CUDOS

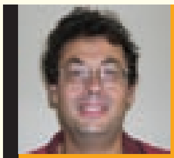
Photonic Structures Program

Annual Report 2004

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

An Australian Research Council Centre of Excellence

Photonic Structures Program



Program Manager: Martijn de Sterke

The objectives of this program are to study the fundamental aspects of the integration and miniaturisation of photonic components. There is a particular focus on the opportunities in this regard presented by photonic crystals. Several key themes epitomise work in the program:

- **The development of numerical tools (complete with sophisticated graphical interfaces) that have enabled rapid investigation and "reduction to practice" of innovative photonic crystal concepts**
- **A series of fundamental investigations of radiation dynamics – trapping, guidance and emission – in photonic crystals**
- **Studies of a range of novel device concepts embodying the fundamental physics that differentiates photonic crystals, with close coupling to eventual experimental implementation.**

Most activities in the program are carried out by the theoretical teams at Sydney and UTS with experiments at Sydney and Macquarie, but the work is tightly coupled to the experimental studies of photonic devices at other nodes discussed in the other three programs.

Photonic circuits project

Project leader: Martijn de Sterke

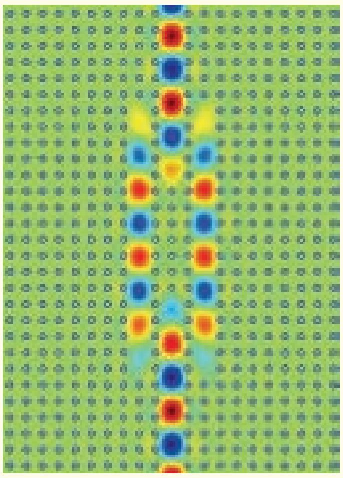
Martijn de Sterke

This project is centered at the University of Sydney and at UTS. The aim is to evaluate some of the basic properties of photonic crystals and to compare these to the properties of devices in conventional waveguide and to bulk devices. In this way we try to answer the key question: in the cold light of day, what can photonic crystals really offer us? Though the project is based at Sydney and UTS, collaborations are ongoing with Macquarie University and with Swinburne.

Photonic-crystal based devices

White, de Sterke, Botten, McPhedran

We have applied the Bloch function method, developed under the Computational Modelling project, to a number of photonic crystal-based devices. The key advantage of this method is that photonic crystal devices can be modelled as if they were thin-film stacks, for which design methods are well known. As an example, we considered a Mach-Zehnder (MZ) interferometer. Conventional MZ interferometers have beam splitters, which let some of the light escape from the structure. In a MZ interferometer in a photonic crystal this option is not available since it would require the light to travel through a bandgap. Since the light can thus not escape it must rattle around through the MZ interferometer, changing the device response strongly. This novel response, which is much steeper than that for conventional devices, is a great advantage for one of the key applications of MZ interferometers: the conversion of a phase modulation to an amplitude modulation.

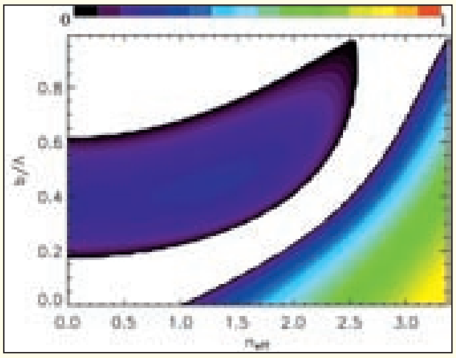


Electric field plot showing the 'on' state of a symmetric photonic crystal M-Z interferometer with two coupled y-junctions. When a phase delay is introduced into one arm, anti-symmetric field components are recirculated through the interferometer producing resonance effects and a considerably sharper phase response than in conventional M-Z Interferometers.

Packing density in photonic crystals

Tomljenovic-Hanic, Steel, de Sterke

One of the key criteria in evaluating the suitability of photonic crystals as building blocks for photonic circuits is the packing density: the number of devices that can be squeezed into a particular area. To evaluate this we compared the minimum distance that needs to be kept between two adjacent waveguides. The idea behind this is that these waveguides play the same role as wires in electrical circuits; the tighter the "wires" can be packed the more devices can be squeezed together. Two waveguides cannot be placed arbitrarily close together, since then the light in the two guides would mix. We have found that in a one-dimensional photonic crystal this minimum distance is smaller than in a conventional geometry, but the difference, roughly 1%, is very small. So as far as this criterion is concerned, photonic crystals and conventional waveguides behave quite similarly.



Summary of the properties of light propagating in a one-dimensional photonic crystal, consisting of silicon and air. Shown on the axes are the fill fraction of silicon, and the effective index of the mode. The coloured regions indicate the positions of bandgaps, with the colour coding showing the rate at which the field decays. The optimum configuration occurs for low, but nonzero silicon fraction and large effective index.

Radiation Dynamics project

Judith Dawes

Project leader: Judith Dawes

In this project we aim to understand how emission and propagation characteristics of light are influenced by photonic crystal structures. Within a photonic crystal, light in the bandgap cannot propagate. This property has implications for the design of highly efficient photonic crystal-based lasers with ultra-low thresholds.

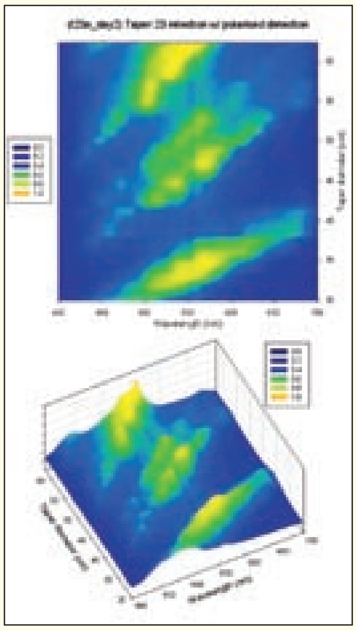
We have used dye molecules, which act as light emitters to probe the optical characteristics of photonic crystal structures. Two photonic crystal hosts are being studied experimentally – tapered microstructured optical fibres and natural sea mouse spines – while modelling has also included macroporous silicon, which has particularly strong bandgap effects. The project is being conducted by an experimental group at Macquarie University in close collaborating with researchers at the University of Sydney.

Radiation characteristics in tapered MOFs

Myers, Dawes, Withford, Magi, Eggleton, Fussell, McPhedran, de Sterke

Dye molecules can be easily introduced into the hollow cored photonic crystal structure of microstructured optical fibres. These fibres can guide light by bandgap effects or by the "index" guiding characteristic of standard optical fibres. We probed the photonic crystal fibres transversely to understand the bandgap effects independently of index guiding. The fibres are tapered to allow their bandgap properties to be probed at accessible (visible and near infrared) wavelengths.

After tapering the hollow core photonic crystal fibres, we measured the reflectance and transmission of the fibres with white light illumination, and introduced dye solution into the central pore of the fibres. Spectral characterisation of the spontaneous emission from the dye solution has shown some dependence on the angle of emission and on the polarisation of the emission.



Reflectance spectra of dye inside a tapered microstructured optical fibre.

Optical properties of Sea Mouse spines

Dawes, Myers, Marshall, Fussell, McPhedran, de Sterke, Prof David McKenzie (U.Sydney)

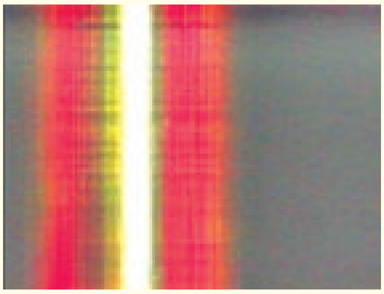
The spines from Aphrodita species (sea mouse, dwelling on Australian coastlines from NSW to SA) are iridescent. The structures producing this iridescence are naturally occurring photonic crystals, and they exhibit a hollow core surrounded by regularly spaced pores of chitin. After characterising the optical reflectance of the structures using a microreflectance spectrometer, we next plan to introduce dye solutions into the hollow central core. The aim is to understand the effect on the spontaneous emission from the dye of a photonic crystal with a degree of long-range disorder, for example on the emission polarisation dependence, or the angular distribution of emission. This lack of long-range order appears to characterise the sea mouse spine structure, with its apparently regular photonic crystal structure. We conducted optical characterisation of the spines, and modelled of the photonic bandgap effects.

Newspaper articles on this subject appeared in the Sydney Morning Herald in February 2004, and The Guardian, April 2004.

Theory of light emission in photonic crystals

Fussell, McPhedran, de Sterke, Dignam

The light emission of atoms located in a photonic crystal can differ profoundly from that in free space. The aim of this activity is to study and bring out these differences, which are changes in the spontaneous emission lifetime (the time it takes for an electron in an excited state to fall down to the ground state), and small changes in the frequency of the emitted light. We completed a comprehensive study showing that in



Spatial map of light reflected from a sea mouse spine.

two-dimensional photonic crystals consisting of holes that are regularly located in silicon, the lifetime for spontaneous emission can be increased by almost a factor 100. We also showed the dramatic effect that at one frequency almost all the light is emitted in the direction parallel to the holes, whereas at a slightly lower frequency most of the light is emitted sideways.

Computational Modelling Project

Project Leader: Lindsay Botten

Lindsay Botten

The computational modelling project supports the work of CUDOS with access to strong mathematical and computational modelling and visualisation techniques. Its primary aims include the development and implementation of new methods and tools for modelling photonic structures and devices, the development of theoretical and computational techniques that address fundamental physical questions that arise in CUDOS research, and the provision of modelling expertise in both specialist and generic tools to other CUDOS programs and projects. In addition to the already strong collaboration with the Photonic Structures projects at Sydney and Macquarie Universities, new collaborations have emerged with groups at Swinburne and ANU.

Late in 2004, the computational infrastructure available to CUDOS was boosted with the acquisition of a dedicated 32 node dual processor Dell Linux Cluster, which is an adjunct to the 152 node cluster located at ac3 in the Australian Technology Park. The new facility will provide CUDOS researchers with state-of-the-art parallel computer system with which to undertake 3D simulations using generic finite difference time domain software and other specialist tools.

Tools development

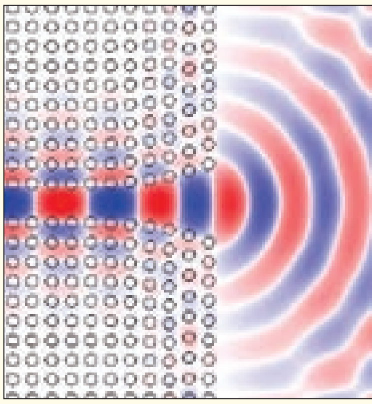
Botten, Norton, Dossou, Asatryan, Langtry

Substantial effort has been devoted to the enhancement of the modelling toolkit during 2004. The Bloch mode tools which are a mainstay of modelling within the CUDOS Photonic Circuits project were substantially extended to handle a much wider range of structures through the introduction of new finite element based methods for computing scattering matrices. The group is also implementing finite difference time domain software and developing a new parallel composite grid FDTD tool based on overlapping grid methods developed in the field of computational fluid dynamics that should be superior in accuracy to conventional techniques. These applications are being parallelised for implementation on the new Dell cluster located at ac3.

Wave propagation in 2D and 2.5D PC waveguides

Botten, Asatryan, Dossou, White, Campbell, Wilcox, de Sterke, McPhedran, Poulton, Brnovic

The Bloch mode toolkit has seen substantial application during 2004 in studying PC devices which have a variety of novel characteristics. Highlights of this work include (a) the characterisation of an optimal taper for the apodization of PC waveguides, (b) the successful design of an optimal Y-splitter with broadband transmittance exceeding 99%, (c) the successful design of a high performance PC based Mach-Zehnder interferometer, and (d) the extension of the techniques to model propagation in superprism structures (in collaboration with the Swinburne group).



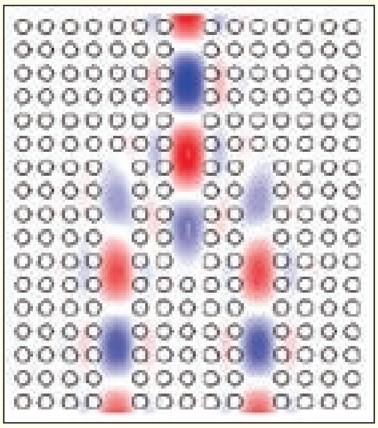
Efficient coupling out of a waveguide using an adiabatic taper.

Impedance models of propagation in PC structures

Botten, Nicorovici, Asatryan, Byrne, White, de Sterke, McPhedran

Work during 2004 capitalised on new theoretical insights into the structure of the Bloch mode basis of PCs and led to the development of impedance/admittance models for propagation in photonic crystal structures. These strongly parallel the theory of conventional guided optics. This theory was applied to model PC structures that exhibit an almost perfect reflectionless coupling for particular frequencies but over a wide range of angles. We interpret the key signatures of this behaviour through those of the gratings and cylinders that comprise the crystal.

In other work, we collaborated with the ANU group led by Barry Luther-Davies to develop a rigorous model that will simulate the Fano resonances of PC slabs fabricated at ANU. The 3D diffraction theory for a grid (i.e. a mesh periodically punctured with holes) of finite thickness has been developed and is presently being implemented.



An efficient photonic crystal Y coupler, as used in a Mach-Zehnder interferometer, that can achieve a transmittance exceeding 99.5% over a very wide wavelength range.