SLOW LIGHT


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Long term goal and motivation

Slow light can lead to strongly enhanced interactions with the optical medium, lowering the intensity requirements for nonlinear effects. One long term goal is to exploit this phenomenon to develop low power nonlinear signal processing devices.

Our second long term aim is to explore, through theory and simulation, novel optical configurations in which the propagation of optical pulses can be slowed down.

CUDOS approach/competitive advantage

Through experiments and theory we study slowing of light in a nonlinear medium with a periodic structure. The efficiency per unit length of nonlinear effects is enhanced through exploiting strong slow light–matter interaction occurring in these structures.

Most linear slow-light research suffers from the effect of dispersion with a consequent broadening of the slow-light pulses. By controlling the nonlinear response of the medium we can prevent this broadening from occurring and balance dispersion. The solitons that result are themselves a special case of slow light propagation.

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 waveguides and photonic crystals fabricated at the ANU/LC, and grating writing performed at the University of Sydney.

Collaboration with Prof. Krauss's group (St Andrews University) has developed for realising silicon and chalcogenide photonic crystal slabs. The group is also working with Prof. Kuipers's group at AMOLF (The Netherlands), on the characterisation of slow-light photonic crystal devices using a heterodyne NSOM technique. A more general collaboration between CUDOS and the European consortium, SPLASH (Slow Photon Light Activated SwitcH), has been built and benefits from a DEST-International linkage grant since October 2007.

Collaboration with DTU Fotonik group at Technical University of Denmark is continuing, with the support of visiting professorial fellowship for Prof. Andrei Lavrinenko through the award of ARC Linkage international grant on "Slow-light photonics" (CI Dr. Andrey Sukhorukov). Following a visit of Dr. Jacob Scheuer (Tel-Aviv University) to ANU/NL with the support of the European Cooperation in Science and Technology (COST) Reciprocal Pilot Programme with Australia, we have completed a joint work on all-optical pulse trapping with dark resonances. As part of the continuing collaboration with Prof. Conelia Denz's group at Munster University, Mr Sebastian Kroesen (student from Munster University) visited ANU/NL to study theoretically slow-light dynamics in nonlinear periodic structures (DAAD travel grant).

Slow light team.

Goals for 2010

Our aims for 2010 were focused on the demonstration of practical applications of slow light. We aimed to demonstrate that with the dramatically enhanced optical non-linearities occurring in our experiments at low powers or along small interaction lengths, slow light could be the basis of new classes of very compact all-optical signal processing devices. In addition, the dispersion engineering in these structures should make them compatible with ultra-high data rates close to the Terabit/s.

Achievements and highlights for 2010

Slow light in silicon photonic crystal waveguides

We used dispersion engineered silicon photonic crystal waveguides designed and fabricated by collaborators in PI Prof. T. Krauss' group at St. Andrews to continue our exploration into slow light enhancement of optical nonlinear effects1. This year saw demonstrations of enhanced four-wave mixing at the CUDOS labs in Sydney2. The conversion efficiency per unit length of the four-wave mixing derived through the Sydney experiments was found to be over an order of magnitude greater than in silicon nanowires. We found that the four-wave mixing bandwidth extended over the low-dispersion slow light band of these engineered silicon slow light photonic crystal waveguides. These experiments showed us the potential of these waveguides as compact four-wave mixers.

In these experiments, we performed optical time division de-multiplexing of a 160Gb/s signal into 10Gb/s channels in an 80µm long dispersion engineered photonic crystal waveguide. Slow light enhanced the four-wave mixing process, allowing us to shrink the length of waveguide necessary to achieve 'error-free' de-multiplexing. The addition of inverse taper mode adaptors to the St. Andrews chips decreased insertion losses and also enhanced the stability of the end-fire coupling technique used, ultimately resulting in more reliable measurements in systems experiments.

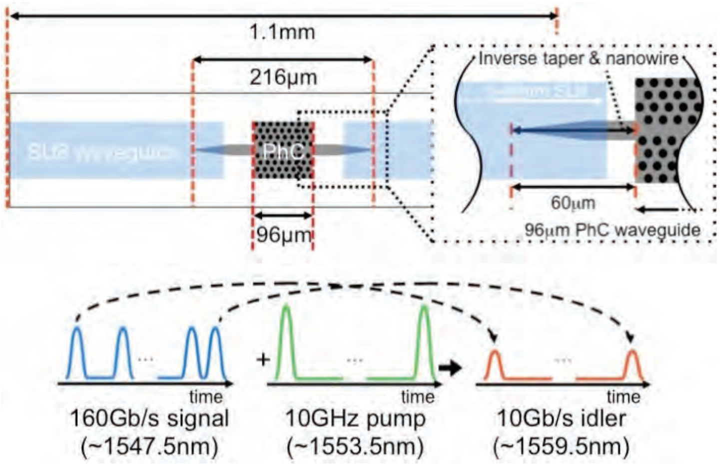


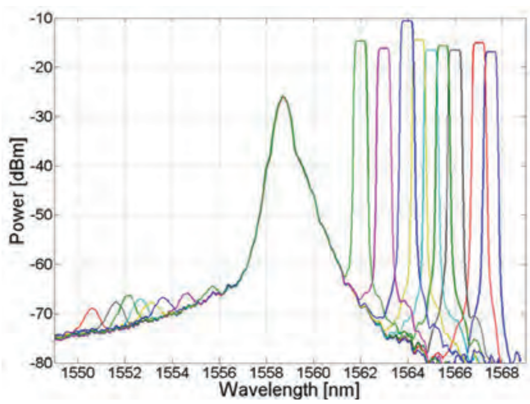
Fig 2: Schematic of the engineered photonic crystal waveguide chip and four-wave mixing based de-multiplexing scheme. Inverse tapers mediate coupling from fibres to nanowire waveguides, which are butt-coupled to the photonic crystal waveguide. On chip, a 160Gb/s signal is mixed with a 10GHz optical clock used to pump the four-wave mixing interaction. The idler product of the nonlinear mixing is a 10Gb/s tributary channel of the 160Gb/s data stream.

We also investigated the limitations of silicon as a platform for ultra-fast nonlinear processing due to the dynamic of free carriers and the associated nonlinear loss[3,4]. These findings highlighted the potential of this material for applications at very high bit rates, where the impairment due to free carrier effects considerably decreases.

Third harmonic emission

Following the successful use of third-harmonic generation in slow light photonic crystal waveguides as an ultra-fast monitor to measure the quality of 640Gbit/s signals[5], investigations into the associated emission of green light from our photonic crystal waveguides progressed. In particular, the role of phase matching was explored experimentally via Fourier optics6. This gave insight into the underlying physics of this process in the presence of high levels of absorption and dispersion – conditions under which numerical investigation of these effects becomes quite difficult. Investigations into THG in dispersion engineered chalcogenide photonic crystal waveguides are also underway, exploring this effect in a medium where the impact of nonlinear losses is greatly reduced.

A



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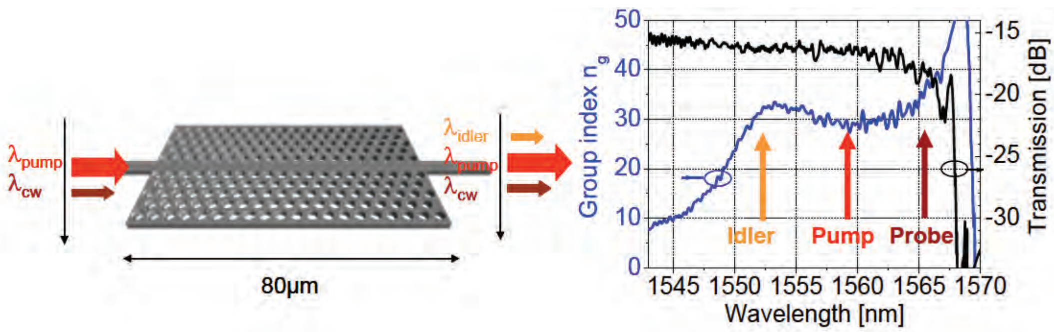

Fig 1: a) FWM spectra of the slow PhC waveguide for different probe wavelengths when launching a constant coupled probe power of 400µW, and a coupled peak pump power of 1W.
b) Schematic partially degenerate FWM in the probed planar PhC waveguide. The pulsed pump and CW probe mix to create an idler wave. (right) Spectral variation of the group index for the dispersion engineered PhC waveguide with the wavelength of the probe, pump and idler highlighted.

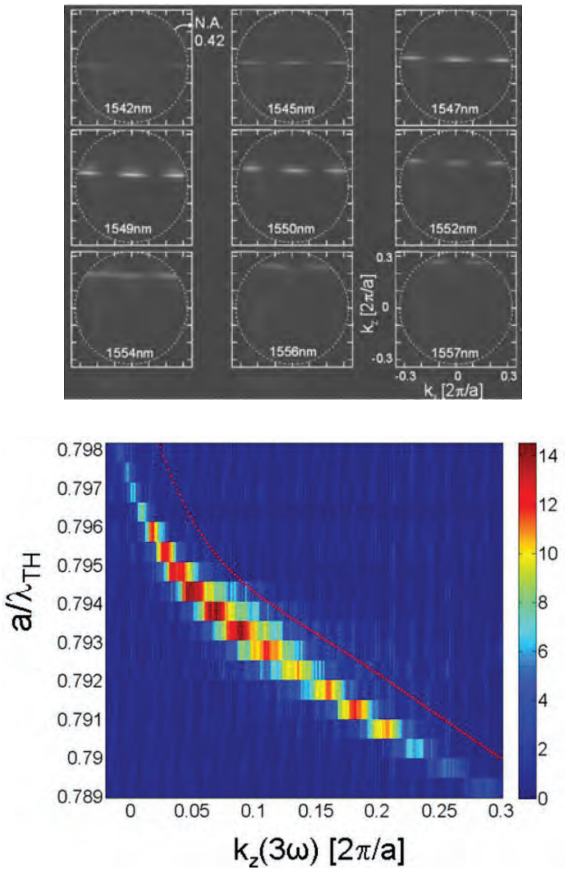

Fig 3: (top) Fourier space images of the third-harmonic emission from the waveguide 4816 - a W1 PhC waveguide with the first row of holes displaced 48nm toward the waveguide defect off-lattice, the second row 12nm toward the defect. Note the variation in the wavevector in the propagation direction kz of the brightest feature of the Fourier space image with probe wavelength, indicating a difference in phase matching between the fundamental mode and third-harmonic. The value the lattice period a is 410nm. (bottom) 2D map of the TH light dispersion (kz(ωTH), ωTH = 3ω) inferred from these images (colorbar increases with the green light intensity). The quasi-phase matching condition (3kz(ω)-2ϖ/a, 3ω) predicted from the calculated fundamental mode dispersion (kz(ω), ω) is superimposed (red dots).

Based on our work in previous years we were invited to write a review article7 about the enhancement of nonlinear effects in periodic structures. This paper tries to unify the different concepts associated with the 1D gratings and 2D photonic crystal platforms, and highlights the advantage of the latter for providing an additional degree of freedom in terms of balancing nonlinearities and dispersion for soliton-like applications through dispersion engineering.

Reflectionless slow-light velocity modulations in coupled-resonator optical waveguides

Periodic photonic structures in the form of coupled-resonator optical waveguides (CROWs) can be used to slow down optical pulses, which propagate through tunneling between neighboring cavities. The propagation velocity can be controlled by varying coupling between the cavities. However, if the modulation of coupling is introduced for velocity adjustment along a CROW, it would usually result in partial pulse reflection. We have revealed[8] that reflections can be completely suppressed, and have developed a mathematical theory which can exactly describe the profiles of such reflectionless potentials. This opens up new possibilities for manipulation slow-light pulses in CROW waveguides.

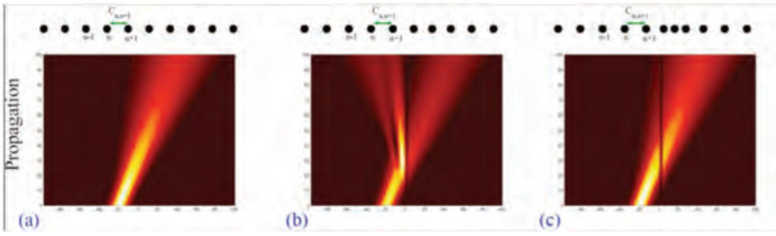

Fig 4: Top row: schematic of coupled resonator optical waveguides with (a) homogeneous arrangement, (b) modulated coupling, and (c) special reflectionless modulation. Bottom row: pulse propagation dynamics.

Nonlinear light trapping in dark cavities

New approaches for optical pulse control in photonic structures employ an analogy with the coherence phenomena in quantum-mechanical systems. In particular, the electromagnetically induced transparency (EIT) is attributed to destructive quantum interference with a narrow transparent window in the absorption spectrum. We developed an on-chip all-optical dynamic tuning scheme for coupled nonlinear resonators employing a single control beam injected in parallel with a signal beam. We show[9] that the nonlinear Kerr response can be used to dynamically switch the spectral properties between an electromagnetically induced transparency and "dark state", where the latter configuration corresponds to pulse trapping inside the double-ring cavity. Such a scheme can be realized in integrated optical applications for pulse buffering and delaying.

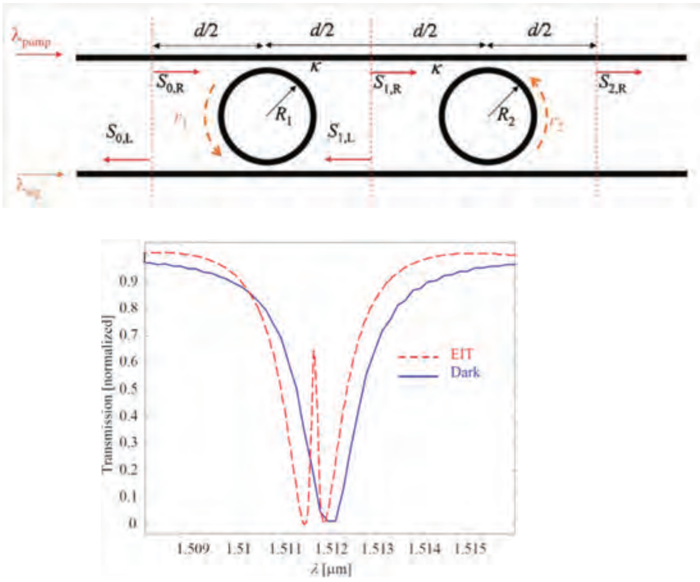

Fig 5: Top: Schematic of the coupled microring resonators structure. Bottom: Probe transmission spectra without pump (dashed curve) and with pump (solid curve).

Slow light in photonic crystals with material loss or gain

Slow-light regime associated with flat dispersion features appearing inside an optical transmission band is most resilient with respect to various perturbations in comparison with band-edge slow-light. We reveal the general features of optical pulse propagation through photonic crystals supporting in-band slow light, when material exhibits loss or gain. We predict that weak material loss (gain) is enhanced proportionally to the slow-down factor, whereas the attenuation (amplification) rate saturates for loss (gain) exceeding a certain threshold. This happens due to hybridization of propagating and evanescent modes. Most remarkably, this allows significant intensity enhancement in the slow-light section for photonic crystal waveguides even under strong material losses[11].

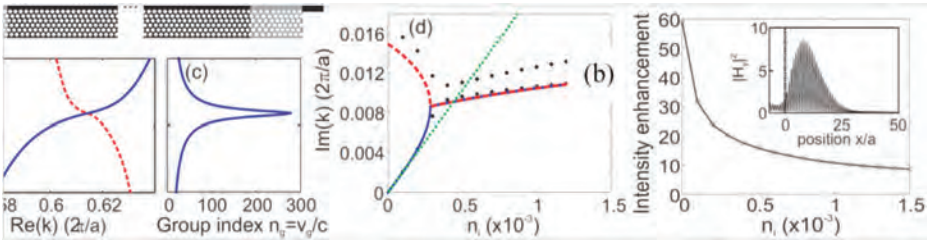

Fig 6: (a) Schematic of photonic crystal waveguide with (i) regular and (ii) slow group velocity regimes. (b) Maximum intensity enhancement vs. loss parameter n_i. Inset shows normalised magnetic field along the waveguide axis for n_i = 1.5x10^{-3}, where the interface between fast and slow sections lies at x = 0.

Coupling into slow-light waveguides

One of our main projects over the last few years has been the challenge of understanding the coupling of light into a slow-light waveguide. Traditionally, this is believed to be necessarily inefficient. However, numerical and theoretical work by others has shown that this is not always so. We showed that the traditional argument suggesting that the coupling is poor is incomplete as it ignores evanescent modes. These modes do not propagate through the medium with constant amplitude, but rather grow or decay exponentially and transfer no energy. We showed that such evanescent modes, decaying in the direction away from the interface with the slow light medium, make it possible for the coupling to be very efficient. This was a somewhat surprising result since these evanescent modes in photonic crystals are usually disregarded in favour of the conventional, propagating modes.

In a collaboration between CUDOS researchers at the University of Sydney and the ANU, with Partner Collaborators Kobus Kuipers and co-workers from AMOLF in the Netherlands and Thomas Krauss and co-workers from the University of St. Andrew in the UK, we set out to provide evidence of the existence of these evanescent modes in photonic crystals. Our samples were designed and fabricated Prof Krauss' lab, and they were analysed by phase- and polarization-sensitive near-field optical measurements in Prof. Kuipers' lab with a data extraction technique developed at the ANU.

The results[11,12] beautifully confirm our expectations. An example is shown in the figure below, which shows the intensity in the waveguide versus position in a photonic crystal waveguide. The vertical white line is the boundary between the fast waveguide on the left and the slow waveguide on the right. The intensity behind the boundary increases gradually and that the width of the field increases as well. The high field strengths are characteristic of slow light and are the reason we use them to enhance nonlinear optical effects. The gradual increase of the intensity is associated with the evanescent modes: immediately behind the interface the slow light field and the evanescent modes interfere destructively and the total field is modest. Moving away from the interface the evanescent mode decays so that only the strong propagating mode is left. The gradual increase of the width of the field is also an indication that evanescent fields are crucial in this geometry.

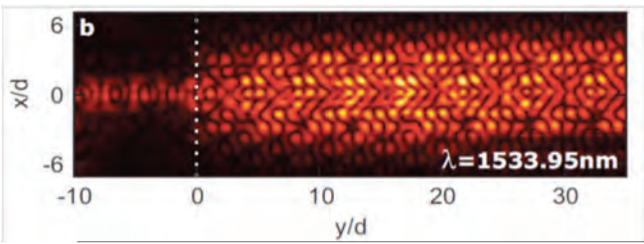

Fig 7: Local intensity versus position in a silicon photonic crystal with a waveguide. The vertical line indicates the boundary between the incident medium on the left where the light travels at a speed close to that in bulk silicon, and the slow medium on the right where the light travels at a fraction of the speed of light.

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