CUDOS

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

ANNUAL REPORT 2006

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 140 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 advanced computing partnerships 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 of a new large memory HPC system by the ac3 consortium ($1M, funded by ARC and partner universities). He serves as a reviewer for eight journals and during 2006 served on the Organizing Committee for ETOPIM 7 (Sydney, 2006), on the Technical Program Committee for PIERS 2006, and on its International Advisory Committee for 2007. During 2006, he presented invited papers at IEEE-NUSOD (Singapore), PIERS (Tokyo), and ETOPIM 7 (Sydney).

Roles and responsibilities within Centre

Within CUDOS, Lindsay Botten leads the Computational Modeling discipline of the Centre, manages the operations of the UTS node and serves on the management Steering Committee of the Centre. His group contributes to the "Optical Switch", the "3D Photonic Bandgap materials" and the "Slow Light" flagship programs. He also leads the Centre's relationship with APAC.

Key areas of research contribution within the Centre

The major focus of Botten's 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 specializes in the development of novel semi-analytic techniques (based on Bloch mode, multipole, finite element and eigenfunction methods) for modeling 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.

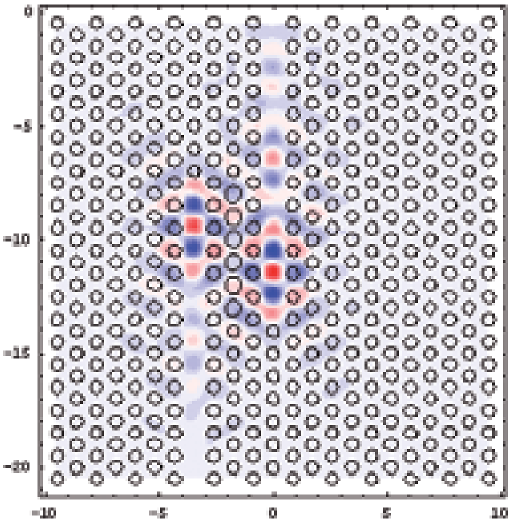
During the year, the group also developed considerable expertise in finite difference time domain methods. Until now, access to FDTD modeling software with the Centre was restricted to workstations and a small dedicated computing cluster located at ac3. Following a submission by Botten, the Board of APAC agreed to fund the acquisition of a 64 processor licence of RSoft FullWave (a industry standard FDTD package) in support of Australian photonics, and CUDOS in particular, for use at the National Facility. The Sydney nodes of CUDOS are now a major user of the National Facility, having been allocated some 280,000 processor hours on the National Facility for 2007.

During 2006, the UTS group was involved in a broad range of research projects involving collaborations with a number of other nodes and activities in support of flagship programs. These are highlighted below.

Development of tools based on Bloch mode methods

We expanded considerably the development of the computational toolkit based on Bloch mode techniques. Amongst this is work (Michael Byrne, Ara Asatryan, Lindsay Botten, Ross McPhedran, Sam Campbell) in the "Optical Switch" flagship to model Fano resonances in PC slabs, in which our Bloch mode/multipole scattering matrix method was extended to handle square and hexagonal geometries, arbitrary incidence configuration and multi-layer structures[1,2]. The generalization of the theory to handle multilayer slabs demonstrated the importance and value of our Fresnel matrix approach over alternative methods (such as those relying on plane waves) which are plagued by numerical instabilities. As an offshoot of this, we (Nicolae Nicorovici, Lindsay Botten, Ross McPhedran, Andrew Kirk) also applied the same approach to the modeling of multi-layer metallic lamellar gratings that are used for sensing purposes [3].

The finite element implementation [4] of our Bloch mode software for modeling linear photonic crystal systems was extended (Kokou Dossou, Lindsay Botten) to support the honours projects to design folded directional couplers (Jamie Vahn) and the efficient, adiabatic coupling of slow light (Jamie Walker). In related theoretical work, the physical constraints of reciprocity and energy conservation allowed the development of an elegant single parameter model for the folded directional coupler, and led to an elegant extension [5] to the classic transfer matrix formulation (Pichard's method) for the modeling of photon conductance in systems (Asatryan, Botten) in which the input and output media have different numbers of propagating channels. As an offshoot of these activities, we are now working to combine the unique modeling features of the Bloch mode tools with the computational strengths of general purpose techniques such as FDTD methods. The basic principles have been established and prototyped for delivery in 2007 through the combined efforts of Jamie Vahn, Lindsay Botten, Mike Steel and Martijn de Sterke.



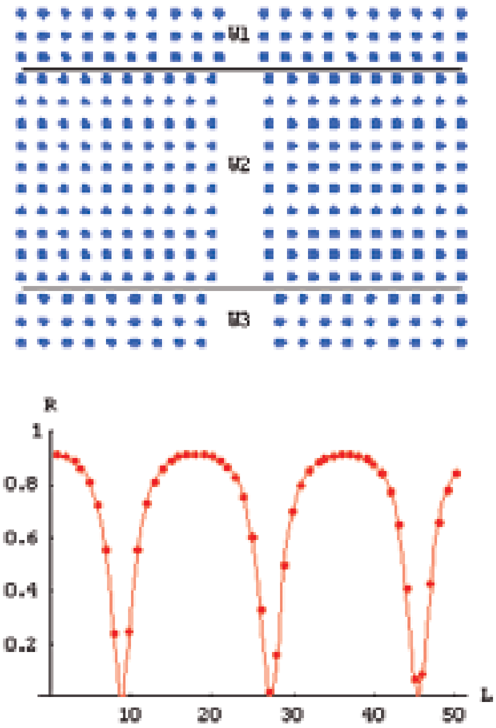
▲ **Figure 1. Field plot for a folded directional coupler near resonance.**

We developed (Botten, Dossou, de Sterke) an elegant impedance formulation for characterizing the scattering processes that occur at the interfaces of photonic crystals structures, and this has been applied to design a simple anti-reflection coating for slow light. The design is a quarter wave film which, when well designed, can yield 100% transmission, and can handle perfectly the very large impedance mismatches that occur between slow and fast light regions.

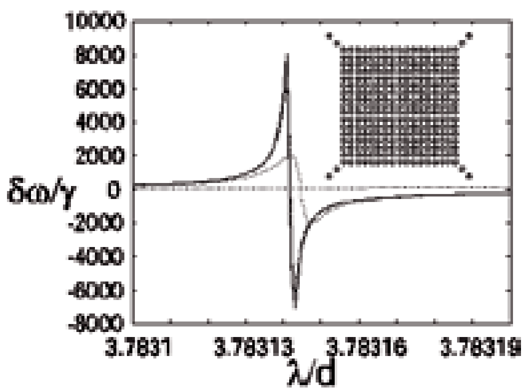
Radiation Dynamic in PC structures

In this work, we (Andrew Norton, Michael Steel, Ara Asatryan, Lindsay Botten) have developed tools to support the experimental radiation dynamics studies of woodpile PCs with embedded sources (quantum dots) fabricated at the Swinburne node. The radiation dynamics is highly dependent on the environment of the source due to the strong scattering that takes place within the photonic crystal. We use FDTD simulation augmented by Mathematica packages developed by the UTS group to handle time and frequency resolved calculations and the necessary near-field to far-field transformations. The full structure is very large and since this implies both long computational times and access to very large memory (up to 80 GBytes), access to the APAC National Facility is vital. We acquired considerable expertise in the use of the FDTD software and knowledge of the "tricks of the trade" needed to yield stable and accurate results, as well as building up a significant library of codes that will be used, in 2007, to model actual experiments.

In other work (Asatryan, Botten, McPhedran, de Sterke and Nicorovici), a comprehensive study of the frequency (Lamb) shift and local density of states (LDOS) in 2D cluster systems was completed using multipole methods [6,7]. The studies revealed extreme sensitivity on cluster size, shape and orientation. By carefully tailoring the shape of the cluster, the frequency shift can be greatly enhanced even for relatively small systems



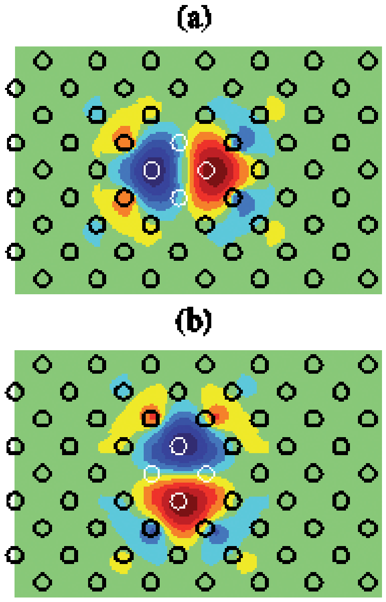
▲ **Figure 2. Variation of reflectance with increasing length of the transition region (W2), from the slow light region of width W1=2d, in which the group velocity is c/100, through the transition of width W2=2.008d, to the high group velocity region of width W3 =2.6d. The reflectance has been totally nullified for a length of L=9d.**



▲ **Figure 3. The extreme effects of cluster shape on the frequency shift. Three curves are shown, (a) with the smallest effect being for the square cluster with the corner scatterers removed, (b) the standard square cluster, and (c) for the square cluster with additional corner cylinders added that shows the greatest frequency shift.**

Defect Modes

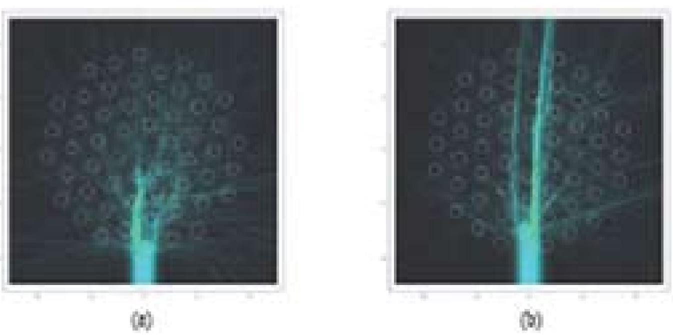
There are computational tools for modeling defect modes in photonic crystal structures (including MOFs), but only the fictitious source superposition method developed within our group can handle the pathological case of poorly confined modes (e.g., near modal cutoff) for which all other techniques fail. Our method is unique because it exactly models an infinite cladding, making it possible to answer fundamental questions about the existence and structure of modes. This year, we (Kokou Dossou, Lindsay Botten) have substantially extended the method [8] to handle general defects that involve the removal of an arbitrary number of scatterers and we are now looking, both theoretically and computationally, at the evolution of defect states with weak perturbations of the structure.



▲ **Figure 4. Field plots for the degenerate pair of modes for a square 2x2 defect in a square lattice, modeled by removing 4 cylinders over 3 rows of a triangular lattice.**

Transverse scattering by a MOF

A new collaboration emerged with our Macquarie colleagues (Graham Marshall, Mick Withford) to model the process of writing a Bragg grating into the core of a MOF using a short wavelength laser (Dougal Kan, Ara Asatryan, Lindsay Botten). Because of the very small wavelength/pitch ratio (0.03) that was involved, the modeling task was very challenging for standard numerical tools and, accordingly, we implemented a multipole treatment which provided both good accuracy and computational efficiency. Good agreement [9] was obtained between modeling and experiment, with our simulations showing extreme sensitivity to both the rotation and the translation of the fibre in a scattering regime that corresponds closely with that of geometrical (ray) optics.



▲ **Figure 5. Intensity plots calculated at an angle (a) that poorly couples to the fiber core, (b) that exhibits near optimal coupling to the fiber core.**

Electromagnetic localization

We continued our interest (Asatryan, Botten McPhedran, de Sterke) in propagation in disordered systems and investigated the scaling theory of Anderson localization in 2D clusters using a renormalization group analysis. Contrary to common belief we have discovered evidence [10] of the existence of a mobility edge (in 2D) — a transition from diffusive propagation to localization in which the field is extinguished by strong scattering. Also this year, during the visit of Prof Valentin Freilikher, we investigated, both theoretically and by numerical simulation, the localization properties of random metamaterial structures comprising alternating left handed and right-handed slabs (Asatryan, Freilikher, Botten, McPhedran). Their properties are very different (e.g., showing an absence of resonances and much longer localization lengths) to those of conventional structures, with this directly attributable to the phase cancellation that results in weaker interference action.

References

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