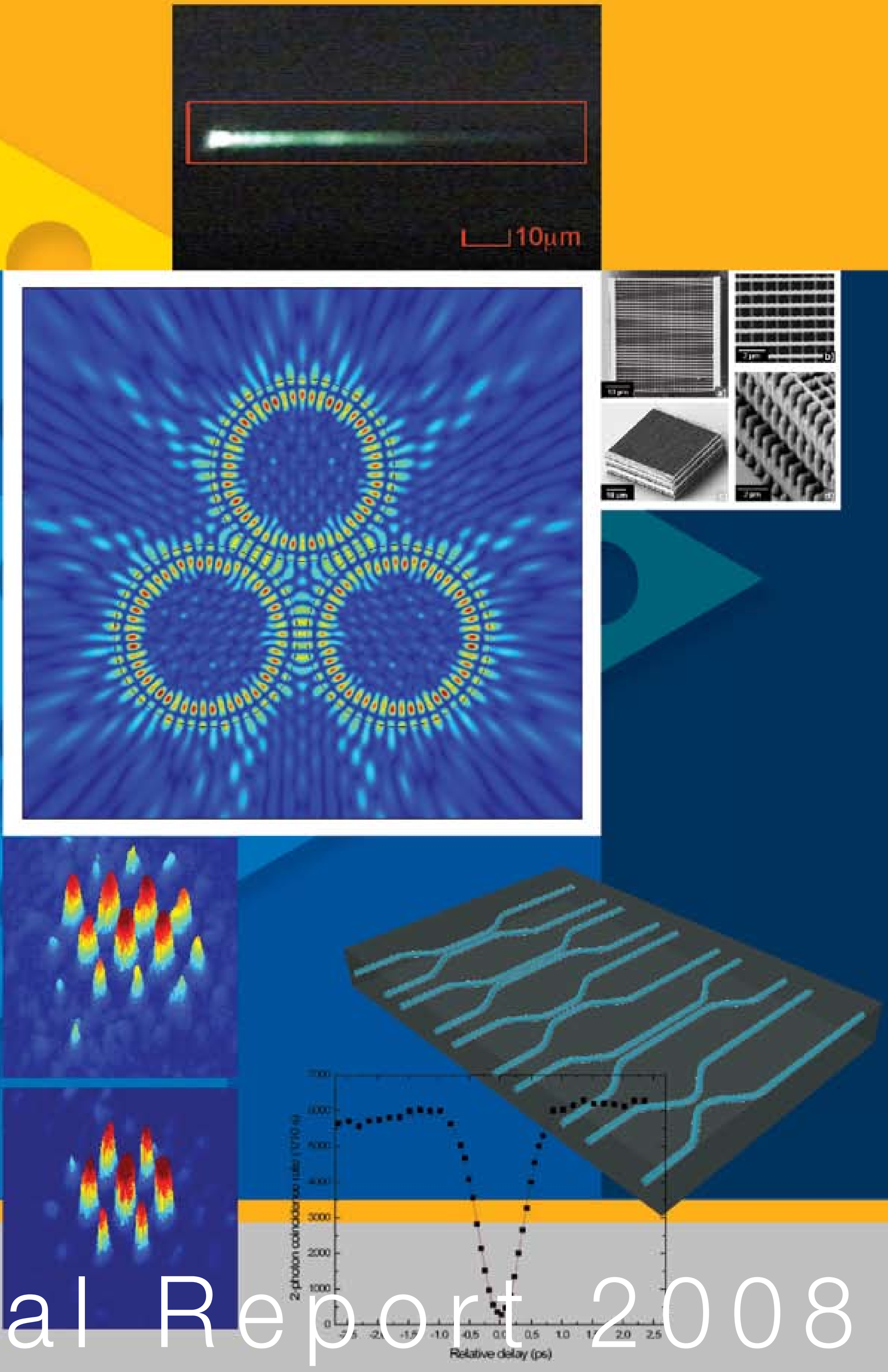
CUDOS

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



Annual Report 2008

Chief Investigator: Lindsay Botten UTS node

CI short biography

Lindsay Botten, a graduate of the University of Tasmania, is the Professor of Applied Mathematics at UTS. During his career, he has made leading contributions in electromagnetic optics in the physical and mathematical understanding of periodic structures including diffraction gratings and photonic crystals. He has in excess of 180 refereed publications and is a Fellow of the Optical Society of America, the Australian Institute of Physics and the Australian Mathematical Society. He has broad expertise in a range of mathematical and computational techniques in electromagnetic theory, and a particular specialisation in the development of semi-analytic tools for modeling propagation and radiation dynamics phenomena based on Bloch mode, multipole and eigenfunction methods, for which he is internationally recognized. He has a strong background in scientific computing and computational mathematics and physics and is a national leader in the Australian advanced computing community through his work over some years as University Services Director of ac3 (Australian Centre for Advanced Computing and Communications), as a Director of APAC (Australian Partnership for Advanced Computing), and through his leadership of the acquisition and installation of a new large memory HPC systems by the NSW consortium in 2003, 2006 and again for 2009. During 2008, he was appointed as Director of National Computational Infrastructure (NCI)—the national peak supercomputing facility funded by NCRIS. He serves a member of the Editorial Board of Proceedings A of the Royal Society and is a reviewer for eight journals. During 2007, he presented an invited paper at ICAM 2008 (Hong Kong) and at the Australia-Japan Nanophotonics Workshop (Canberra).

Key areas of research contribution within the Centre

Within CUDOS, Lindsay Botten leads a substantial research effort in the development of novel theoretical methods and computational tools, and manages the activities of the UTS node of the Centre (comprising 3 academic staff, 3 research staff, 2 PhD students and 2 Honours Students). The major focus of the UTS group is to advance modeling expertise within the Centre and to support research programs with strong electromagnetic modeling skills and advanced computational techniques. The group contributes to the "Optical Switch", the "3D Bandgap Devices" and the "Slow Light" flagship programs and specializes in the development of novel semi-analytic techniques (based on Bloch mode, multipole, finite element and eigenfunction methods) for modelling propagation and radiation dynamics in photonic crystal devices and resonant structures. Such methods are important because they provide real physical insight into the underlying electromagnetic processes, while simultaneously yielding excellent accuracy and computational efficiency. The UTS group also has considerable expertise in finite difference time domain methods. Access to the substantial computational resources needed for FDTD modeling is provided through access to the NCI National Facility.

Researchers and students: (including collaborators)

Researchers

UTS: Lindsay Botten, Ara Asatryan, Kokou Dossou, Andrew Norton, Chris Poulton, Adel Rahmani

Sydney: Martijn de Sterke, Ross McPhedran, Nicolae Nicorovici

ANU: Yuri Kivshar, Ilya Shadrivov, Andrey Sukhorukov

Students

UTS: Michael Byrne, Dougal Kan. Kesava Jay, Trevor Manning

Sydney: Sam Campbell, Felix Lawrence, Sahand Mahmoodian, Parry Chen

ANU: Sangwoo Ha

International collaborations

Israel: Valentin Freilikher (Bar-Ilan University), Sergey Gredeskul

UK: Tom White (St Andrews University)

USA: Graeme Milton (University of Utah)

France: P Chaumet, K Belkebir

Germany: H Schwefel

Canada: Sophie Larochelle

Research achievements during 2006

During 2007, the UTS group was involved in a broad range of research projects. These involve a growing number of collaborations and at the end of 2007 we are now working with all of the original nodes of CUDOS – Sydney, Macquarie, Swinburne, and ANU – in some cases in connection with Flagship projects, and in others, on frontier topics in photonics and related areas. These are highlighted below.

Development and application of Bloch mode tools

The development of the computational toolkit based on Bloch mode techniques continued during 2008, driven primarily by new applications. These included contributions to the slow light flagship project involving a collaboration of UTS (Dossou, Botten) from ANU (Ha, Sukhorukov, Kivshar), Sydney (de Sterke, McPhedran) and St Andrews (White). Following on from our work last year, in which the UTS team developed modeling tools that confirmed a novel and very general prediction that antisymmetric couplers can support the dispersionless tunneling of slow light [1], we have extended this to couple the PC based directional coupler to external ridge waveguides. The periodic supercell on which the modeling is based is problematic when radiation modes (associated with the ridge waveguides) are involved and so the modeling tools have been enhanced by the inclusion of perfectly matched layer boundary conditions during 2008. Application of these tools in collaboration with the ANU group is planned for 2009.

Last year we reported a major advance in our ability to conceptualize and design anti-reflection coatings for photonic crystals through the *extension of the concept of impedance to photonic crystals* (Botten) and its application and demonstration by Felix Lawrence who is supervised by de Sterke, Botten and Dossou. In contrast to previous heuristic approaches in defining a PC impedance, our approach is exact and physically significant, deriving directly from the PC Bloch modes.

The proof of concept work last year was for the simpler case of a square symmetric lattice and for long wavelengths in which a scalar approximation suffices. This year the theory has been extended considerably to handle up-down symmetric lattices and, in particular, the more interesting case of hexagonal lattices, and also to deal with multiple propagating states that occur at shorter wavelengths.

The major advantage of the impedance concept is its ability to characterize the electromagnetic properties of each PC medium by such a quantity. We have demonstrated its validity and applicability by applying it to the design of two layer anti-reflection coatings, with our first work published in Applied Physics Letters [2]. By varying the PC layer impedances, it is possible to balance the reflections at the three interfaces so that they cancel, leaving zero reflection. While there are several ways in which we can control layer impedances, we have chosen the simplest and most practical, namely stretching the lattice in the direction normal to the interface, Fig 1 (a). Rather than solving for PCs with a suitable impedance, we try many possible layers, constructing a “database” of PC impedances and propagation constants at our target frequency, incident angle and polarization. With this and an interpolation routine, the calculation of the reflection off possible coatings is almost instantaneous, with the coating being the layer combination that generates the lowest reflection.

The results in Fig 1 show the reflectance of the uncoated PC which we optimize for a normalized frequency a/λ = 0.38 and an incident angle of 30° (TM polarization). Uncoated, the PC has a reflectivity of R =94% (Fig. 1b) while using the above procedure, and including three Bloch modes in the calculations for each PC, the optimization yields a coating with an outer layer 1.5 times as thick as for a regular hexagonal lattice, and an inner layer 0.69 as thick. Increasing the number of Bloch modes, for a more rigorous calculation, yields R =0.26% (Fig 1c) for the optimized structure.

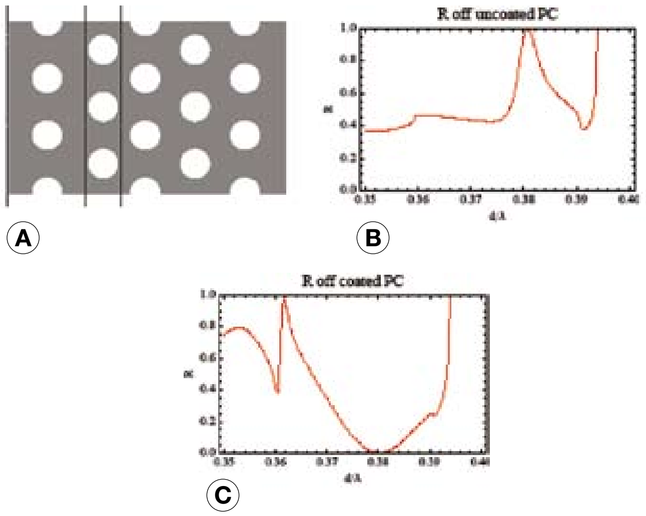


Fig 1. (a): Schematic of a two layer coating. The inclusions are uniform but the thicknesses of the layers parallel to the interface vary; (b): Bulk reflectivity of PC with parameters given in text; (c): Reflectivity with AR coating.

Using broadly similar Bloch mode and transfer techniques, Sam Campbell (supervised by Botten, McPhedran, and de Sterke) has developed a *Fresnel formulation for a multi-element lamellar diffraction grating*, based on Bloch mode techniques [3]. During 2008, the team extended the analysis [4] to model *slanted lamellar grating layers*, the motivation for which was to introduce a new mechanism by which to tune resonances.

The theory commences with the formulation of *Fresnel matrices for shifted semi-infinite lamellar gratings*, from which the transfer matrix is formed. The limit as the shift is made infinitesimal in size is taken, and by cascading an infinite number of these shifted layers, the transfer matrix of a slanted lamellar grating is developed in the form of an elegant matrix exponential. From this the reflection and transmission scattering layers may be deduced, underpinning all subsequent calculations.

This theory has been further extended to the general case of conical incidence, with a further article in press in JOSA A in 20089. This has led to a very interesting homogenization result (Fig. 3), namely that the structure homogenizes to a uniaxial crystal (with optical axis perpendicular to the grating interfaces for all angle of incidence), in the limit that the slant angle becomes arbitrarily extreme (90 degrees).

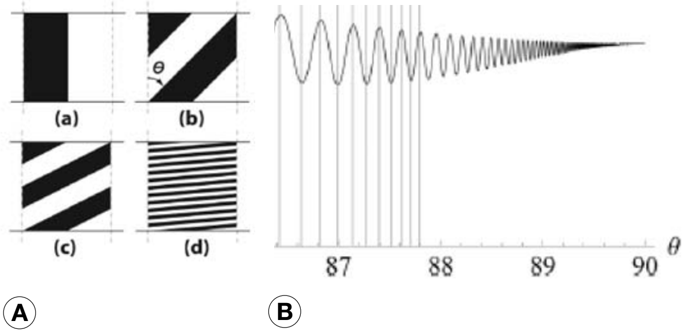


Fig 2. (a): Schematic periods of slanted lamellar gratings with increase angles of slant. (b): Reflectance from a normal incidence (TM) lamellar grating with increasing slant angle. The limit matches that predicted by homogenization theory.

In research related to the 3D bandgap PC flagship, UTS PhD student, Dougal Kan, supervised by Chris Poulton, Ara Asatryan, and Lindsay Botten has extended the multipole Bloch mode tools to defect structures (e.g. waveguides, cavities) for 3D woodpile geometries. During 2008, there was substantial progress in building and verifying the models and computer codes which can now undertake field reconstructions and undertake transmission calculations using the Bloch mode transfer matrix approach. The developed modules have been applied to calculate the band structure and to characterize planar and point defects for woodpile photonic crystals. Q-factors have been calculated as functions of defect size and the strength of the perturbation, and the dependence of defect modes on incidence angle has also been calculated. The results will be used in the design of low loss slow light waveguides, with a publication planned for 2009.

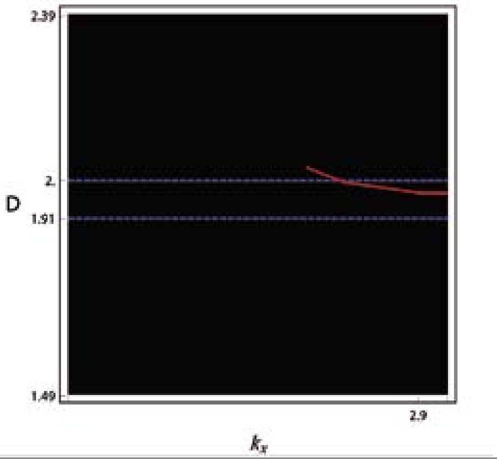


Fig 3. Dispersion curve for a planar defect mode for a woodpile PC crystal in the ΓM direction.

Development of finite difference time domain modeling tools

The development of FDTD tools has been continued in the context of the 3D bandgap and optical switch flagship projects, with computational resources made available by a grant on the NCI National Facility. In the former, we (Norton, Botten, Asatryan and Rahmani) continued the development computational tools for modelling the radiation dynamics, field profiles and transmittance of the woodpile structures [5] being developed at Swinburne. This has allowed the optimization of the defect mode frequency with PC geometry and the characterization of Q-factors of planar defect modes.

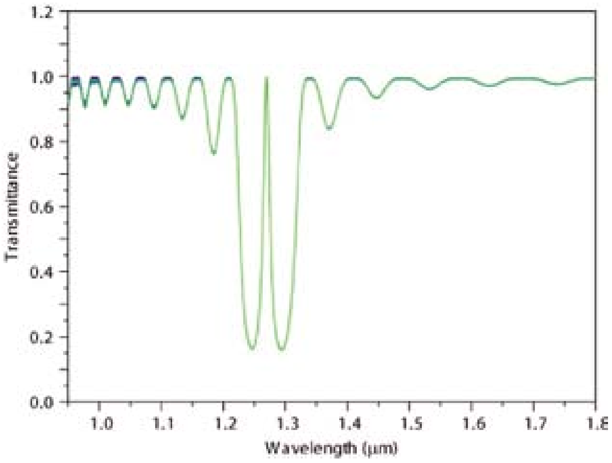


Fig 4. Transmittance spectrum for a 40 layer polymer rod woodpile of polymer rods on either side of an air-gap defect. The size of the air-gap has been optimised so that the frequency of the defect mode occurs at the centre of the bandgap for the woodpile.

In support of the Optical Switch project, Chris Poulton modelled the coupling between a fibre taper and slow waveguide modes in a PC [6]. In collaboration with University of Sydney colleagues, Christian Grillet and Michael Lee, he used a combination of state-of-the-art parallel computation, together with simple physical models, to model the coupling between slow-light waveguide cavities and curved fibre tapers, which can be used experimentally to couple light into and out of the slow-light waveguides, as well as for rapid measurement of the dispersion of these waveguide modes. They first calculated the resonances of a slow-light PC waveguide using a parallelized wavelet-based FDTD algorithm, with the wavelet basis reducing the numerical dispersion inherent in all FDTD methods and enabling the simulation of the numerically "large" problem over a sufficiently extensive frequency range. The distribution of the curved fibre-taper mode was then calculated analytically, allowing the coupling between the slow-light modes and the curved taper to be estimated by examining the overlap of the fields in k-space), and compared with experimental measurements.

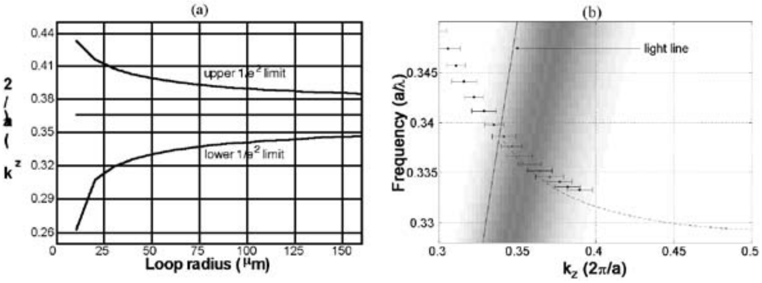


Fig 5. Dispersion and coupling diagrams for the fibre taper and waveguide.

In further work, Adel Rahmani and colleagues from with the Institut Fresnel developed a new computational method for the study in the time domain of the scattering of electromagnetic waves by arbitrary objects. The approach is based on the coupled dipole method and is able to handle dispersive, anisotropic, inhomogeneous three dimensional scatterers of arbitrary shape [7].

In collaboration with H. Schwefel of the Max Planck Institute, Erlangen, Chris Poulton has been investigating high frequency resonances in coupled dielectric discs that form an important building block for a large range of nanophotonic devices. In general, the calculation of the resonant frequencies and consequent field distributions of these structures must be performed numerically by solving an eigenvalue problem for Maxwell's equations, with the resonant frequencies lying in the complex plane, the imaginary part of the frequency corresponding to the inverse of the resonance lifetime.

While for low frequencies this process is straightforward, the numerical solution becomes computationally expensive at high frequencies with the search for eigenfrequencies in the complex plane becoming a slow and unreliable process. During 2008 Poulton and Schwefel developed an alternate approach based on multipole expansions and were able to re-formulate the method in the manner of a scattering quantization approach. In this way, the resonances are readily and efficiently calculated by plotting eigenvalues of a simpler subsidiary problem in the complex plane. This work has been presented at NANOMeta [8].

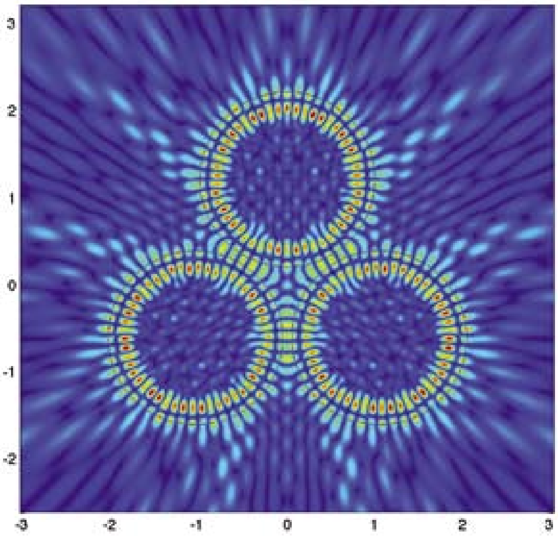


Fig 6. High frequency resonant state of a three-cylinder system. ncyl=1.5, ka=22.46-0.052i, Distance between cylinders d = 0.1 a.

Slow Light

In joint work with Tom White of St Andrews, we (Botten, Dossou, de Sterke and McPhedran) considered the efficient coupling of light into a slow waveguide mode (with the slowness associated with an inflection point in the dispersion curve). Remarkably, the coupling into this slow mode, which has a group index ng>1000, can be essentially perfect without any transition region. This amazingly efficient coupling [9] is mediated by an evanescent mode in the slow medium—one which has an substantial amplitude, and so helps satisfy the boundary conditions, but does not transport any energy. Underpinning this study has been semi-analytic methods which have given considerable insight into the coupling mechanism—one in which the evanescent mode is very similar to the propagating state yet is still orthogonal to it.

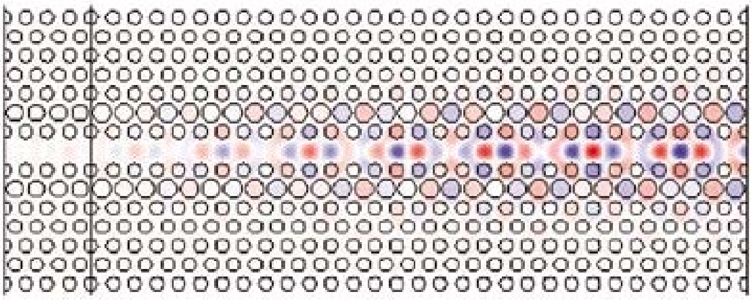


Fig 7. Efficient coupling into a slow-light waveguide (at the bottom of the interface) without transition region.

In other work, Adel Rahmani and colleagues at the Institut des Nanotechnologies de Lyon considered active photonic devices using slow-light confinement [10]. They designed, modelled and fabricated a new type of semiconductor microlaser which exploits a clever confinement of a slow-light mode in a PC waveguide to achieve low-threshold, room-temperature lasing using InAsP quantum wells as the gain medium.

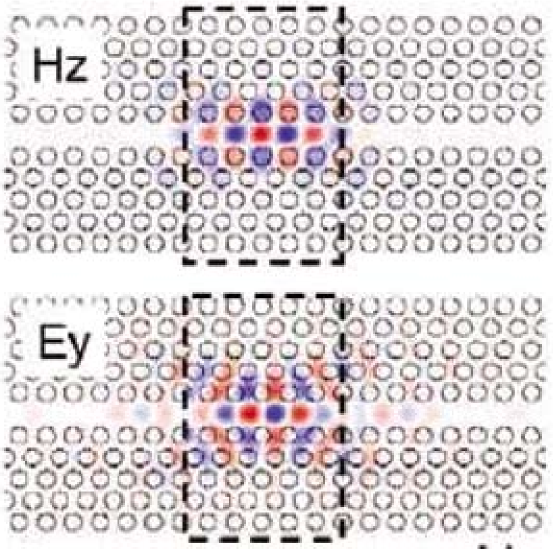
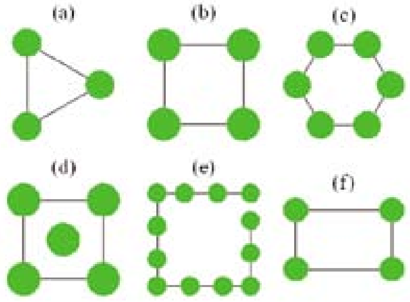


Fig 8. Computed field distribution of a slow-light mode in a PC waveguide confined by a PMMA layer.

Defect Modes

Through the introduction of defects into photonic crystal lattices with a band gap, it is possible to concentrate or localize fields, thus forming the foundation of useful devices such as waveguides, cavities, couplers etc. While defect structures and the field modes they support are widely studied, almost all such studies are computational in nature. The work commenced last year with a UTS / Sydney collaboration involving Kokou Dossou, Chris Poulton, Lindsay Botten (UTS), and Ross McPhedran and Martijn de Sterke (Sydney) who developed a theory for single defects based on a Bloch mode Green's function formulation. We demonstrated, by taking gap edge asymptotics, a fundamental exponential law which relates the change in frequency of the defect states to the relative change in electrical energy of the Bloch modes on the band-edge, and to the density of states in the photonic crystal [11]. This year, the theory has been put onto a firm mathematical footing [12] and, together with Sydney PhD student Sahand Mahmoodian, has been extended to encompass tight binding modeling and also the study of composite defects comprising multiple defect cavities of the type found in photonic devices such as PC ring resonators. Based on the symmetry of these structures, we have derived simple expressions for the dispersion equations (which come from the eigenvalues of a block circulant matrix), allowing us to investigate their modal properties (dispersion relations, cutoff, degeneracy, mode symmetry. All of the theoretical results have been extensively validated by numerical simulation based on our generalised Fictitious Source Superposition method. Publications on this work are in press in 2009.



Rotationally symmetric structures and some others.

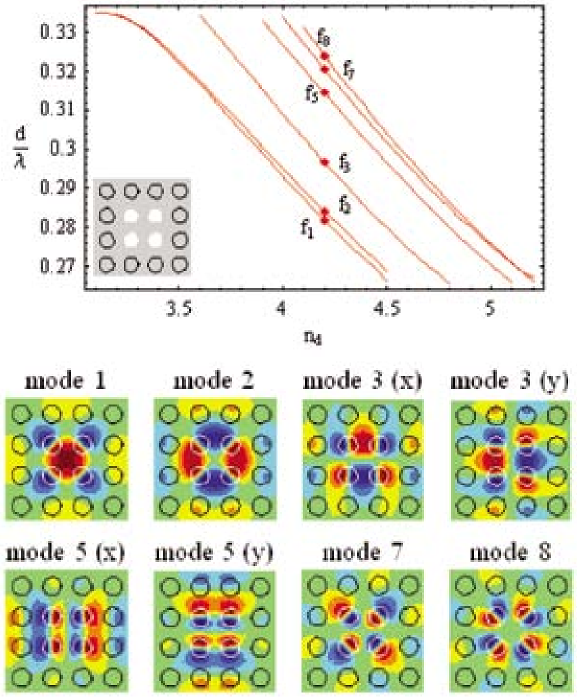


Fig 9. 2x2 composite defects in a square lattice. The left panel shows the defect dispersion curves; these curves originate from a degenerate band edge. The right panel shows the defect modes corresponding to the frequencies $f_1,\ldots,f_8$ indicated by the dots on the left panel.

Defect mode calculations are invariably expensive computationally, particularly near band edges. Using concepts from solid-state physics, we have been able to split the solution into a combination of Bloch functions and an envelope function that satisfies a simple differential equation. This formalism will not only enable the quick and convenient calculation of defect states, but also yield simple models that give significant insight into the creation and evolution of defect modes. We are in the process of exploring the range of applications of this method, which can be applied to point defects, clusters, and photonic crystal waveguides, and anticipate publications in 2009 arising from this work.

Metamaterial Studies

The UTS group now has a substantial program of research underway in metamaterials, encompassing both random and structured (periodic) systems. This work will be further enhanced in 2009 and beyond through the award of a new ARC Discovery Grant titled "Novel effects of metamaterials on propagation and localisation of electromagnetic waves in photonic crystal structure".

Our work on Anderson localization in mixed (normal and metamaterial) commenced last year in collaboration with the groups of Valentin Freilikher and Yuri Kivshar and led to the discovery of a surprising result [13], namely that in one-dimensional disordered stacks the introduction of metamaterials substantially suppressed Anderson localisation and led to long wavelength localization length that were orders of magnitude longer than that for normal materials, and which satisfy a quantitatively different power law — behaving as the sixth power, rather than the square, of the wavelength. In work this year we have derived an elegant and simple formula that describes the localization length as a function of the wavelength in mixed stacks when both layer refractive index and thickness disorder are present. Numerical calculations are in excellent agreement with the theoretical predictions (Fig. 10).

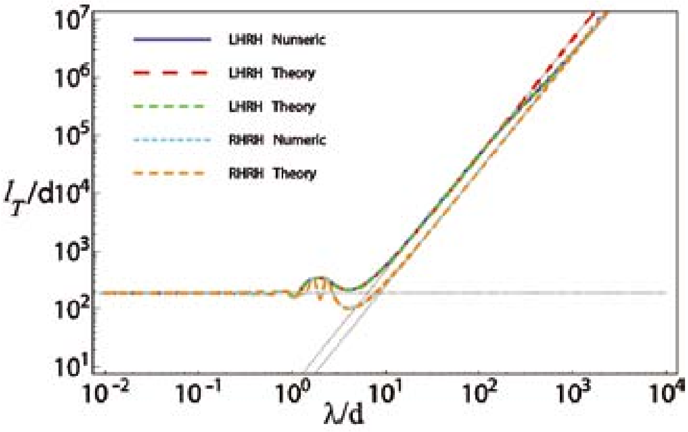


Fig 10. Asymptotic estimates (theory) and simulations (numeric) of the localisation length vs wavelength for normal (RHRH) and mixed (LHRH) stacks with both refractive index and thickness disorder.

In related work, Sydney PhD Student Parry Chen, supervised jointly by Ross McPhedran, Martijn de Sterke and Lindsay Botten, is investigating propagation in metamaterial photonic crystals using semi-analytic methods. This work is described in detail under Ross McPhedran's entry.

Ara Asatryan and Lindsay Botten are also investigating the properties of PCs composed entirely of metamaterials and mixed materials PCs comprising both normal and metamaterial inclusions. Calculations of the local density of states (LDOS) in such structures (Fig. 11) have shown that the LDOS in a finite cluster composed solely of metamaterial cylinders (solid line) is two orders of magnitude lower than for the corresponding cluster composed entirely of normal materials (dashed line) at the gap wavelength for the corresponding infinite PC. Furthermore, the band gap exhibited by the metamaterial cluster is up to four times wider then the corresponding photonic crystal composed entirely of normal materials.

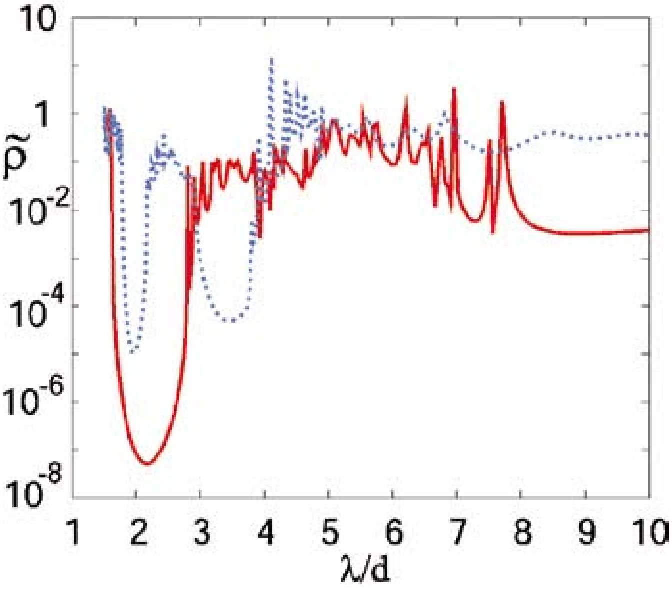


Fig 11. LDOS spectra for a square 121 cylinder cluster of cylinders with refractive indices $n=\pm3$ and radii $a+0.3d$.

Adel Rahmani and colleagues from the Institut Fresnel have developed a theory of optical forces on Rayleigh particles with arbitrary dielectric permittivity and magnetic permeability. They have also developed a method, based on a Green tensor approach (coupled dipole method), to study optical forces on an arbitrary object with both electric and magnetic properties (with an Optics Express paper in press)

Other work

In other work during 2008, Kokou Dossou in collaboration with Sophie Larochelle (Laval University) has studied the contribution to birefringence of UV-induced modification of the stress distribution in optical fibers[14] using finite element methods.

Chris Poulton, in collaboration with Ross McPhedran has studied the propagation of bending waves in thin plates. Periodic structuring of these plates (thus forming so-called "platonic crystals") can lead to extremely unusual wave behaviour, including extremely flat bands and vibration gaps with extremely high bandwidth. We have performed the calculation of the Bloch modes of these structures and have examined several of their many unusual properties.

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