Chief Investigator: Lindsay Botten

CI short biography

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 200 refereed publications and is a Fellow of the Optical Society of America, the Australian Institute of Physics, the Australian Mathematical Society, and the Electromagnetics Academy. He possesses broad expertise in a range of mathematical and computational techniques in electromagnetic theory, and has a particular specialisation in the development of semi-analytic tools for modelling propagation and radiation dynamics phenomena based on Bloch mode, multipole and eigenfunction methods, for which he is internationally recognised.

He has a strong background in scientific computing, computational mathematics and physics, and is a leader in national high-end, research computing through his work over the years as University Services Director of ac3, a Member of the APAC Board, through leadership of grants for the acquisition of new HPC systems for the NSW consortium in 2003, 2006 and 2009, and, from 2008, as Director, National Computational Infrastructure (NCI)—the national peak supercomputing facility funded by NCRIS, EIF and a number of partner organisations including ANU, CSIRO, Geoscience Australia and Intersect. He also serves a member of the Editorial Board of Proceedings A of the Royal Society and is a reviewer for eight journals.

Key areas of research contribution within the Centre

Within CUDOS, Lindsay Botten leads a substantial research program in the development of novel theoretical methods and computational tools, and manages the activities of UTS node of the Centre (comprising 2 academic staff, 2 research staff). The major focus of the UTS group is to advance modelling expertise within the Centre and to support research programs with strong electromagnetic modelling skills and advanced computational techniques. The group contributes to the "3D Bandgap Devices" and the "Slow Light" flagship programs and specialises 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 and 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 modelling is provided through access to the NCI National Facility and, from 2011, CUDOS will be supported as one of NCI's Flagship Programs.

Researchers and students: (including collaborators)

Researchers

UTS: Lindsay Botten, Chris Poulton, Ara Asatryan, Kokou Dossou,

Sydney: Martijn de Sterke, Ross McPhedran, Nicolae Nicorovici (deceased)

Macquarie: Mike Steel

ANU: Yuri Kivshar, Ilya Shadrivov, Andrey Sukhorukov, Tom White

Students

UTS: Dougal Kan

Sydney: Felix Lawrence, Sahand Mahmoodian, Parry Chen, Casey Handmer, Bjorn Sturmberg, Scott Brownless

International collaborations of the group

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

USA: Graeme Milton (University of Utah)

Germany: H Schwefel

Canada: Sophie Larochelle

Research achievements during 2010

During 2009, the UTS group was involved in a broad range of research projects and collaborations.

Development and application of Bloch mode tools

The development of the computational toolkit based on finite element and Bloch mode techniques has continued during 2010, driven primarily by new applications.

Kokou Dossou and Lindsay Botten have developed a *three-dimensional (3D) vectorial finite element method (FEM)* for modelling 3D periodic structures with arbitrary geometry. Since the new tool is based on a diffraction grating formalism, it can be used to simulate a wide ranges of problems arising in the study of photonic crystals (propagation, scattering, Bloch modes, coupling between photonic crystal elements, etc). The numerical solution of the full vectorial electromagnetic field problems has proven challenging due to the need to enforce the field continuity of tangential fields (across material interfaces) while allowing discontinuities in normal field components. Indeed, the development of an accurate and robust FEM is an area of active research that combines numerical analysis with topology and geometry. In validating the code, which will play an important role in the development of semi-analytic Bloch mode approaches for 3D structures, we have tested the method against published results and, in particular, a checkerboard grating (see Fig. 1). Our broad aim is to implement this as an omnibus tool for modelling 3D photonic crystal and metamaterial structures efficiently and accurately. Since such models are computationally intensive, however, supercomputing access is a necessity.

Fig 1: Schematic of checkerboard gratings and transmittance curve under a normal incidence.

The UTS group (Dossou, Asatryan, Poulton and Botten) has developed a *advanced modal theory for modelling diffraction and scattering by photonics crystal slabs* (either dielectric or absorbing) and has been collaborating with colleagues at Sydney (Sturmberg, McPhedran and de Sterke) in applying the theory to study and optimise absorption in silicon nanowire arrays for photovoltaic applications. The theory uses a vectorial FEM approach for the computation of the modes of the photonic crystal slab (PCS), and a semi-analytic approach thereafter to compute the interface (Fresnel) reflection and transmission matrices using overlap integrals and solve the diffraction problem (see Fig. 2). The FEM approach, an adaptation of the method originally developed for optical fibre modelling, is computational attractive since it formulates the determination of modes as a generalised (linear) eigenvalue problem, making the search for modes much simpler, and more accurate, than alternative methods, and the resulting diffraction code to be intuitive, accurate and efficient. The use of this tool to study the design and optimisation of highly efficient absorbers for photovoltaic applications is discussed elsewhere in this report. Papers reporting on this work will be prepared during 2011.

Previously, we reported a major advance in our ability to conceptualise 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, a PhD student at Sydney, who is supervised by Botten, Dossou, de Sterke, and McPhedran,. The focus of the most recent work has been to exploit the technique to *study photonic crystal surface modes*, with the dispersion relation being derived from the singularity in the generalised Fresnel surface reflection matrix in a manner analogous to the derivation of the surface plasmon dispersion relations [1].

Since publication of the previous report, work has continued to build upon the successful 2009 honours project of Casey Handmer in which he together with Sydney (de Sterke, McPhedran), Macquarie (Steel) and UTS colleagues (Rahmani and Botten) developed theoretical and computational techniques to enhance the amplitudes of the non-propagating evanescent orders in resonant dielectric gratings. This led to the ability to *design blazed gratings* with spectra tailored to generate *steerable sub-Rayleigh field concentrations* on a surface. Two papers have been published: one which investigates the enhancement and customisation of evanescent fields necessary to create a virtual and passive scanning probe [2], and another which focuses on the theoretical methods and computational techniques [3].

In research related to the 3D bandgap PC flagship, UTS PhD student, Dougal Kan, supervised by Poulton, Asatryan, and Botten has developed efficient computational tools for computing the defect modes of linear defect waveguides embedded in a 3D woodpile structure. Most recently, the group has extended the *fictitious source superposition method to compute defect modes in 3D structures*, obtaining results for woodpile linear waveguides and woodpile resonators (see Fig. 3). This method [4, 5] is unique in that it is capable of simulating a waveguide structure without resorting to the need for a super-cell; this means that accurate results for this computationally intensive problem can be obtained in a quick and efficient manner. Interestingly, near-constant dispersion was observed over a large portion of the Brillouin zone, with this appearing to be a characteristic behaviour of the woodpile geometry. This raises the possibility of engineering a slow-light waveguide for which out-of-plane scattering losses are largely non-existent. We have also begun computations of the properties *of surface states in woodpiles.*

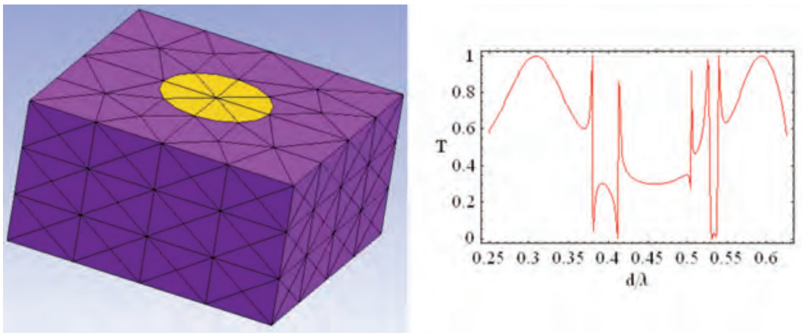


Fig 2: FEM mesh and transmission spectrum of a photonic crystal slab.

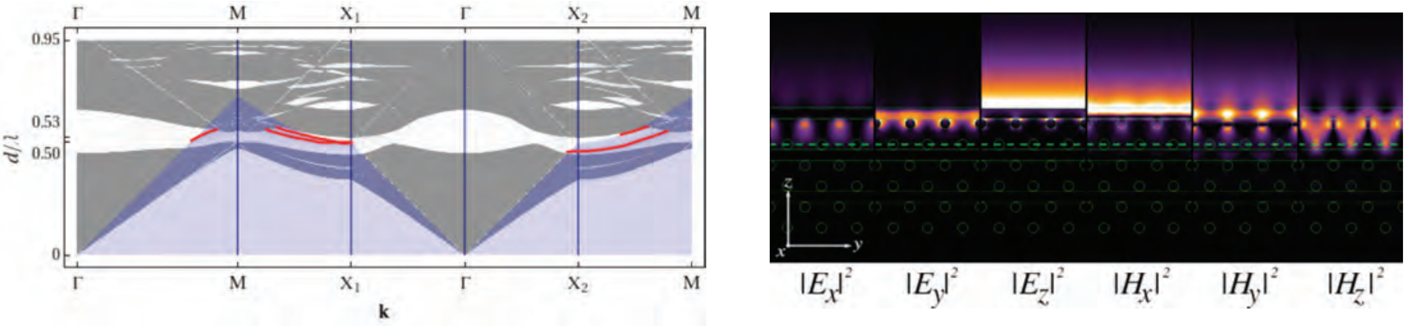
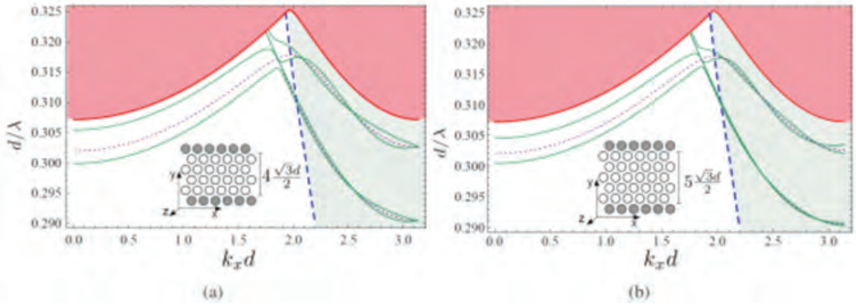


Fig 3: a) Surface modes (red) of a chalcogenide woodpile (the light cone is shaded in blue). b) Surface mode field components. The mode extends a large distance from the surface of the woodpile, which fills the lower half-plane.

In Honours work by Scott Bownless (Sydney), a UTS (Dossou, Botten) and Sydney (de Sterke, Mahmoodian, Lawrence) collaboration has extended the previous study of properties of *coupled waveguide modes* to the case *hexagonal photonic crystals*. The properties of coupled waveguide modes in photonic crystal structures are particularly interesting as they can differ markedly from those of conventional rib waveguides, e.g., the possibility of both odd and even symmetric fundamental modes in a coupled PC waveguides, with mode symmetry determined by the number of layers in the barrier. The extension to hexagonal structures has yielded dispersion curves that exhibit unusual intertwining (see Fig. 4), the behaviour of which is determined by the hexagonal nature of the lattice and the width of the barrier between the coupled waveguides. We have developed an elegant, physical interpretation for the properties observed and a novel, asymptotic, perturbation theory that precisely explains the mechanism by which these appear [6].



(a)
(b)

Fig 4: Dispersion curves of CWMs for (a) PCWs separated by four rows (staggered geometry) and (b) PCWs separated by five rows (inline geometry). The purple dashed curve and the solid green curves are for a single waveguide and for CPCWs, respectively.

Defect Modes — semi-analytic models for cavity modes in photonic crystals

Semi-analytic models of shallow defect states: In work undertaken jointly by the Sydney and UTS nodes, Sydney PhD student Sahand Mahmoodian, and CUDOS researchers Chris Poulton, Kokou Dossou, Lindsay Botten, Ross McPhedran and Martijn de Sterke, have been developing a semi-analytic theory for cavity modes in photonic crystals. The linear properties of PC resonators are usually obtained using direct numerical methods such as the Finite-Difference Time-Domain and the Finite Element methods and although these algorithms can be applied to almost any structure, they are computationally expensive and become increasing less efficient for states close to the band-edge. In recent work, we have developed and validated a semi-analytical method for the computation and analysis of localised resonant states with frequencies close to photonic crystal band edges. The method [7] results in a differential equation for the envelope function of the confined state that is readily solved to determine good approximations to both frequencies and fields. We have since used this method to study the properties of shallow waveguide cavities and (with A. Sukhorukov, ANU) have calculated the exotic behaviour of cavity modes arising from “split” band edges.

Backward modes in nanocavity plasmonic waveguides: In conjunction with researchers at ANU (Neshev, Sukhorukov, Miroshnichenko, Xu, Kivshar) and as part of the PhD of Liu Wei (ANU), Chris Poulton has investigated plasmonic coupled waveguides consisting of dielectric embedded into a metallic matrix [8]. It has been demonstrated that a complete spectral gap can be achieved in a symmetric structure composed of four such coupled waveguides

Phononic modes in waveguides: In a collaboration with Ravi Pant and Ben Eggleton (Sydney), Chris Poulton has investigated vibrational modes in nanophotonic chalcogenide waveguides. Using a model developed by Poulton (UTS), the group computed the acoustic modes and hence the Brillouin scattering in these waveguides. The theoretical study of chalcogenide rib waveguides (by Honours student Hannah McFarlane, Sydney) showed that the polymer coating commonly used to protect the chacogenide surface can be used to suppress Brillouin scattering in these waveguides. Experiments are currently in progress with the aim of confirming this prediction.

Structured systems of lossy materials and metamaterials

During 2010, the UTS group continued its research into complex systems involving lossy real materials and metamaterials—encompassing both random and structured (periodic) systems. This work has been further enhanced through the award of an ARC Discovery Grant “Novel effects of metamaterials on propagation and localisation of electromagnetic waves in photonic crystal structure” for 2009-11. Over the past year, Asatryan and Botten, in collaboration with colleagues from ANU, Sydney and Israel, have continued our studies of *Anderson localisation in disordered 1D stacks* comprising normal and metamaterial layers. Based on our general and accurate theoretical framework [9] we have extended our studies to consider the effect of polarisation [10] on localisation and have developed short and long wavelength asymptotes of the localisation length at the Brewster angle. The work is now being further extended to study dispersion effects.

In other work concerned with *propagation is lossy structures and metamaterials*, PhD student Parry Chen, working with McPhedran, de Sterke (Sydney), Asatryan, Poulton and Botten (UTS), and Steel (Macquarie), has been studying the complexities of band structures in periodic lossy and metamaterial; systems and of relating the group and energy velocities to the properties of the Bloch modes. One paper, which considers the formulation of a generalised expression for group velocity in terms of modal fields (valid for both lossless and absorbing photonic crystals), has been published [12] while a second, which considers the nature of folded bands and the meaning of infinite group velocity, has been submitted for publication.

In further work, a Sydney (McPhedran, Nicorovici (deceased)) and UTS (Poulton, Asatryan and Botten) collaboration has been investigating *densities of states in lossy materials.* The local density of states (LDOS) is an important physical quantity in many photonic systems as it governs the emission of sources. The focus of our work has been on how this quantity is affected by the presence of loss in realistic materials, with the answer to this question facilitating the study of fundamental physical properties of metamaterials in a rigorous manner. The focus of work in 2010 has been the extension of existing methods for calculating LDOS to the case of coated lossy cylinders [12,13].

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