Focus issue introduction: nonlinear optics

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Abstract: It is now fifty years since the original observation of second harmonic generation ushered in the field of nonlinear optics, close on the heels of the invention of the laser. This feature issue celebrates this anniversary with papers that span the range from new nonlinear optical materials, through the increasingly novel methods that have been developed for phase matching, to emerging areas such as nonlinear metamaterials and plasmonic enhancement of optical properties. It is clear that the next fifty years of nonlinear optics will witness a proliferation of new applications with increasing technological impact.

OCIS codes: (190.0190) Nonlinear optics; (160.4330) Nonlinear optical materials.

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These simultaneous feature issues of *Optics Express* and *Optical Materials Express* are coordinated with the 10th Nonlinear Optics topical meeting that took place 17–22 July 2011 in Kauai, Hawaii, USA. The meeting brought together a diverse group of scientists from around the world who share an interest in the frontiers of research in nonlinear optics. The meeting included a special symposium celebrating the 50th anniversary of the first nonlinear optics experiment demonstrating second-harmonic generation of a ruby laser. The topical meeting attracted 164 participants from 24 different countries. There were 123 oral presentations, including 30 invited papers and 24 poster presentations. Topics discussed at the meeting included nonlinear optical materials, spatial effects in nonlinear optic interactions, applications of nonlinear optics in quantum optics and optical telecommunication, high-field laser systems based on optical parametric chirped-pulse amplification, and nonlinear optical crystals that have been the strength of the NLO meeting, and also included rapidly developing areas such as terahertz generation and nonlinearities, filamentation, plasmonics, quasi-phase matching, and nonlinear nanophotonics.

The special symposium featured six speakers who have made important contributions to the field of nonlinear optics: Steve Harris (Stanford University, "Long and Short Entangled Photons"), Nicolaas Bloembergen (University of Arizona, "The Birth of Nonlinear Optics"), Amnon Yariv (California Institute of Technology, "The Beginnings of Quantum Nonlinear Optics and Phase Conjugate Optics—Answers to Communication Challenges"), Ron Shen (University of California at Berkeley, "Surface Nonlinear Optics"), Robert Byer (Stanford University, "50 Years of Nonlinear Optics, Tunable Sources from OPS to Coherent X-rays") and Gérard Mourou (Ecole Polytechnique, Paris, "Nonlinear Optics from Quartz to Vacuum"). Figure 1 is a picture of the symposium speakers together with the conference chairs.

Fig. 1. Speakers at special symposium celebrating 50 years of nonlinear optics together with conference chairs (from left to right: R. Shen, G. Mourou, S. Cundiff, N. Bloembergen, D. Gauthier, S. Harris, B. Boulanger, A. Yariv, R. Byer, T. Taira, credit: B. Hirsch, OSA).

The idea of creating a feature issue coordinated with the Nonlinear Optics meeting was first put forward by Takunori Taira, who wanted to publicize the 50 year anniversary to the broader optics community and to create a permanent record of the current state of the field. His idea quickly took root with broad support from the other conference organizers and the journal editors. In addition to these coordinated special issues of *Optical Materials Express*

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and *Optics Express*, the December issue of the *Journal of the Optical Society of America B* [1] will feature eight invited review papers on the foundations of nonlinear optics.

The *Optical Materials Express* collection, edited by Yanqing Lu and Robert Norwood, includes four invited papers and six contributed papers from presentations at the NLO 2011 meeting. These papers cover a wide range of recent advances in the NLO community, from the improvement of traditional nonlinear materials to new materials development, and novel phase-matching techniques. At the same time, the emerging area of nanophotonic nonlinear optics is receiving increased attention. For an example of new developments involving existing materials, crystal quartz, the archetypal optical material in which second harmonic generation was first observed is shown by S. Kurimura *et al.* [2] to contain precisely controlled stress-induced periodically twinned structures in which quasi-phase-matched (QPM) 193 nm second harmonic generation (SHG) can be observed. A. Zukauskas *et al.* [3] report that periodically poled KTP/ RKTP crystals with submicrometer domain size have been obtained, enabling unique nonlinear backward SHG and mirrorless optical parametric oscillators (MOPO). Large-aperture axis-slant periodically poled Mg-doped $LiNbO_3$ makes this QPM crystal more suitable for handling high-power/energy lasers, as discussed by H. Ishizuki *et al.*) [4], an increasingly important requirement with the development of fiber lasers and diode lasers of unprecedented power and efficiency. A new single crystal, $PbIn_6Te_{10}$, with excellent transparency from 3 to 25 μm is discussed by S. Avanesov et al. [5], pushing nonlinear optics to the far infrared. In their paper, V. Kemlin *et al.* [6] discuss another recently discovered mid-infrared nonlinear crystal $CdSiP_2$, and the obtained nonlinear optical and refractive index dispersion properties are very helpful for its practical application.

The combination of metamaterials with nonlinear optics can be viewed as a new branch in the evolution of QPM, while at the same time connecting with the emerging field of nanophotonics; appropriately, an overview of various phase-matching solutions in nonlinear metamaterials is presented. Some interesting metamaterial-inspired techniques support a wide range of phase-matching configurations that are impossible to achieve in conventional homogeneous materials, such as described by A. Rose *et al.* [7]. On the other hand, the effort in synthesizing and growing new crystals is always continuing. L. Xu *et al.* [8] report that two-photon absorption for intra-tissue refractive index shaping (IRIS) opens a new window for bio-medical applications by providing much larger refractive index changes than previously observed.

New organic and composite materials for NLO continue to receive attention owing to the exceptionally large microscopic nonlinearities enjoyed by organic chromophores and quantum dots and the ability to combine a deep understanding of the origin of these microscopic nonlinearities with a well-developed theoretical framework for connecting these microscopic nonlinearities to macroscopic NLO properties. A new NLO chromophore for optical limiting, *bis*(terpyridyl)osmium-(porphinato)zinc- *bis*(terpyridyl)osmium, is discussed by Chi *et al.* [9] that exhibits both strong two-photon absorption and excited state absorption in the near infrared (900–1300 nm); when this supermolecule is dissolved and the solution incorporated into a capillary waveguide, orders of magnitude enhancement in the optical limiting efficiency was observed. A novel nonelectric field oriented second-order NLO polymer is presented by Sugita *et al.* [10] that takes advantage of the ferroelectric order present in the host polymer poly (cyanophenlyene sulfide) that allows the standard NLO chromophore Disperse Red 1 to obtain polar order. Given the practical challenges of electric field poling, this is a worthwhile approach toward broadening the applications for second-order NLO polymers. Finally, the subject of plasmonic enhancement of linear and nonlinear optical properties has received great attention over the past decade, since the potential enhancement effects are enormous. Klopfer and Jain [11] present simulation results for the potential enhancement of two-photon absorption induced fluorescence from quantum dots placed at the center of core-shell dielectric/metal plasmonic nanostructures, indicating that optimized nanostructures can enjoy up to five orders of magnitude plasmonic enhancement.

Although the number of published papers in this feature issue is limited, we think they reflect the continued high level of innovation in the field, and certainly it is historically

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evident that new materials hold a special significance in NLO. Optical materials scientists and engineers will continue to pursue new uniform, bulk, stable materials with wide transparency ranges and large nonlinear coefficients, in inorganic, organic, or composite form. It is clear that artificial microphotonic and nanophotonic structures will play increasingly important roles in NLO material development. Intellectually interesting developments such as nonlinear metamaterials have attracted attention that may accelerate their entry into real applications.

The *Optics Express* collection, edited by Magnus Karlsson and Dmitry Skryabin, comprises seven invited and 16 contributed papers divided into six sub-topics, which will be briefly described below. We believe these papers provide an excellent 2011 snapshot of the nonlinear optics research front.

There are five papers within the Lasers, Mode Locking and Parametric Oscillation category. Li *et al.* [12] describes a vector-theory analysis of a novel fiber laser structure and investigates its stability properties. The paper by Fukuchi and Moeda [13] describes a rational-harmonic mode-locked fiber laser based on bismuth-oxide fibers that can operate up to 40 GHz with low supermode noise. Another fiber laser work is that of Renninger *et al.* [14], which demonstrates stable passively mode locked femtosecond pulse generation over a broad parameter regime. A microchip UV laser producing megawatt pulses is demonstrated by Bhandari and Taira [15]. In the paper by Vainio *et al.* [16], the stability properties of a cw parametric oscillator in the 1580 nm regime are investigated.

There are two papers in the Waveguide Arrays category. Eilenberger *et al.* [17] describes light bullet propagation and decay in such arrays, and Setzpfandt *et al.* [18] analyzes dynamics of solitons in second-order arrayed media. Both papers provide comprehensive introductions describing significant recent progress achieved in this active area.

In the area of Frequency Conversion, Combs and Nonlinear Waveguides, there are seven papers. The paper by Yost *et al.* [19] describes spectroscopy based on combs in the soft X-ray (XUV) regime, and the paper by Zhi *et al.* [20] describes combs generated by multiple orders of Raman gain. The Raman effect also is the basis for the work of Ma *et al.* [21], who use specialty fibers to demonstrate a Raman threshold independent of the fiber length. Sum- and difference-frequency generation is used by Leo *et al.* [22] in AlGaAs waveguides based on birefringent phase matching, and by Tehranchi *et al.* [23] for wavelength conversion in gratings. The Cherenkov radiation from optical solitons, which is known to play a significant role in supercontinuum generation in optical fibers, is now used to create mid-infrared radiation around 2 μm generated through the cascaded quadratic nonlinearity in bulk crystals, as demonstrated by Bache *et al.* [24]. In a comprehensive paper by Seaberg *et al.* [25], X-ray imaging with a record resolution of 22 nm is demonstrated.

In the area of Nonlinear Absorption and Dispersion, two-photon absorption is characterized by Cirloganu *et al.* [26] for direct bandgap materials and by Pouget *et al.* [27] in silicon. Wahlstrand *et al.* [28] describe theoretically and experimentally how a static field can be used to control the generated photocarriers in GaAs. Stegeman *et al.* [29] describe a novel theoretical model for nonlinear dispersion in centrosymmetric media.

There are two papers related to Terahertz Generation. First, Li *et al.* [30] who describe the use of a mirror and a NiO slab to improve the extraction of THz radiation. Second, is the paper by Hayashi *et al.* [31], demonstrating terahertz pulse generation with peak powers exceeding 100 W.

Finally there are three papers dealing with Nonlinear Materials and Spectroscopy. The paper by Du *et al.* [32] is based on ultrafast spectroscopy to characterize chlorophyll molecules. Lim *et al.* [33] uses second harmonic generation to measure the thermal properties of the nonlinear material. Greenberg *et al.* [34] observes a strong, fifth-order nonlinearity in clouds of cold atoms.

We believe these contributions effectively represent the diverse research area that nonlinear optics has transformed into, spanning from novel nonlinear-physics concepts and models to very applied work within spectroscopy or telecommunications. Emerging areas such as biophotonics and terahertz technology are represented as well, and we hope that this

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feature issue will be of interest to a wide range of researchers in this rapidly expanding area of optics.

It is our great pleasure to introduce this feature issue during the 50th anniversary year of nonlinear optics. Half a century ago NLO was entirely in the realm of fundamental research, with applications only possible in the dreams of researchers. Today, numerous high-performance NLO materials have been developed and find application in everyday devices such as laser pointers and throughout the laser industry. Various phase-matching approaches have been proposed and demonstrated, resulting in dramatic increases in nonlinear conversion efficiency and wavelength range. We believe NLO materials are likely to enjoy both increased prevalence and more sophisticated use throughout a broad range of scientific disciplines and industry applications. We appreciate the outstanding work of all the contributors to this special issue and highly encourage the readers of this issue to continue to develop novel theoretical, experimental, and engineering approaches in this exciting and ever changing field.

We would like to extend our sincerest thanks to all reviewers and authors for their efforts in improving the manuscripts during the review process. Our appreciation to David Hagan and C. Martijn de Sterke, Editors of *Optical Materials Express* and *Optics Express*, for their generous support of publishing coordinated feature issues. Finally, we wish to thank the journal staff, in particular Marcia Witherspoon, Meghan Cook, Monica Payne, and Theresa Miller, for their excellent support during the production of this feature.

NLO 2011 Conference Chairs

Benoît Boulanger, Steven T. Cundiff, Daniel J. Gauthier, and Takunori Taira

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