are explored.

Various laser systems have been used to study, in the last decade, the ignition of different fuel mixtures. This method of ignition is being investigated to improve combustion, which is the main process for obtaining energy for humanity, but which also pollutes and generates greenhouse gas emissions with negative influences on the environment. Grigore and Pavel [9] used a compact, spark-plug-like Nd:YAG/Cr^{4+}:YAG laser to study laser ignition (LI) of H_2/air mixtures in a constant-volume combustion chamber (CVCC). LI was performed at a single point, using a single laser pulse, but also operating the laser in pulse-burst mode with trains of up to five pulses. The experiments were performed at room temperature, with H_2/air mixtures having a relative equivalence ratio, λ in the range of 1.5 - 5.0 and up to an initial pressure of 9 bar in the CVCC. It was found that pulse-burst mode LI does not significantly influence the maximum pressure compared to single-pulse LI, but reduces the total combustion time, especially for lean ($\lambda>4.0$) H_2/air mixtures. Lean ignition limits were determined, noting differences between them, depending on the initial pressure, by using single pulse and pulse-burst LI. The results may be useful for using H_2 in internal combustion engines.

The development of the HiPoLas laser ignition system, with emphasis on the recent V generation of this device, is discussed by Kroupa et al. [10]. The results obtained in 10 years of investigations in the field of rocket engine LI are mentioned and the recent efforts made to achieve a fiber-distribution prototype based on diffractive optical elements are discussed. Tests performed on different combustor types and various propellant mixtures are described, as well as considering full-scale rocket engines under flight-like conditions. The technology is now prepared to pass flight certification tests, with a first flight using this type of laser ignition expected in the coming years. The possibility of using multimode optical fibers with a large cladding-to-core ratio for spatial beam division in the ignition of rocket engines was investigated by Tabakaev et al. [11]. In the experiments, the beam delivered by a compact Hipolas Gen V laser (40-mJ maximum pulse energy, 2-ns duration, 1064-nm wavelength) was coupled to such fibers with different characteristics. A fiber coupling efficiency of nearly 100% and pulse energy of 16.6 mJ was transmitted through a 2 m long fiber (this one with 400-μm diameter core and 720-μm cladding) which was bent even at a radius of 0.15 m. Damages of the fiber ends were not observed after 100 laser pulses. Additional experiments concluded that multimode interference within the fiber is the primary contributor to fiber damage. These results are expected to be useful in laser systems for rocket engines, by reducing their cost and complexity, but also in other areas, such as laser-induced breakdown spectroscopy or laser material processing.

Many scientific applications, including coherent control of matter, the development of compact accelerators and table-top x-rays sources, or the building of ultrafast electron-diffraction

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instruments, require the use of high-energy THz radiation. To create energetic sources of THz radiation, one can increase the fluence of the drive-laser source, while optimizing the phase-matching process in the nonlinear crystal by fine-tuning the spectral, temporal, and spatial properties of the laser pulses. In addition, increasing the aperture of the nonlinear medium allows the accommodation of high-energy laser pulses, allowing for scaling of the nonlinear process. Matlis et al. report results on high-energy THz generation using large aperture periodically-poled, MgO-doped $LiNbO_3$ (LA-MgO:PPLN), realized as voltage-poled bulk, but also as in-house assembled, manually-poled wafer-stack structures [12]. THz pulses with over 100 µJ energy were obtained from a large aperture (10×15 mm^2 area) voltage-poled LA-MgO:PPLN, this being a record for this technique. Cryogenic cooling was implemented, for the first time, to obtain manually-poled wafer-stack MgO-doped $LiNbO_3$ devices, thus reducing THz absorption for larger stacks. Potassium titanyl phosphate (KTP) was considered as an alternative material, as it has a high-damage threshold; thus, manually-poled wafer stacks of KTP were tested. The experiments yielded THz pulses with 207 µJ energy from wafer-stacked MgO-doped $LiNbO_3$ and with energies up to 125 µJ in wafer-stacked KTP. The advantages and disadvantages of both large-aperture approaches are discussed and directions for future experiments are proposed.

The transmission spectra in the vacuum-ultraviolet and mid-infrared regions for quartz were investigated by Ishizuki and Taira [13]. Quasi-phase-matched (QPM) quartz structures were constructed by a multi-stacking technique and ultraviolet laser emission at 266 nm was demonstrated using the pump at 532 nm with pulses of 0.5 ns duration. The aim is to obtain QPM quartz by the multi-stacking method that would be useful for generating THz radiation under intense laser pumping.

Tetrahydrofuran (THF) is a colorless and readily volatile organic solvent, used in the production of resins, adhesives or detergents, for various coatings, or as battery electrolytes. Xu et al. used Raman spectroscopy and a two-dimensional correlation Raman analysis to investigate three distinct bonding states in THF-water solutions of different concentrations [14]. A discussion on the changes in bond length and angles is made based on density functional theory. The results are helpful for the development of new applications of THF-water solutions, of interest for scientific studies or in various other fields.

De Vito et al. conducted a detailed study of laser-induced damage in antireflection (AR) coated, large aperture Yb:YAG ceramic media using nanosecond pulses [15]. They used S-on-1 and raster scan testing techniques to evaluate the laser-induced damage threshold of various AR coatings on several Yb:YAG substrates. The study found that a coating's survival in an ex-situ raster scan at 5 J/cm^2 fluence correlated with long-term survival in DiPOLE (Diode Pumped Optical Laser for Experiments) amplifiers at fluences up to 3 J/cm^2. The results are valuable for designing compact amplifier systems capable of operating at high fluence levels.

The management of heat generation within laser gain media is essential for the designing and successful realization of high-intensity laser systems. In this process, a thorough understanding of the laser medium's thermal parameters is of paramount importance. In addition, because a laser can be operated at different temperatures, the way these parameters vary with temperature must be evaluated and used appropriately to obtain the expected laser performance. Sato et al. measured the linear thermal expansion, the change of optical path length and the thermal diffusivity of undoped $Y_3Al_5O_{12}$ (YAG) single crystal and ceramics over a wide temperature range, 160 K to 500 K [16]. Several thermal properties of YAG, such as the thermal conductivity κ, the linear thermal expansion coefficient α, the temperature coefficient of refractive index dn/dT, the thermal diffusivity D, and the specific heat C_p were tabulated. In addition, numerical expressions for these parameters have been proposed for the studied temperature range. The following studies aim to clarify the dependence of Nd-doping concentration on these parameters, both for single crystal and ceramic Nd:YAG, thus providing a fairly powerful tool for laser design.

Nd^{3+}:YVO_4 is a well-established laser medium, known for its favorable spectroscopic and optical properties, including a high absorption cross-section, broad optical transparency across the 400-5000 nm spectral range, a large effective emission cross-section, and polarized emission. These characteristics make it suitable for the development of microchip lasers. However, the conventional single-crystal growth methods for producing high-quality, large-sized Nd:YVO_4 crystals are typically complex, difficult to control, and costly. As a result, ceramic processing methods are being explored as an alternative approach to fabricate transparent Nd:YVO_4 laser media in larger dimensions. In the case of non-cubic crystal ceramics, which exhibit birefringent scattering at grain boundaries, magnetic field alignment techniques are widely utilized to control crystallographic orientation. Liu et al. employed a colloidal processing technique, based on electrostatic repulsion and/or steric stabilization, to prepare a highly stable and well-dispersed YVO_4 nano-powder slurry [17]. This was subsequently used to form a textured YVO_4 green body via slip casting under the influence of a magnetic field. The green body was then sintered using the spark plasma sintering method. Optical characterization of the resulting ceramics revealed that transmittance was significantly enhanced through microstructural control enabled by this texturing approach. The study concluded that this method is also applicable to the orientation control of Nd-doped YVO_4 ceramics, which will be the subject of future investigations.

The devastating earthquake of March 2011, which struck Japan's east coast and resulted in a major accident at Fukushima Daiichi Nuclear Power Station (FDNPS), remains a tragic and unforgettable event. For safety, inspections that provide information about the composition of nuclear elements and their distribution at damaged FDNPS reactors must be done remotely, for example using a robotic arm. Batsaikhan et al. present the effort made to develop a device that includes a laser microchip coupled to a long (>100 m) fiber-optic cable (FOC), of interest for laser-induced breakdown spectroscopy (LISB) investigation of nuclear fuel debris [18]. The influence of gamma radiation dose on the transmission in the visible and near-infrared (NIR) spectra for FOC with different lengths is investigated. It is shown that FOC with high-OH groups have higher transmission in a high-radiance environment, compared to FOC with low-OH groups. It was estimated that a FOC with a length even of 870 m ensures good transmission of the Nd:YAG/Cr^{4+}:YAG laser radiation (1064 nm wavelength, duration of 800 ps) used in the experiments. Analysis of Gd in some mixed oxide samples was done for high-OH FOC of different lengths. A microchip laser-induced breakdown spectroscopy (FC AW-mLIBS) system coupled to a 200-m-long high-OH FOC allowed the identification of Gd lines in the visible spectrum. Qualitative and quantitative analysis were conducted in the NIR spectrum using FOC with lengths greater than 200 m length, showing no transmission losses over an extended period.

We hope that readers will find these articles interesting and are confident that fundamental research and societal applications in the field of solid-state lasers will continue with outstanding results, some of which may be presented at the TILA-LIC 2025 conference, 23 - 25 April 2025 in Pacifico Yokohama, Yokohama, Japan. We would like to thank all the authors and show our gratitude to the reviewers for their valuable efforts that led to the publication of this issue. We are also grateful to Mrs. Kelly Cohen and Mrs. Carmelita Washington from the Optica staff for the exceptional support through the launch of this feature issue, as well as in the review and production processes.

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