CUDOS

The Centre for Ultrahigh bandwidth Devices for Optical Systems (CUDOS)

ANNUAL REPORT 2006

Professor Yuri Kivshar

Yuri Kivshar received his PhD in 1984 from the USSR Academy of Science and was at the Institute for Low Temperature Physics and Engineering (Kharkov, Ukraine). From 1988 to 1993 he worked at different research centres in USA, France, Spain, and Germany. In 1993 he accepted an appointment at the Research School of Physical Sciences and Engineering of the Australian National University where presently he is Professor and Head of the Nonlinear Physics Centre. Yuri Kivshar has published more than 350 research papers in peer-reviewed journals including more than 15 book chapters and review articles and 2 books published in 2003 (Academic Press, translated to Russian in 2005) and 2004 (Springer-Verlag). His interests include nonlinear guided waves, optical solitons, nonlinear atom optics, photonic crystals, and stability of nonlinear waves. Professor Yuri Kivshar was a recipient of the Medal and Award of the Ukrainian Academy of Science (1989), the International Pnevmatikos Prize in Nonlinear Physics (1995), the Pawsey Medal of the Australian Academy of Science (1998). In 1999 he was appointed as an Associate Editor of the Physical Review (first Australian), and in 2002 he was elected to the Australian Academy of Science. He is a Fellow of the Optical Society of America and the American Physical Society.

Key areas of research contribution within the Centre

Nonlinear optics, fiber optics, nanophotonics, photonic crystals, parametric processes and frequency conversion, all-optical devices and technologies.

Roles and Responsibilities in Centre

Deputy Director, CUDOS; Director, ANU node.

Awards, honours, major international visits

His recent awards include the Boas Medal of the Australian Institute of Physics (2006) and the Lyle Medal of the Australian Academy of Sciences (2007).

In 2006 he visited more than 20 research laboratories including the University of Jena (Jena, Germany), the Max-Born Institute (Bonn, Germany), Max-Plank Research Group in Photonics (Erlangen, Germany), Electro-technical University (Tokyo, Japan), University of Osaka (Osaka, Japan), National Taiwan University (Taiwan), and many others.

Key areas of research activity

Yuri Kivshar leads several research projects within the CUDOS program and is Deputy Director of the Centre. His main research activity aims to develop innovative concepts of all-optical communication and information technologies and to carry out both theoretical and experimental studies on the photonic-crystal physics and engineering, optical solitons, and microphotonic nonlinear switching devices in order to promote the new field of photonic crystals, to enhance its development in Australia and provide linkages between leading edge R&D and industry in an important emerging technology. His current research activities, which fit within two CUDOS Flagship projects Slow Light and Tunable Microphotonics, involve the studies of spatiotemporal dynamics of light propagation, nonlinear interaction and control of light in periodic photonic structures, and theoretical studies of photonic crystals and related devices.

Research achievements during 2006

Slow-light optical bullets in nonlinear Bragg-grating waveguide arrays

We demonstrated that propagation direction and velocity of optical pulses can be controlled independently in structures with multiscale modulation of the refractive index in transverse and longitudinal directions. We revealed that, in arrays of waveguides with phase-shifted Bragg gratings, the refraction angle does not depend on the speed of light, allowing for efficient spatial steering of slow light. In this system, both spatial diffraction and temporal dispersion can be designed independently, and we identified the possibility for self-collimation of slow light when spatial diffraction is suppressed for certain propagation directions. We also showed that broadening of pulses in space and time can be eliminated in nonlinear media, supporting the formation of slow-light optical bullets that remain localized irrespective of propagation direction [Sukhorukov AA, Kivshar YS, PHYSICAL REVIEW LETTERS 97, 233901 (2006)].

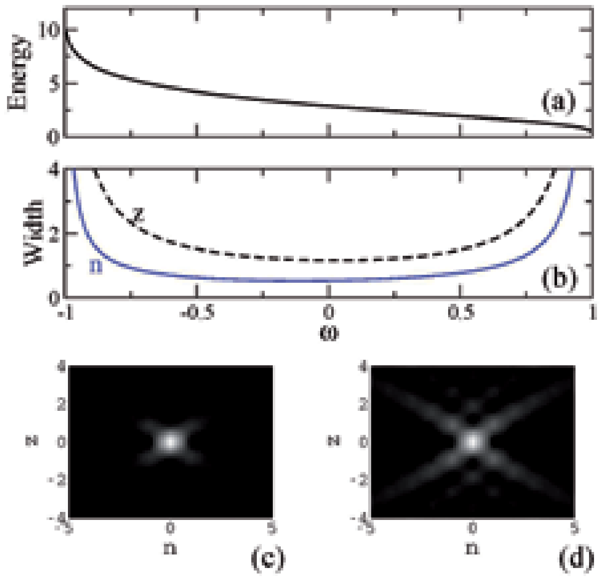


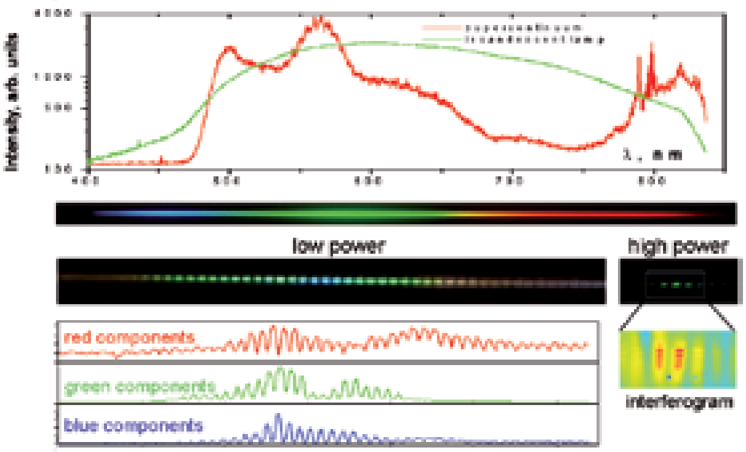
Figure 1. Family of the light bullets characterized by (a) energy and (b) width along the transverse (solid) and longitudinal (dashed) directions vs. the frequency tuning inside the spectral gap. (c-d) Intensity profiles of two examples of slow-light optical bullets.

All-optical switching, bistability, and slow-light transmission in photonic crystal waveguide-resonator structures

We analyzed the resonant linear and nonlinear transmission through a photonic crystal waveguide side-coupled to a Kerr-nonlinear photonic crystal resonator. First, we extended the standard coupled-mode theory analysis to photonic crystal structures and obtained explicit analytical expressions for the bistability thresholds and transmission coefficients which provide the basis for a detailed understanding of the possibilities associated with these structures. We found that the discrete nature of the photonic crystal waveguides allows a geometry-driven enhancement of nonlinear effects by shifting the resonator location relative to the waveguide, thus providing an additional control of resonant waveguide transmission and Fano resonances. We further demonstrated that this enhancement may result in the lowering of the bistability threshold and switching power of nonlinear devices by several orders of magnitude. Finally, we showed that employing such enhancements is of paramount importance for the design of all-optical devices based on slow-light photonic crystal waveguides [Mingaleev S et al, PHYSICAL REVIEW E 74, 046603 (2006)].

Polychromatic solitons in nonlinear photonic lattices

We studied dynamical reshaping of polychromatic beams due to collective nonlinear self-action of multiple-frequency components in periodic and semi-infinite photonic lattices and predicted the formation of polychromatic gap solitons and polychromatic surface solitons due to light localization in spectral gaps. We showed that the self-trapping efficiency and structure of emerging polychromatic solitons depends on the input spectrum due to the lattice-enhanced dispersion, including the effect of crossover from localization to diffraction in media with defocusing nonlinearity. We demonstrated that interfaces between two nonlinear periodic photonic lattices offer unique possibilities for controlling the nonlinear interaction between different spectral components of polychromatic light, and a change in the light spectrum can have a dramatic effect on the propagation along the interface. We predicted the existence of polychromatic surface solitons that differ fundamentally from their counterparts in infinite lattices [Motzek K, et al, OPTICS LETTERS 31, 3125 (2006); OPTICS EXPRESS 14, 9873 (2006)].



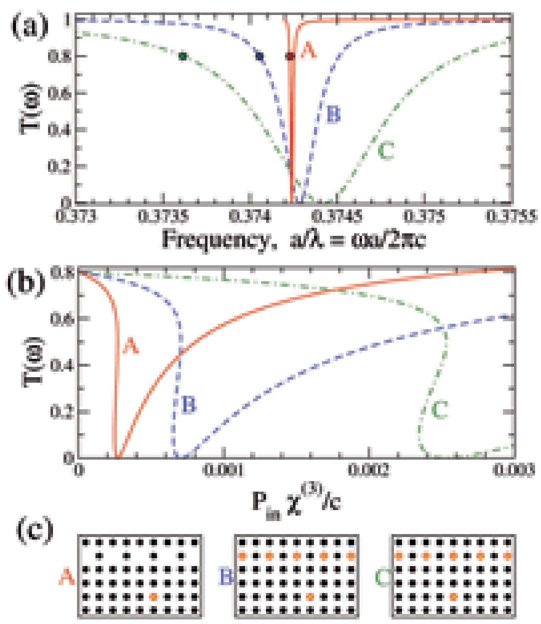
▲ **Figure 2. Generation of a supercontinuum optical gap soliton. Top: spectrum of the generated supercontinuum, compared to the spectrum of white light lamp. Bottom: output intensity distribution for low laser power (left) and high power (right). Bottom right: interferogram demonstrating the staggered localized structure.**

Phase matching and interference of nonlinear parametric processes

In collaboration with the experimental group from the Macquarie University, we demonstrated the simultaneous generation and internal interference of two second-order parametric processes in a single nonlinear quadratic crystal. The two-frequency doubling processes are Type 0 (two extraordinary fundamental waves generate an extraordinary second-harmonic wave) and Type I (two ordinary fundamental waves generate an extraordinary second-harmonic wave) parametric interactions. The phase-matching conditions for both processes are satisfied in a single periodically poled grating in $LiNbO_3$ using quasi-phase-matching (QPM) vectors with different orders. We observed an interference of two processes, and compared the results with the theoretical analysis. We suggested several applications of this effect such as polarization-independent frequency doubling and a method for stabilizing the level of the generated second-harmonic signal [Johnston B, et al., OPTICS EXPRESS 14, 11756 (2006)].

Tunable all-optical switching in periodic structures with liquid-crystal defects

We suggested that tunable orientational nonlinearity of nematic liquid crystals can be employed for all-optical switching in periodic photonic structures with liquid-crystal defects. We considered a one-dimensional periodic structure of Si layers with a local defect created by infiltrating a liquid crystal into a pore, and demonstrated, by solving numerically a system of coupled nonlinear equations for the nematic director and the propagating electric field, that the light-induced Freedericksz transition can lead to a sharp switching and diode operation in the photonic devices [Miroshnichenko A, et al., OPTICS EXPRESS 14, 2839 (2006)].



▲ **Figure 3. Design of a novel type of nonlinear switch. Linear transmission spectrum and nonlinear bistable transmission for three different side-coupled waveguide-resonator photonic-crystal structures. Example A represents a close to optimal structure with inter-site location of the resonator whose resonance frequency lies close to the edge of the passing band. Closed circles indicate frequencies with T=80% that are used for achieving high-contrast bistability in (b). Red circles in (c) indicate positions of the nonlinear polymer rods.**

Zener tunneling in two-dimensional photonic lattices

We discussed the interband light tunneling in a two-dimensional periodic photonic structure, as studied recently in experiments for optically induced photonic lattices. We identified the Zener tunneling regime at the crossing of two Bloch bands, which occurs in the generic case of a Bragg reflection when the Bloch index crosses the edge of the irreducible Brillouin zone. Similarly, higher-order Zener tunneling involves four Bloch bands when the Bloch index passes through a high-symmetry point on the edge of the Brillouin zone. We derived simple analytical models that describe the tunneling effect, and calculated the corresponding tunneling probabilities [Shchesnovich V, et al., PHYSICAL REVIEW E 74, 056602 (2006)].

Broadband diffraction management of white light in photonic lattices

We introduced periodic photonic structures where the strength of diffraction can be managed in a very broad frequency range. We showed how to design arrays of curved waveguides where light beams experience wavelength-independent normal, anomalous, or zero diffraction. Our results suggested opportunities for efficient self-collimation, focusing, and reshaping of beams produced by white-light and supercontinuum sources. We also predicted the possibility of a multicolor Talbot effect, which is not possible in free space or conventional photonic lattices [Garanovich I, et al, PHYSICAL REVIEW E 74, 066609 (2006)],

With Prof. Wieslaw Krolikowski, Yuri Kivshar leads the experimental studies of linear and nonlinear aspects of localization and control of light in periodic photonic structures, including the studies of nonlinear effects in optically-induced and fabricated photonic periodic structures. Some of the major recent highlights of those projects are:

- Experimental studies of photonic Bloch oscillations and for observation of Zener tunnelling of light in two-dimensional periodic optically-induced photonic lattices, supported by an extensive theoretical analysis [Trompeter H, et al., PHYSICAL REVIEW LETTERS 96, 053903 (2006)]
- Observation of reduced-symmetry two-dimensional spatial gap solitons in square optical lattices; the analysis and experimental confirmation of the enhanced mobility of these self-trapped nonlinear modes [Fischer R, et al., PHYSICAL REVIEW LETTERS 96, 023905 (2006)]
- Experimental demonstration of nonlinear surface waves localized at the edge of an array of nonlinear waveguide with the propagation constant within the bandgap; these modes are identified as an nonlinear analogue of optical Tamm states [Rosberg CR, et al., PHYSICAL REVIEW LETTERS 97, 083901 (2006)]

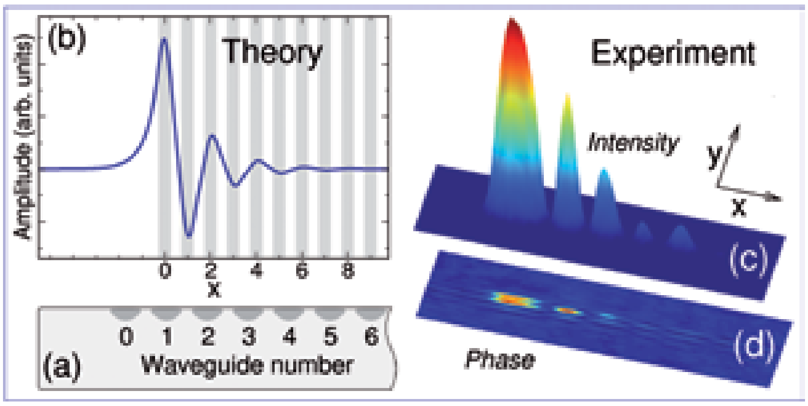


Figure 4. Theoretical prediction (a,b) and experimental observation (c,d) of nonlinear Tamm states in a truncated periodic photonic lattice. (a) Schematic of the waveguide array geometry; (b) theoretical profile of a nonlinear Tamm state-a surface gap soliton, (c) three-dimensional representation of the nonlinear surface state observed experimentally above then localization threshold, (x,y) are the horizontal and vertical sample coordinates, respectively. (d) Experimental plane-wave interferogram demonstrating the staggered phase structure of the nonlinear surface Tamm state. This work has been highlighted in the special issue "Optics in 2006" of the OSA magazine "Optics and Photonics News"

- Observation of linear propagation and nonlinear localization of polychromatic light generated by a supercontinuum source in one-dimensional periodic structures [Sukhorukov A, et al., OPTICS EXPRESS 14, 11265 (2006)].