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To cite this version:

Carlota Canalias, Sergey Mirov, Takunori Taira, Benoit Boulanger. Feature issue introduction: shaping and patterning crystals for optics. Optical Materials Express, 2017, 7 (9), pp.3466-3470. 10.1364/OME.7.003466 . hal-01707174

HAL Id: hal-01707174

https://hal.science/hal-01707174v1

Submitted on 12 Feb 2018

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Introduction | Vol. 7, No. 9 | 1 Sep 2017 | OPTICAL MATERIALS EXPRESS 3466

Optical Materials EXPRESS

Feature issue introduction: shaping and patterning crystals for optics

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Abstract: Shaping and patterning of bulk or thin layer crystals and ceramics are one of the new frontiers in the field of laser and nonlinear optics. These technical aspects are rarely published, but they are crucial for the fundamental studies as well as for technology and applications. This special issue features 15 articles that focus on the orienting, cutting, polishing, coating, bonding, writing guides, or poling crystals and ceramics for bulk- or micro-optics. We have here a corpus of contributions describing the techniques as well as the gain they bring in terms of functionality or performance of the fabricated components devoted to optics and photonics.

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OCIS codes: (130.3120) Integrated optics devices; (140.3615) Lasers, ytterbium; (230.1480) Bragg reflectors; (140.3570) Lasers, single-mode; (140.3380) Laser materials; (220.1920) Diamond machining; (140.3580) Lasers, solid-state; (140.3530) Lasers, neodymium; (140.3540) Lasers, Q-switched; (230.7380) Waveguides, channeled; (130.3990) Micro-optical devices; (190.7110) Ultrafast nonlinear optics; (230.4000) Microstructure fabrication; (140.3390) Laser materials processing ; (230.7370) Waveguides; (160.0160) Materials; (160.4670) Optical materials; (140.0140) Lasers and laser optics; (140.3070) Infrared and far-infrared lasers; (160.6000) Semiconductor materials; (190.0190) Nonlinear optics; (310.0310) Thin films; (090.0090) Holography; (230.5298) Photonic crystals; (190.0190) Nonlinear optics; (190.4410) Nonlinear optics, parametric processes; (160.2260) Ferroelectrics; (140.7090) Ultrafast lasers; (140.5680) Rare earth and transition metal solid-state lasers; (220.4241) Nanostructure fabrication; (140.5960) Semiconductor lasers; (250.5230) Photoluminescence; (260.1180) Crystal optics; (190.4400) Nonlinear optics, materials.

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#306079 https://doi.org/10.1364/OME.7.003466
Journal © 2017 Received 30 Aug 2017; published 1 Sep 2017

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Crystals are fantastic media exhibiting intrinsic laser and nonlinear properties at the root of many aspects of classical and quantum optics, leading to a huge panel of applications in both fundamental science and technology. Looking for new crystals or ceramics, improving their quality by optimizing the growth process are necessary but not sufficient for pushing the limits of performance. The expression and optimization of the optical properties also depend on the shape of the crystal, on patterns that can be inscribed at the micrometer scale of the surface or of the bulk, as well as on the grain size of ceramic media. These considerations also apply for the measurement techniques of optical properties with the target of increasing the accuracy. The 15 articles of this feature issue address these various aspects showing unexpected performances reached using recent shaping and patterning techniques.

Femtosecond (fs) lasers have open the door to new ways for the fabrication of waveguides. Calmano *et al.* presented highly efficient high power single longitudinal mode waveguide lasers achieved by combining a tapered waveguide Bragg grating with a Yb:YAG crystalline waveguide laser in a hybrid approach. Both structures were fabricated by fs-laser writing. They achieved 1.59 W of output power in a single longitudinal mode and 4.71 W of output power with a spectral bandwidth of 38 pm. The slope efficiency was 66% and the laser threshold 92 mW [1]. The paper of Waeselmann *et al.* described a continuous wave laser activity in neodymium-doped sapphire ridge waveguides. The ridges were prepared using diamond blade dicing of thin Nd^{3+}: sapphire films grown on sapphire substrates by pulsed laser deposition. Lasing was realized at wavelengths of 1092 nm and 1097 nm for ridge waveguide orientations addressing the σ- and π-polarization, respectively. A maximum slope efficiency with respect to incident pump power of 12% was achieved in σ-polarization with a ridge cross section of $40.8 \times 2.6\ \mu m^2$ and a ridge length of 8 mm. With an available incident pump power of 2.8 W from a Ti:sapphire laser, a maximum output power of 322 mW was realized [2]. Croitoru *et al.* inscribed circular, buried depressed-cladding waveguides by direct fs-laser beam writing in diffusion-bonded Nd:YAG/Cr^{4+}:YAG composite media. Passive Q-switch operation was achieved using the pump at 807 nm with a fiber-coupled diode laser. Laser pulses at 1.06 μm with energy of 15.7 μJ and 3.9-ns duration were obtained from a waveguide of 150-μm diameter that was realized in a 10.3-mm long, 1.0-at.% Nd:YAG/Cr^{4+}:YAG composite medium. The length of Nd:YAG crystal was 7.0 mm and initial transmission of Cr^{4+}:YAG saturable absorber crystal was 0.70. The average output power reached 1.13 W [3]. The transformation from $Y_3Al_5O_{12}$ to perovskite $YAlO_3$ crystal phase was observed during ultrafast laser writing in the bulk of $Y_3Al_5O_{12}$ single crystal by Okhrimchuk *et al.* [4]. The control of the phase transformation was demonstrated by tuning the parameters of laser writing. The phenomenon is interpreted in terms of structural changes in the overheated garnet melt under laser heating followed by rapid solidification, and at least 1-ms dwell time of overheated melt is required to start spontaneous crystallization. The

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appearance of the perovskite phase was confirmed by Raman spectroscopy, quantitative phase and polarization microscopies [4].

Surface relief microstructures are efficient for reducing external reflections, as shown by Hobbs *et al.* [5]. An expanded study has been completed of the pulsed and continuous wave (CW) laser induced damage threshold (LiDT) of surface relief anti-reflection (AR) microstructure (ARMs) etched in zinc selenide (ZnSe) crystals and chromium-ion-doped (Cr:ZnSe) laser gain media. In multiple-sample *per* variant testing at wavelengths of 2095 and 2940 nm, the pulsed laser damage resistance of ARMs textured ZnSe crystals was found to be equivalent to untreated, as-polished crystals, with an LiDT as much as 5 times that of thin-film AR coated ZnSe crystals. Similar results were found for Cr:ZnSe crystals tested at 2940 nm, but mixed results were found for pulse testing at 2095 nm. In accumulated power CW damage testing at a wavelength of 1908 nm, neither untreated nor ARMs treated ZnSe crystals could be damaged after long duration exposures at a maximum system intensity of 28.6 MW/cm^2, a value many times higher than typically found with thin-film AR coated ZnSe. For Cr:ZnSe gain media, the CW LiDT was observed to be dependent on the focused beam size at the sample surface, with thresholds for untreated and ARMs-treated Cr:ZnSe being nearly equivalent, ranging from 0.6 MW/cm^2 for the largest spot size, to 2.1 MW/cm^2 for a spot area 4 times smaller. An operational laser test was performed where an ARMs textured Cr:ZnSe crystal operated with higher slope efficiency and 1.5 times the output of a thin-film AR coated crystal in an identical resonator configuration [5].

Sticking by diffusion bonding or optical contact is now a days well mastered. Li *et al.* explained that bonds established with Onyx's adhesive-free bonding (AFB) technique between optical materials, such as trivalent rare-earth ion doped YAG, un-doped YAG, or sapphire, rely on Van der Waals forces. They applied the AFB technique to fabricate true crystalline fiber waveguides for high power, high beam quality laser emission, and walk-off compensated nonlinear crystal stacks for high efficiency, high beam quality optical nonlinear conversion [6]. Stenhouse *et al.* report direct bonding of 5mmΦ x 500µm thick polycrystalline CVD-grown diamond to 25mmΦ x 4mm ZnSe *via* a plasma-assisted technique. In addition, diamond to C-cut sapphire bonding is demonstrated using the same approach. Durability of the diamond/ZnSe bond is tested over a temperature range – 40 °C to 150 °C and under various ramp rates, demonstrating strong adhesion over the majority of the bond up to a temperature of 80 °C. Optical transmission at a wavelength of 1µm shows near ideal transmission when compared to bare ZnSe. Heatspreading performance of the bonded composite is investigated using a pump-probe arrangement, demonstrating at least two-orders of magnitude reduction in the thermal-lens power compared to ZnSe alone [7]. Zheng *et al.* showed shape design of sapphire/Nd^{3+}:YAG based distributed face cooling (DFC) chip with reduction of thermal effects as compared with those from a conventional Nd^{3+}:YAG chip. The CW diode laser pumped round-trip cavity loss was 0.51% from a 9-disk bonded DFC chip, which was close to the theoretically calculated total Fresnel reflection loss of 0.2% from 8 Sapphire/Nd^{3+}:YAG interfaces. The depolarization ratio from an 8-disk bonded DFC chip was 40 times lower than that from YAG/Nd^{3+}:YAG chip. The DFC chip underwent no crack at pump power of 86 W while Nd^{3+}:YAG single chip suffered crystal crack under pump power around 54 W. Over megawatt peak power from DFC tiny integrated laser is demonstrated at 1 kHz with 3-pulse burst modes. It is concluded that DFC structure could relieve thermal effects as expected [8].

Quasi-phase-matching led to a revolution in nonlinear optics. Roux *et al.* designed and demonstrated newcomers in the field of frequency down-converters based on quasi-phase matching. It dealt to low-loss orientation-patterned gallium antimonide ridge waveguides suited to parametric conversion from pumping lasers around 2 µm to mid- infrared wavelengths around 4 µm. Thanks to careful control of the epitaxial growth conditions including low N-type doping and to an optimized dry etching process, losses as low as 0.7 dB/cm at 2 µm and 1.1 dB/cm at 4 µm are obtained [9]. Trajtenebrg-Mills *et al.* well

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demonstrated that shaping light in second order nonlinear interaction is a compact way of controlling both shape and frequency of the output, a desirable trait for many different applications such as optical communication, particle manipulation, microscopy, spectroscopy, and quantum information. The use of patterned nonlinear crystals, combining holographic methods with electric field poling, has proven a useful way to create arbitrary one- and two-dimensional shapes, as well as beams that follow curved trajectories. Using structured light as an input beam has also been shown to produce light with special properties, such as vortex beams carrying orbital angular momentum, curved Airy beams, and others [10]. The article of Ayoub *et al.* described the experimental investigation of ferroelectric domains close to the phase transition in a nonlinear photonic crystal exhibiting disordered domain distribution implementing Cerenkov second-harmonic generation. The interplay of domain structures and the second-harmonic signal is studied exemplarily in strontium barium niobate measuring the far-field distribution as well as imaging domain structures microscopically [11]. Vasilyev *et al.* exploited the transition-metal-doped II-VI semiconductors that possess a unique blend of physical, spectroscopic, optical, and technological parameters. These materials enable high power lasers in important middle-infrared range. Furthermore, they combine superb ultra-fast laser capabilities with high nonlinearity and polycrystalline microstructure, which provides random quasi-phase matching. They developed flexible design of femtosecond polycrystalline Cr:ZnS and Cr:ZnSe lasers and amplifiers in the spectral range 2–3 μm. They obtained few-optical cycle pulses with a multi-Watt average power in a very broad range of repetition rates 0.07–1.2 GHz. They also reported on efficient nonlinear frequency conversion directly in the polycrystalline gain elements of ultra-fast lasers and amplifiers including second harmonic generation with sub-Watt power and generation of an octave-spanning middle-infrared supercontinuum [12].

Exotic shapes and geometries of crystals can lead to new metrological and technical achievements. Kodigala *et al.* present two different fabrication approaches for a suspended lasing membrane with intricate sub-micron patterning for an InGaAsP/InP platform. One approach involves a hydrogen silsesquioxane (HSQ) electron beam lithography resist as a dry etch hard mask and another with an added chromium (Cr) hard mask. The Cr hard mask process allows for fine control over patterned dimensions in comparison to the HSQ mask. This is crucial to both membrane stability and device performance. Both approaches are heavily susceptible to dry etch requirements and the etching window used for membrane release. The techniques presented here are of practical interest to the design of membrane based devices with applications in microfluidic biosensors and flexible laser membranes [13]. A simple method to generate second-harmonic conical waves with tunable cone angles (apex angles) only using a cube uniaxial nonlinear crystal is proposed by Li *et al.* [14]. The formation mechanism is based on the birefringence phase-matching among a plane fundamental wave, a spherical fundamental wave, and a conical second-harmonic wave. The cone angle in our demonstration of the method could be continuously adjusted from 0 to 30° by just rotating the crystal, which is the largest reported tunable range. Moreover, a tunable range of 0–68° could be achieved by using several crystals with different cut angles. The polarization and the longitudinal distribution of the generated second-harmonic wave are theoretically analyzed. The measured conversion efficiency was around 7%, and it decreased with the increasing of the cone angle [14]. Bulk crystals cut and polished as spheres or cylinders are unique tools for measuring the angular distribution of any linear or nonlinear optical property as well as for designing widely and continuously tunable parametric devices. In their article, Ménaert *et al.* described the specific techniques of shaping such high quality samples, and their use in methods of optical measurements and devices that they have implemented [15].

We hope that this feature issue will encourage the readers to use and develop the original techniques that are described in this feature issue. Perhaps this issue will also prompt new ideas of shaping and patterning to push the limits of crystals in the framework of photonics in

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the 21st century. We thank all of the authors and reviewers very much for their nice contributions. We also warmly thank the OSA staff for their outstanding work throughout the review and production processes.

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