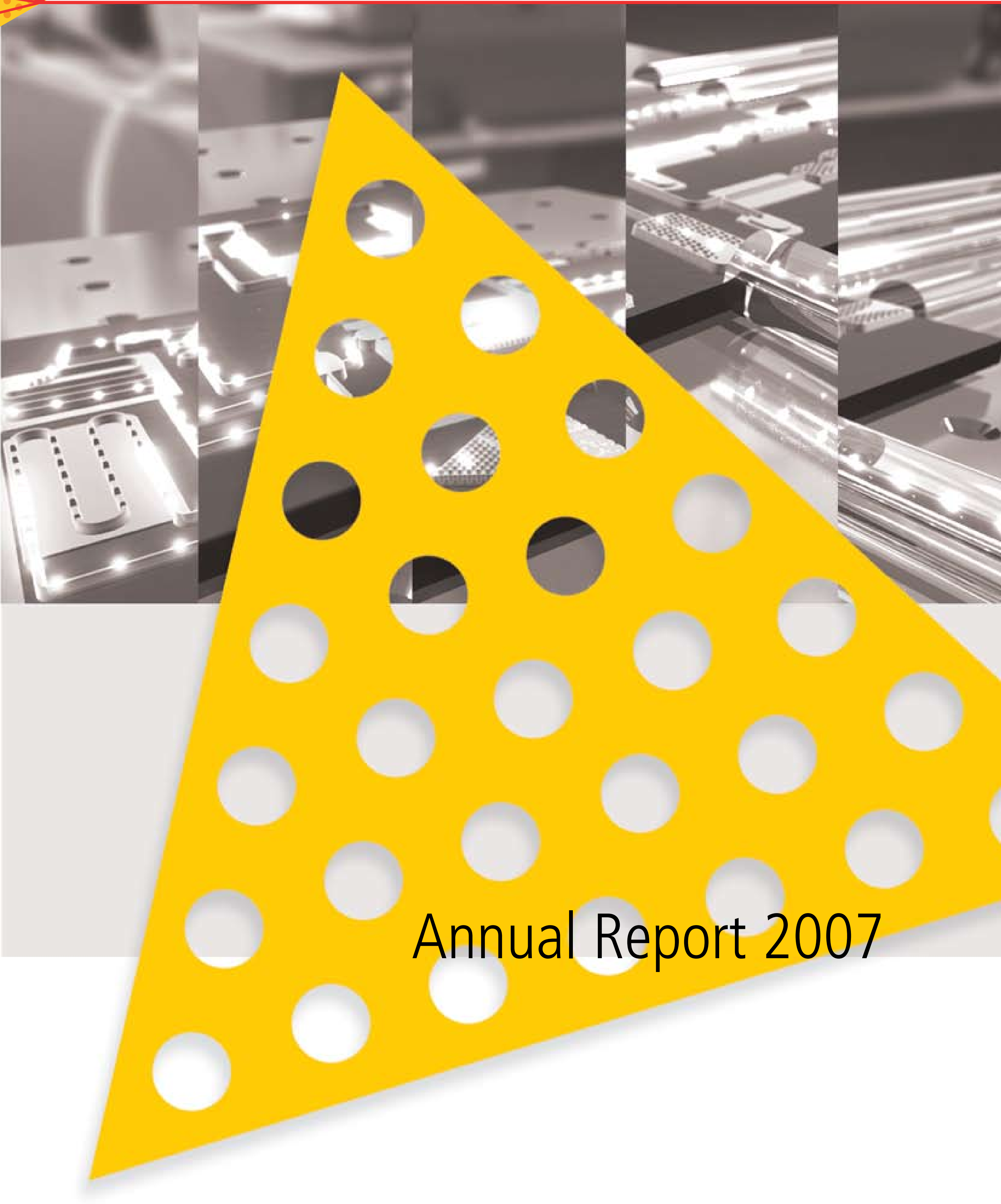
CUDOS

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

An Australian Research Council Centre of Excellence



Annual Report 2007

Professor Lindsay Botten

Lindsay Botten, a graduate of the University of Tasmania, is 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 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 ac3 consortium. He serves a member of the Editorial Board of Proceedings A of the Royal Society, is a reviewer for eight journals, and during 2007 served on the International Advisory Committee for the PIERS conferences in Beijing and Prague. During 2007, he presented an invited paper at PIERS (Beijing).

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 UTS node of the Centre (comprising 3 academic staff, 3 research staff and 2 PhD 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. His group contributes to the “Optical Switch”, the “3D Bandgap Devices” and the “Slow Light” flagship programs and they specialize 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, enhanced substantially in 2007 with the appointment of two new members of academic staff, Drs Chris Poulton and Adel Rahmani. Access to the substantial computational resources needed for FDTD modeling was boosted substantially in 2007 with the acquisition by APAC of a substantial licence (128 processors) of the RSoft FullWAVE software – initiated by CI Botten who is a member of the APAC Board. The ongoing relationship between CUDOS and APAC is managed by Botten, with the Sydney nodes of CUDOS now a major user of the APAC National Facility, having been allocated some 280,000 hours on the National Facility in each of 2007 and 2008.

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
Macquarie: Graham Marshall, Mick Whitford
ANU: Yuri Kivshar, Ilya Shadrivov, Andrey Sukhorukov
Swinburne: Min Gu, Baohua Jia

Students:

UTS: Michael Byrne, Dougal Kan
Sydney: Sam Campbell, Felix Lawrence, Sahand Mahmoodian, Jamie Vahn, Jamie Walker
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)

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 2007, driven by applications. Amongst these is a contribution to the slow light flagship project, and a new collaboration with the ANU group. In the first part of this work, Dossou, Botten, de Sterke and Walker considered the coupling light into a slow light waveguide. The problem is significant because of the difficulty of efficiently coupling light into (out of) slow mode regions due to the large mismatch between the characteristic impedances of the two regions. The reduction, or minimization, of impedance mismatches is vitally important as they are the source of insertion losses and stray light, both of which reduce the signal-to-noise ratio of the device. We demonstrated theoretically that through the use of a photonic crystal analogue of the quarter wave anti-reflection layer (of thin film optics) it is possible to design a coupler from a fast to a slow light waveguide with perfect efficiency [1].

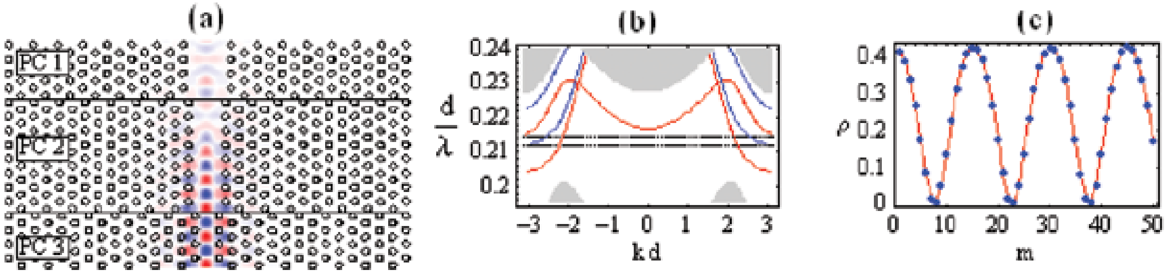


Fig 1: (a) Schematic of the coupling structure; (b) Band structure for PC 1 (red) and PC 3 (blue); (c) Reflectance ρ of the entire optimized structure versus μ, the length of PC 2.

In subsequent work, involving a new collaboration with the ANU group (Sukhorukov, Ha, and Kivshar), the UTS team (Dossou, Botten) developed modeling tools which confirmed the novel and very general prediction that antisymmetric couplers can support the dispersionless tunneling of slow light (with a paper in press in 2008). The extension of this work, in the context of the slow light flagship, involves collaboration with Tom White of St Andrews University. In this, the PC device will be coupled to external ridge waveguides, with the modeling of this requiring the implementation of perfectly matched layer with finite element method that underpins the Bloch mode tools.

Our ability to conceptualize and design anti-reflection coatings for photonic crystals has taken a major step forward this year through the extension of the concept of impedance (familiar in electric engineering and thin film optics applications) to photonic crystals (Botten) and its application and demonstration by honours student Felix Lawrence supervised by de Sterke, Botten and Dossou. Our definition, in contrast to the heuristic approaches to date, is both exact and physically based, being defined directly in terms of the Bloch modes of the PC. In this environment, the impedance is a matrix (rather than a scalar) quantity, but aside from that essential difference, it mirrors the role of impedance in circuits, and facilitates the adoption of thin film design concepts in the PC context. We have exemplified this [2] by successfully designing a two layer antireflection coating (see Fig. 2) which entails the solution of a computationally demanding multi-dimensional optimisation problem for the radii of the cylinders in the anti-reflection layers. The parameterisation of the problem through the introduction of the impedance greatly reduces the computational demands and makes feasible the solution of a problem that, otherwise, would not be possible.

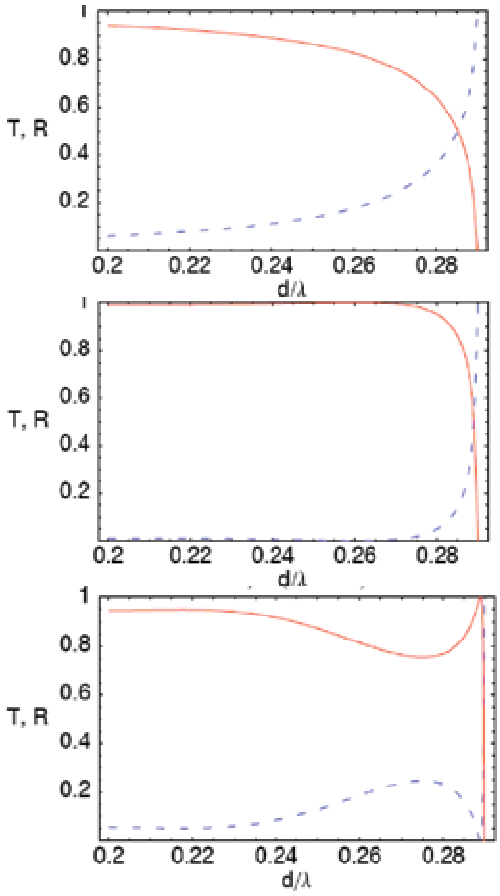


Fig 2

Using broadly similar techniques, Sam Campbell (supervised by McPhedran, de Sterke and Botten) has developed a Fresnel formulation for a multi-element lamellar diffraction grating, based on Bloch mode techniques [3]. This is being used in the semi-analytic study of Fano resonances and also in studies aimed at optimizing the blaze of Bragg gratings by sloping the grating facets. In this, an elegant approach (based on matrix exponentials) to the modeling of the slanted lamellae, allowing for a continuous (rather than a stepped) profile, has been developed during 2007.

Work has continued on the modeling of Fano resonances in 2D photonic crystal slabs, in the context of the “Optical Switch” flagship (Byrne, Asatryan, Botten). Whilst our modeling, to date, has been for an incident plane wave, the typical experimental setup has a Gaussian beam, and so this year’s work has been to investigate the effect of a beam on the frequency and width of resonances. The Gaussian beam has been approximated by an expansion of plane waves of specific polar and azimuthal angles of incidence and preliminary results show that, relative to purely plane wave simulations, the resonances are significantly wider and are shifted towards shorter wavelengths.

In research related to the 3D bandgap PC flagship, Kan, Asatryan, Botten, and Poulton are extending our multipole Bloch mode tools to defect structures (e.g. waveguides, cavities) in woodpile geometries. The work is still in its early stage but already a prototype implementation of the foundation tools for computing scattering matrices in supercell geometries has been demonstrated, and the implementation of the Bloch mode scattering matrix method, needed to model extended structures, is underway.

Development of finite difference time domain modeling tools

Much of the development of FDTD tools has been pursued in the context of the 3D bandgap and optical switch flagship projects. In the former, Norton, Botten, Asatryan and Rahmani have undertaken the development of a comprehensive range of computational tools for modelling the radiation dynamics, field profiles and transmittance of the woodpile structures being developed at Swinburne. Extensive use is made of the FDTD software running on the APAC National Supercomputing Facility. While details of this work are provided under the heading of the particular flagship project, it is relevant that a computational study of near fields (see Fig. 3) has been completed and this together with experimental measurements is being prepared for publication by the Swinburne / UTS groups. In related work [4], we also studied the Lamb (frequency) shift of sources in 2D photonic clusters and showed that the frequency shift is highly enhanced at the edge of the band gap and is highly sensitive function of the shape, size and orientation of the cluster.

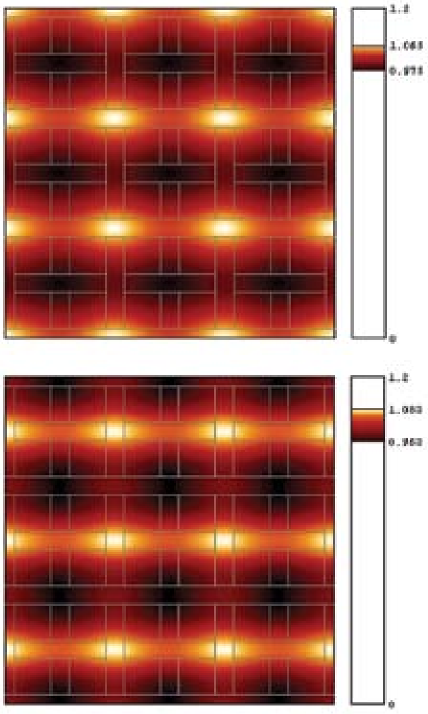


Fig 3: Near field intensity plots at the exit face of a woodpile PC at frequencies just below (left) and just above (right) the bandgap, showing the respective concentration of the fields within the rods and within the voids between them.

In support of the Optical Switch project, Chris Poulton has been modeling the coupling between a fibre taper and a PC resonant cavity (see Fig 4) using a parallelized, wavelet based FDTD algorithm, implemented on the ac3 cluster. This tool, developed by Poulton and colleagues in Germany, reduces the numerical dispersion generally associated with other FDTD methods and enables the efficient simulation of "computationally large" structures. The FDTD modeling generates the cavity defect mode and the coupling with the fibre taper is then determined by computing overlap integrals. More details of this work are provided under the relevant flagship heading, with work continuing in 2008 to optimize the coupling geometry.

In addition, to these, we have been exploring the possibility of using FDTD computational techniques to increase the accessibility of the Bloch mode methods in which that the CUDOS group specializes. While the Bloch mode tools are demonstrably useful, both computationally and in the development of semi-analytic asymptotic approximations [4], their accessibility is restricted by the specialist multipole and finite element method underpinnings used to calculate scattering matrices that provide the Bloch modes. To enhance the availability of these tools Vahn, Botten, Steel, de Sterke have been exploring the use of FDTD tools (which are widely available in photonics research laboratories) to replace the scattering matrix foundations. A prototype that computes only propagating Fresnel coefficients has been developed and its further development, and scattering matrix methods involving both propagating and evanescent orders, will be pursued during 2008.

Defect Modes

Through the introduction of defects into photonic crystal lattices which exhibit a band gap, it is possible to concentrate or localize

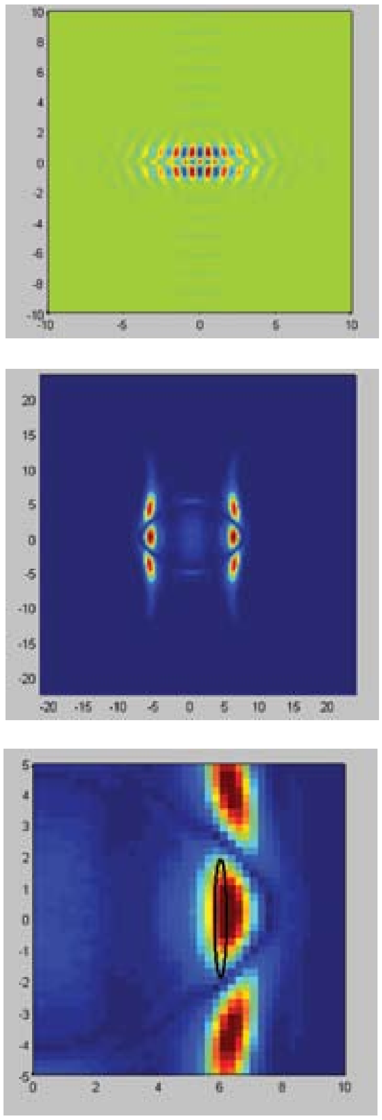


Fig 4a): Calculated defect state. b): Representation of the defect in reciprocal space. c): Close up of the reciprocal space overlap between the defect state and (black contour) the fundamental mode of a silica fibre taper.

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. While significant theoretical work has been undertaken in a quantum mechanical setting, there is comparatively little theory about the evolution of modes of electromagnetic fields. Accordingly, motivated by a discussion with Costas Soukoulis, a pioneer in the field of photonic crystals, Dossou, Botten, McPhedran, de Sterke, Asatryan, Poulton and Mahmoodian sought to understand the evolution of defect states from the edge of the band gap. Beginning with single defects, we developed a Bloch mode Green's function formulation and, taking gap-edge asymptotics, we demonstrated 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 [4]. All of the theoretical results have been extensively validated by numerical simulation using the generalised Fictitious Source Superposition method [7]. In subsequent work, we are extending the single defect theory to handle multiple defects (see Fig. 5) using both gap edge asymptotics and a tight binding treatment.

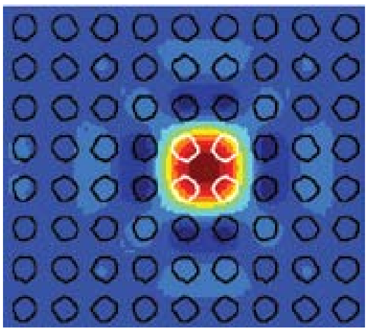


Fig 5: The four defect modes of a square defect (comprising the four cylinders in white whose dielectric constant has been varied) in a square lattice. The mode symmetries follow in a straightforward manner from the solution of the eigenproblem for a circulant matrix.

Electromagnetic Localization

Anderson localization, which is amongst the most fascinating and universal phenomena in the physics of disordered systems, has been comprehensively studied for some decades in 1D, 2D and 3D electromagnetic systems in conventional (right-handed) materials. In recent years, there has been growing interest in metamaterials which are artificial composites with electromagnetic properties (negative permeability and permittivity) not found in normal materials. While such structures were studied as a theoretical curiosity some four decades ago, their realization in the laboratory has led to a surge of interest in these materials which are refractively left-handed. During the visit of Valentin Freilikher (Israel) in 2006, we commenced a theoretical and computational study of propagation and localization in disordered stacks in which the layers alternate between normal and metamaterials. This study gave quite remarkable results and led to a new collaboration for us with the ANU Nonlinear Physics Centre. Specifically, we uncovered the surprising result that the introduction of metamaterials substantially suppresses Anderson localisation and lead to a long wavelength localization lengths which are 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 (see Fig. 6). Our Physical Review Letter [8] also revealed that long wavelength resonances, a classical signature of localization in normal materials, largely disappear when metamaterials are introduced. In related work involving 2D disorder stacks of normal materials [9], we undertook a scaling analysis and discovered, contrary to widely held belief, evidence of a mobility edge – the transition from diffusive propagation to localization with increasing disorder.

Other work

In other work during 2007, we developed an elegant extension to the classic transfer matrix formulation (Pichard's method) for the modeling of photon conductance in systems in which the input and output media have different numbers of propagating channels [10]. A UTS-Macquarie collaboration (Marshall, Kan, Asatryan, Whitford, Botten) investigated the effect of scattering by the microstructure on transversely coupled laser light into the core of a photonic crystal fibre and demonstrated that there are preferred angles and translational positions of the microstructure for preferentially coupling laser light into the fibre core (for writing gratings) [11]. A collaboration between McPhedran, Milton, Nicorovici and Botten investigated the cloaking of dipoles in the quasistatic (low frequency) by anomalous resonance. This study [11], elaborated in detail in the report of CI McPhedran., provided numerous animations of cloaking in discrete systems that clarified the underlying physical mechanism of cloaking.

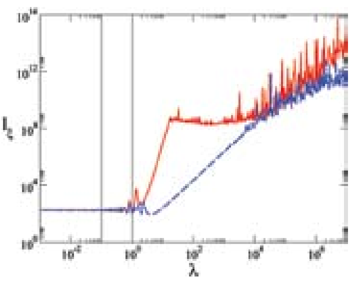


Fig 6: Localization length as a function of wavelength for normal materials (blue) and for mixed stacks (red), clearly showing the λ^2 and λ^6 dependence for refractive index disorder.

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