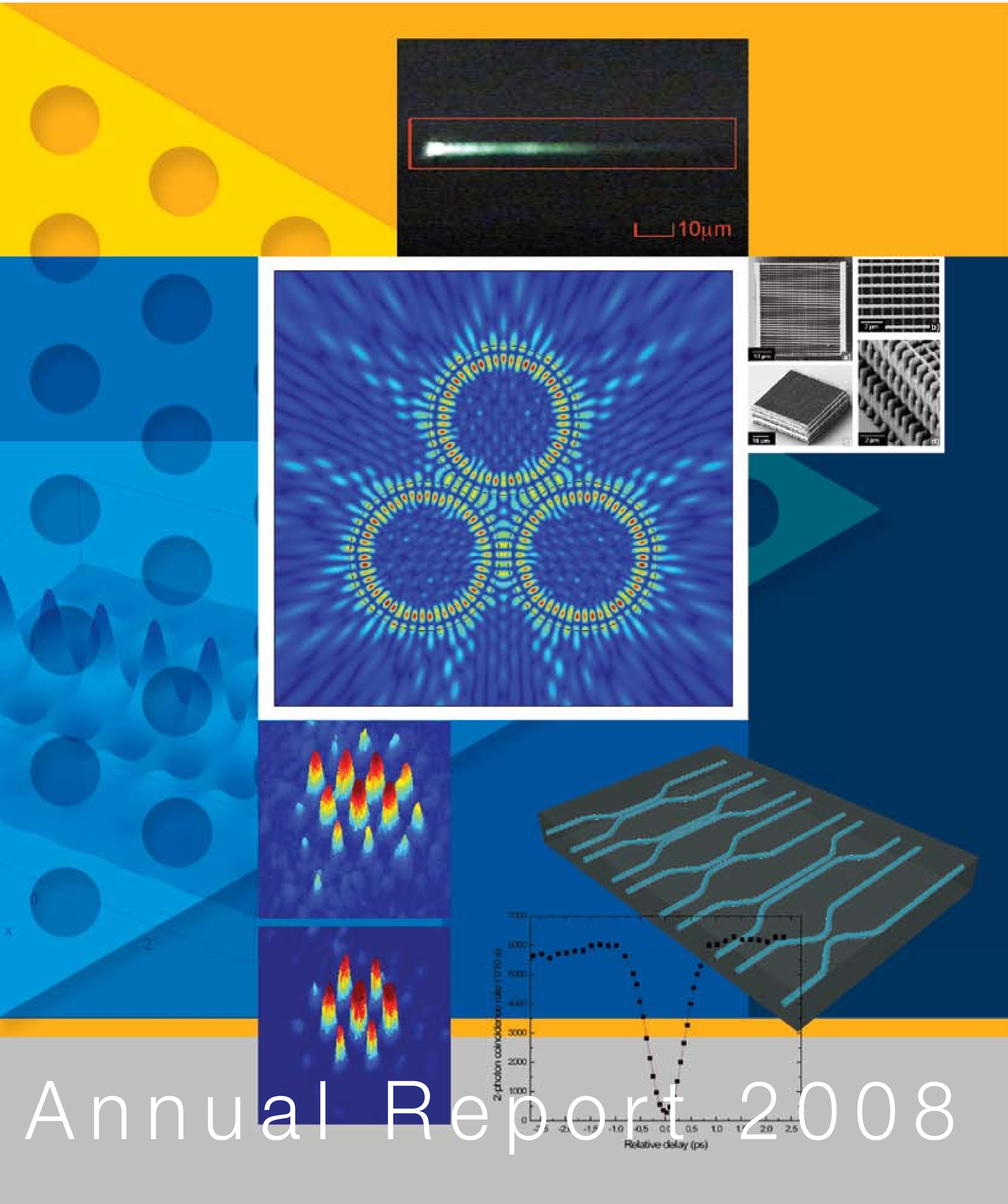
CUDOS

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



Annual Report 2008

SLOW LIGHT

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Four year vision/long term goal and motivation

Apart from its intrinsic scientific interest, slow light has the key feature that interactions with the optical medium are strongly enhanced, leading, for example to increased gain and losses. More importantly for CUDOS, the strength of nonlinear interactions strongly increases, lowering the threshold intensity for nonlinear effects, with obvious advantages for the operation of nonlinear signal processing devices. Slow light is therefore an enabler for other flagship projects as well as being an intrinsically fascinating physical process.

CUDOS strategy/competitive advantage

CUDOS' approach is unique in slow-light research. Other approaches suffer from the effects of dispersion, which leads to a broadening of the slow-light pulses. Our approach relies on nonlinear soliton generation, thus preventing this broadening from occurring.

Collaborative links

This is a collaborative project between researchers at the University of Sydney, the Australian National University (ANU/NL and ANU/LC) and the University of Technology of Sydney. Different aspects of the theoretical work are carried out at the three universities. The experimental work is a collaborative effort, with chalcogenide samples fabricated at the ANU, grating writing performed at the University of Sydney, while chalcogenide photonic crystal slabs are fabricated at the ANU. More recently, collaboration with Prof. Krauss group (St Andrews University) has been developed for realising silicon and chalcogenide photonic crystal slabs. We are also working with Prof. Kuipers' group at AMOLF (Amsterdam) on the characterisation of slow light devices using a heterodyne NSOM.

We are part of a wider collaboration between CUDOS and the European consortium, SPLASH (Slow Photon Light Activated SwitcH), which also involves Polimi in Milan (Prof. Andrea Melloni) and Glasgow University (Prof Marc Sorel, Prof. Richard de la Rue) supported in part by a DEST-International linkage grant since October 2007. Collaboration with DTU Fotonik group at Technical University of Denmark is also developing by way of a visiting professorial fellowship for Prof. Andrei Lavrinenko funded by an ARC Linkage international grant on "Slow-light photonics" (chief investigator Dr. Andrey Sukhorukov, ANU).

Goals for 2008

The aims for 2008 were threefold. The first goal was to improve our fundamental understanding of slow light effects, through the identification of the practical limitations to observe slow light

Slow light team.

(such as nonuniformities and randomness in gratings…) and the demonstration of slow light enhancement of nonlinear effects in periodic structures. The second goal was to demonstrate that low power pulses could be delayed with limited distortion by propagating through chalcogenide Bragg grating waveguides, thereby forming a slow gap soliton. The third objective was focused on the investigation of new designs that would exploit slow light for realising routing and switching devices with small footprint and low power consumption.

Achievements and highlights for 2008

Practical limitations in 1D periodic structures for slow light

One of our main aims this year was the observation of slow light and gap solitons in a grating in chalcogenide glass. This work was delayed by the discovery of significant imperfections in the chalcogenide gratings. These hinder the formation of gap solitons and, even if they are formed, prevent them from traveling slowly. We believe that the imperfections are associated with the build-up of dust on the upper surface of the glass, thereby blocking the writing beams at least partially. We are working on ways to prevent this.

We studied the propagation of gap solitons in Bragg gratings with small imperfections, i.e., with small variations in their period and/or its strength [1]. We suspect that these imperfections prevent us from observing very slow gap solitons in silica glass, gap soliton with velocities less than approximately 0.2 c/n, where c/n is the velocity in the uniform medium. Numerical solutions of the propagation typically lead to results shown in Fig 1a: the soliton propagates seemingly unaffected by the randomness, until it is suddenly reflected. If it is reflected again, the soliton bounces back and forth (see Fig 1a). To understand this, we developed an analytic approach based on an effective particle picture. This predicts that the soliton propagates as a classical particle in a slowly-varying potential. The potential is determined by the imperfections, subjected to a low-pass filter. When the value of this potential exceeds the total "energy" of the soliton, it is reflected. This is illustrated in Fig. 1b, which shows the grating strength versus position, and Fig. 1c, which shows the associated potential. The positions where the potential is highest (at z~140 and z~300) indeed correspond to the positions where the soliton reflects in Fig 1a. While the project was completed successfully, the results do not correspond to the gap soliton characteristics observed in the laboratory. Evidently our inability to observe very slow gap solitons is not associated with grating imperfections. The hunt continues.

In conclusion, while significant grating imperfections make the experiment impossible, smaller imperfections have a minor effect.

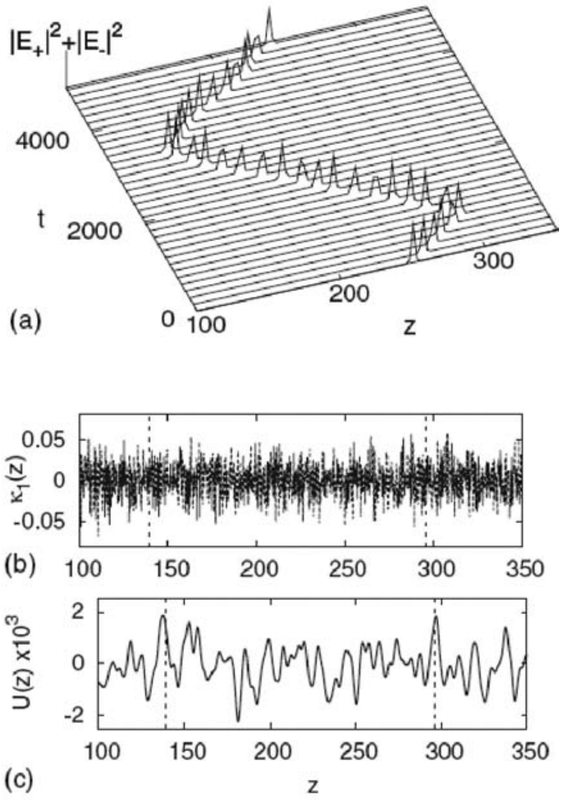

Fig 1. (a) Soliton trapping as simulated for a particular disorder (represented in (b)) in a 1D grating [1]. (c) shows the corresponding potential energy. Vertical dotted lines in (b) and (c) indicate the reflection points.

Slow light enhancement of nonlinear effects in periodic structures

In collaboration with Prof. Krauss' group at St Andrews, the Sydney University team investigated the enhancement of nonlinear Kerr effects in the slow light regime. These experiments were carried out onto a series of silicon photonic crystal waveguides (see Fig. 3a) with a controlled group velocity (between c/10 and c/50) and a reduced group velocity dispersion to avoid the distortion of the slow light pulse that tends to compromise the benefit of slow light. Using this platform, third harmonic generation – i.e. the emission of visible green light from near-infrared pulses – has been observed out of these tightly confined waveguides with a strong enhancement due to slow light (see Fig 2). This was presented as a postdeadline paper at the European Conference on Optical Communications (ECOC) in September 2008.

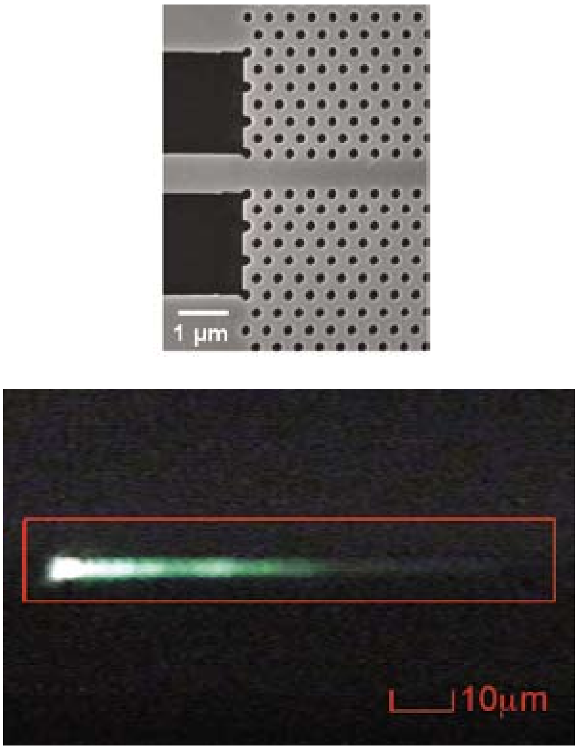

Fig 2. (a) Scanning Electron Micrograph of a dispersion engineered slow light photonic crystal waveguide connected to a nanowire. (b) Green light obtained through third harmonic generation occurring in the photonic crystal waveguide (highlighted as the red box) and measured on a CCD camera.

Other evidence of this slow light nonlinear enhancement has been found on these waveguides by measuring the pulse spectral broadening due to self phase modulation [2]. These experiments also revealed the simultaneous enhancement of nonlinear two photon absorption as well as free carrier related dispersion and absorption due to slow light (see Fig. 3). These results have direct consequences on how slow light could be efficiently exploited in practical nonlinear devices. In particular, they re-emphasize the potential for slow light in photonic crystals to realize nonlinear functions over short scale lengths and/or at low threshold powers. They also point to the potential limitation of silicon material in combination with slow light structures due to these additional nonlinear losses.

Efficient slow-light coupling in a photonic crystal waveguide without transition region

In a collaboration between UTS, Sydney University and Tom White (University of St Andrews), we have considered the efficient coupling of light into a slow waveguide mode (associated with an inflection point in the dispersion curve). Remarkably, the coupling into this slow mode, which has a group index n_g>1000, can be essentially perfect without any transition region (see Fig. 4). We show that this efficient coupling occurs thanks to an evanescent mode in the slow medium – one which has an appreciable amplitude, and so helps satisfy the boundary conditions, but does not transport any energy [3].

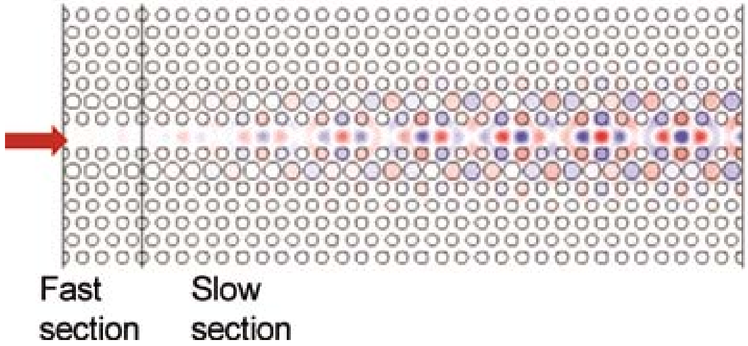

Fig 4. Field distribution corresponding to the transmission from a regular "fast" waveguide (left of the interface) into a slow-light waveguide (right hand side). An efficient coupling is visible without any transition region.

Demonstration of slow light couplers based on periodic structures

We designed slow light couplers that may find applications for the simultaneous tuning of the pulse delay combined with spatial switching [4,5]. A general symmetry analysis of the slow-light dispersion associated to these coupled periodic waveguides has been performed at ANU and at UTS. A universal dependence of the dispersion on the longitudinal shift between coupled periodic waveguides has been predicted analytically and confirmed by numerical modeling for photonic crystal waveguides, nano-pillar arrays and nanowires with holes (see Fig. 5)

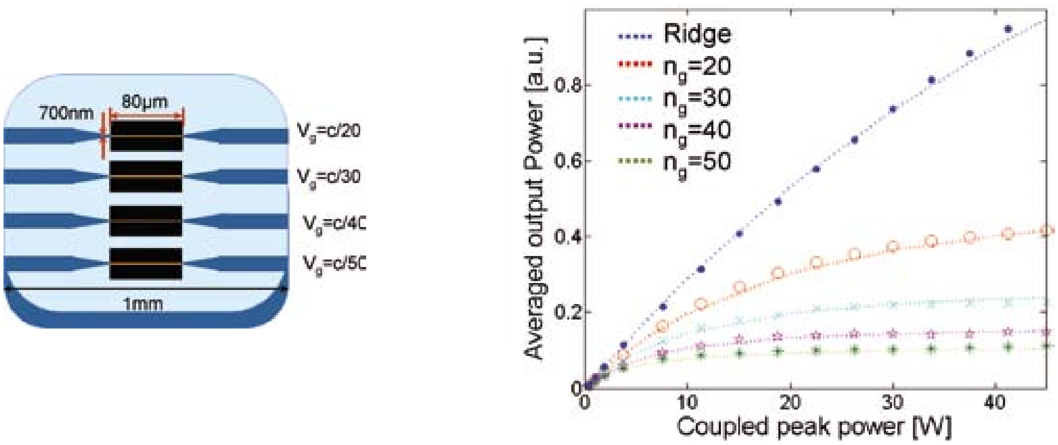

Fig 3. (a) Schematic of the silicon chip including a series of dispersion engineered photonic crystal waveguides with different group velocities. (b) Associated transmission through these waveguides which shows a saturation effect at high power that is related to nonlinear absorption and is enhanced at lowest group velocities [2].

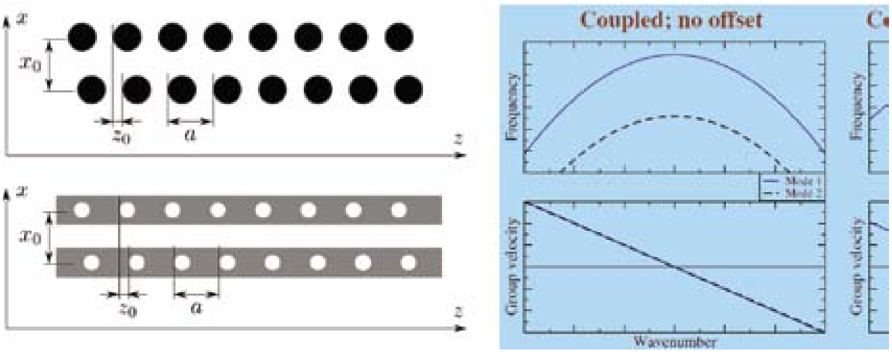

Fig 5: Results of the analytical prediction of the universal dependence of slow-light dispersion (right) for coupled periodic waveguides with different longitudinal offsets. The model is valid for both geometries displayed on the left [4].

An experimental proof-of-principle demonstration of slow-light coupling and the associated dynamics has been performed at ANU at microwave frequencies. For processing the experimental data, we developed an original method that allows us to extract the dispersion in periodic waveguides with high spectral resolution, overcoming the limitations of commonly used Fourier-transform methods (see Fig.6) . Sangwoo Ha won the Outstanding Student Presentation Award at the Frontiers in Optics 2008 conference of the Optical Society of America for his talk "Observation of Slow Light Tunneling in Coupled Periodic Waveguides".

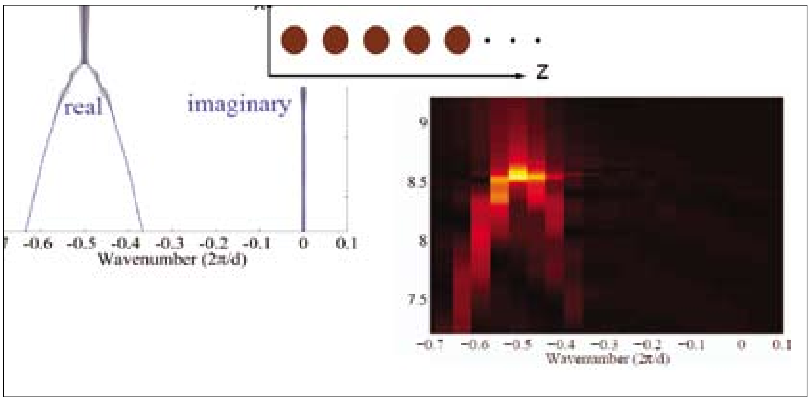

Fig 6: Left: dispersion in a periodic waveguide, extracted from experimental near-field measurements using an original approach. The spectral resolution is dramatically improved compared to the spatial Fourier transform method presented on the right.

Slow light switching in nonlinear Bragg-grating couplers

Further theoretical investigations were carried out at ANU following the promising studies on Bragg grating couplers, which showed that slow gap solitons could be all-optically switched between two phase shifted gratings. In particular, we showed that nonlinear self-action can support efficient slow-light propagation and switching between coupled Bragg-gratings even under the presence of structural detunings from the optimal conditions [6]. These results were selected as one of the monthly Research Highlight of the Nature Photonics journal in September 2008. Experiments are currently in progress at ANU to characterize laser-written Bragg-grating structures fabricated at Macquarie University.

Targets for 2009

For 2009 we will continue to investigate slow light within various architectures, namely one dimensional (1D) grating realised on silica waveguides and chalcogenide waveguides as well as two-dimensional (2D) photonic crystals (chalcogenide and silicon). The main goal of 2009 will be to exploit the slow light nonlinear enhancement that we have demonstrated in 2008 to realise nonlinear devices requiring either lower power or smaller footprint. This includes for instance the realization of an all-optical regenerator based on slow light enhanced self phase modulation and filtering as well as the construction of switching and routing devices for the manipulation of slow light. We also plan to consider effects of nonlinearity on slow-light cavities. In parallel, we will continue to investigate how other nonlinear effects (such as Raman scattering, Four Wave Mixing) may benefit from slow light periodic structures. Another key aim is to understand in detail why the experiments with chalcogenide gratings were not successful. Solving this will open the door to new classes of experiments.

References

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