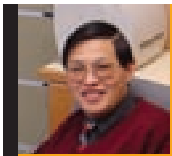
CUDOS

Microphotonics Program

Annual Report 2004

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

An Australian Research Council Centre of Excellence



Program Manager: Min Gu

The objectives of this program are to investigate the physics of nonlinear two and three dimensional photonic crystals and to produce three dimensional photonic crystals with optical characteristics suitable for optical processing applications. The most iconic of these is the demonstration of a "superprism" – a photonic element whose spectral dispersion is many orders of magnitude stronger than that of a normal refractive prism.

The rich vein of physics in nonlinear photonic crystal systems has been mined by Professor Kivshar's group to yield five publications during the year in the prestigious journal Physical Review Letters, a landmark achievement by any standard. The group at Swinburne has continued its experimental program to develop 3D photonic crystals with strong theory support being provided by groups at the ANU, Sydney and UTS.

Min Gu

3-D Photonic Crystals

Project Leader: Min Gu

During 2004 we focused our work on three aspects of 3D photonic crystal production. We implemented a super-resolution optical system that enabled the fabrication of 3-D photonics crystals with bandgaps in the near-infrared wavelength region. We fabricated 3-D photonic crystals by incorporating a liquid crystal doped polymer into void-dot-based 3-D photonic crystals. The crystals can be tuned electrically or optically. Finally, designs for a super prism based on the woodpile geometry were investigated for potential application as a superprism.

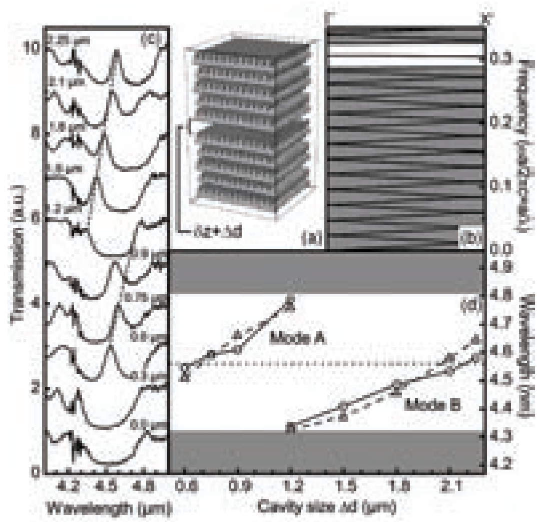
Dr Martin Straub with the equipment used to produce 3D photonic crystals.

Functional 3-D photonic crystals

Ventura, Mathews, Zhou, Straub, Wu, Gu, Wang, Kivshar

One of our milestones during 2004 was the fabrication of 3-D photonic crystals using a void-dot-based technique, which provides a powerful method for introducing point and line defects into 3-D lattice structures. This leads to 3-D photonic crystals with designed cavity modes, an important step towards all-optical processing in a 3D geometry. The 3-D photonic crystals of diamond, face-centred-cubic, and body-centred-cubic lattice structures show bandgaps at various angles of incidence. These were compared with the theoretical prediction from the ANU, in which the in-plane and out-of-plane bandgap properties were characterised. Aaron Mathews studied the effect of the reduced symmetry in the unit-cell geometry on the value of the absolute bandgap and the frequencies of localised defect modes using the Swinburne parameters.

We also fabricated 3-D photonic crystals with embedded planar defects in the middle of a woodpile lattice as an offset in the layer spacing. Cavity modes were observed as a sharp peak in infrared transmission measurements within the bandgap.

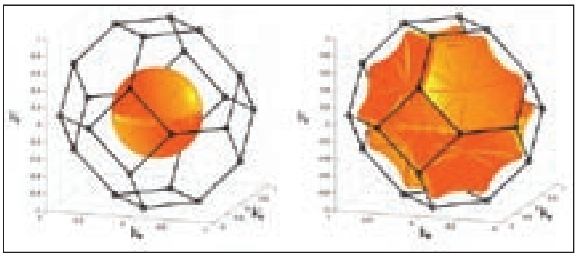


(a) Sketch of a twenty four-layer woodpile structure with a microcavity of size Δd in its centre. (b) Supercell calculation of photonic bands for a structure with a cavity size Δd of 2.1 μm. Shaded regions are frequencies outside the bandgap. The flat band within the bandgap denotes the cavity mode. (c) Infrared transmission spectra in the stacking direction for Δd from 0.3 to 2.25 μm. (d) Variation of experimental (circles) and calculated (triangles) cavity mode wavelengths with the cavity size.

Superprisms

Gu, Serbin, Botten, De Sterke

We investigated the distribution of the electromagnetic field in a superprism to lead to a clear picture of the design approach required to fabricate a super-prism from woodpile 3D photonic crystals. In this three-node collaboration (Swinburne, Sydney, UTS) photonic band structure calculations have shown that



▲ **Calculated iso-energy surfaces for a woodpile structure having a contrast in refractive indices of 1.56 for frequencies far below the bandgap (left image, behaves like a homogeneous medium) and slightly above the bandgap (right image, strong superprism effects).**

there is a strong anisotropy at frequencies slightly above partial bandgap in the (Γ-Z)-direction, leading to strong superprism effects. This becomes clear when investigating the iso-energy surfaces of these structures, which show strong deviation from a spherical shape.

Nonlinear photonic crystals project: Nonlinear localised modes

Project leader: Yuri Kivshar

In this project we study the fundamental physics of non-linear interactions in photonic lattices. These may be induced optically and their effect studied experimentally as well as theoretically.

Yuri Kivshar

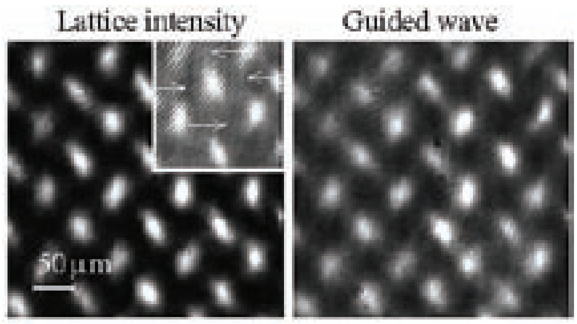
Optically-induced photonic lattices and waveguide arrays

Neshev, Hanna, Krolikowski, Sukhorukov, Desyatnikov, Rosberg, Kivshar

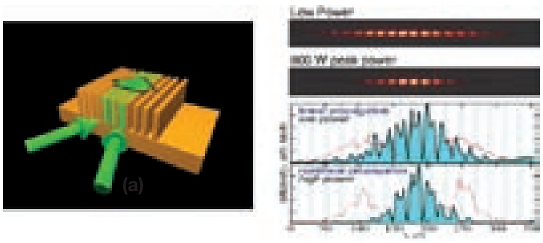
We continued our studies of strong nonlinear effects and gap solitons in optically-induced photonic lattices in photorefractive strontium barium niobate crystals. We demonstrated the engineered generation of spatial gap solitons and their steering, multi-gap mode interaction and coupling, and tunable positive and negative refraction near the spatial Bragg resonance. This project was recently joined by a new PhD student, Mr. Christian Rosberg from Denmark who will continue the studies of nonlinear effects in optically-induced lattices.

We performed theoretical studies of different types of two-dimensional photonic lattices and generated these in experiments, including novel vortex-lattice structures in a photorefractive crystal. We demonstrated that the light-induced periodically modulated nonlinear refractive index is highly anisotropic and nonlocal, and depends on the lattice orientation relative to the crystal axis.

We also analysed the Bloch oscillations in these structures. First, we studied numerically the dynamics of a wide optical beam in an optically induced lattice. In order to induce periodic oscillations of the beam we proposed the use of a spatially varying background illumination. It appears that a gradient in the illumination does induce a transversal oscillation of the beam. We had a first experimental demonstration of this effect.



▲ **Left: Example of a two-dimensional optically-induced photonic lattice with a vortex-like phase structure.
Right: probe beam lattices guided by the photonic structure.**



▲ **(a) Experimental head-on geometry. (b,c) Experimental results for the generation of gap solitons in weakly coupled waveguide arrays and optically-induced photonic lattices. Shown are: (b) photographs of the beams at the array output, and (c) the output beam profiles for light propagating in optically-induced nonlinear lattices, where shading marks the minima of the refractive.**

As the next step, we investigated Bloch oscillations in permanent periodic structures created by Titanium in-diffusion in lithium niobate wafers. First, we conducted numerical simulations of beam propagation in periodic structures with various types of chirps. Simulations show clear oscillations of the beam. In collaboration with the RMIT group of Professor Austin we studied experimental aspects of this effect.

Bloch-wave filtering and gap solitons in low-index photonic lattices

Sukhorukov, Kivshar

We formulated a general approach to engineering all-optical switching in photonic structures with low-index refractive index contrast such as AlGaAs waveguide arrays, optically-induced lattices and polymer photonic crystals. In particular, we suggested a novel approach to the soliton switching in periodic photonic lattices based on the concept of Bloch-wave filtering, when waves of different bandgaps can be selectively reflected or transmitted through an engineered defect, which acts as a low or high-pass filter for Bloch waves. We demonstrated this concept for discrete and gap solitons in binary waveguide arrays.

In collaboration with experimental groups in Israel and Canada, we reported the first experimental observation of discrete gap solitons in binary arrays of optical waveguides. We observed the gap soliton generation when the inclination angle of an input beam is slightly above the Bragg angle, and showed that the propagation direction of the emerging gap soliton depends on the input power as a result of an inter-band momentum exchange.

Nonlinear photonic crystals project: Nonlinear switching

Project leader: Yuri Kivshar

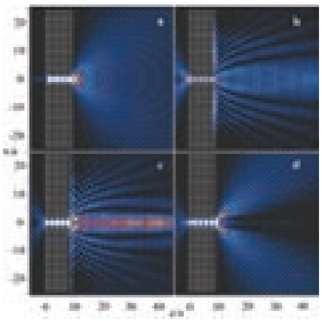
A rich range of nonlinear phenomena occur in photonic crystal waveguides that can lead to optical switching. In this project we study a range of manifestations of these phenomena.

Beaming effect in photonic crystal waveguides

Morrison, Kivshar

We analysed, by extensive FDTD simulations, different ways to enhance the directional emission from photonic crystal waveguides through the recently predicted beaming effect. In particular, we demonstrated that substantial enhancement of the light emission can be achieved by adjusting the input wavelength, using a positive surface corrugation, increasing the refractive index of the surface layer, and inducing a near-surface mode. We also considered the similar effect for the PBG structures created by holes rather than rods and show that these two types of structures demonstrate quite different effects and require different approaches.

Spatial distribution of the Poynting vector for the light emitted from a photonic waveguide: (a) unchanged surface; (b-d) three types of engineered surface.



Spontaneous emission and Lamb shift in photonic crystals

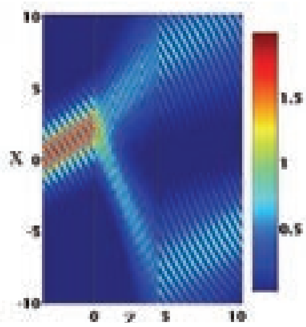
Wang, Kivshar

Motivated by a controversy between several theoretical studies, we developed a universal theoretical approach to study spontaneous emission of atoms in photonic crystals. A position-sensitive generalised Lorentzian formalism for the decay of an excited atom in photonic crystals was derived, and a numerical method for calculating the local coupling strength, proportional to the photonic local density of states, has been presented. For weak interaction with pseudo gaps, the generalised Lorentzian formulism may be reduced to the famous Lorentzian spectrum. In this case, we introduced a lifetime distribution function for an assembly of atoms and found that it depends strongly on the spread configuration of these atoms in space, which successfully clarifies the tremendous discrepancy between different experiments. For the photonic crystals with large full gaps, we found that the atomic position can fundamentally change the decay behavior of an excited atom: in strong interaction positions, the atomic decay is non-classical or exhibits an envelope-damped Rabi oscillation. We also predicted giant Lamb shifts for hydrogen atoms in photonic crystals and revealed that in inhomogeneous electromagnetic environment, the dominant contribution to the Lamb shift comes from real photon emission, while the contribution from emission and re-absorption of virtual photon is negligible.

Wave transmission in materials with negative refraction

Shadrivov, Feise, Kivshar

We analysed transmission of electromagnetic waves through a one-dimensional periodic layered structure consisting of slabs of a left-handed metamaterial and air. We derive the effective parameters of the metamaterial from a microscopic structure of wires and split-ring resonators possessing the left-handed characteristics in the microwave frequency range, and then study, by means of the transfer-matrix approach and the FDTD numerical simulations, the transmission properties of this layered structure in a bandgap associated with the zero averaged refractive index. By introducing defects, the transmission of such a structure can be made tunable, and we study the similarities and differences of the defects modes excited in two types of the bandgaps. We also studied the defect-induced nonlinear transmission in such structures and demonstrated bistable switching and tunable nonlinear transmission in an unconventional bandgap that corresponds to the vanishing average refractive index, and compare the observed effects for two different types of band.



Beam transmission through a slab of the birefringent metamaterial with mixed negative refraction. The TM polarised component experiences negative refraction, while the TE polarised component refracts normally. Coordinates are normalised to the free-space wavelength.

Nonlinear Fano resonances in photonic crystal waveguides

Miroshnichenko, Kivshar

We developed the general theory of linear and nonlinear Fano resonances in photonic crystal waveguides. First we derived an effective discrete model that includes nonlinearity through a discrete defect, the model is similar to the familiar Fano-Anderson model but it includes nonlocal interactions. We showed that in the nonlinear regime the Fano resonance is robust and quite generic, and may lead to bistability. We have applied this theory to the studies of Fano resonance in two-dimensional photonic crystals with high-Q resonators. In the nonlinear regime the discrete defect can be excited affect the transmission. Our analysis shows that the presence of nonlinearity leads to the shift of the position of Fano resonance and the bistability in transmission. We also applied a similar approach in the scattering in quadratic nonlinear waveguide arrays.