CUDOS

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

ANNUAL REPORT 2006

SLOW LIGHT

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Four year vision/long term goal and motivation

The generation and harnessing of slow light is a fundamental problem in physics that has a number of significant applications. Many of these are driven by a fundamental property of slow light: if a pulse of light slows down, and thus also the rate at which energy is transported, then the peak intensity of the pulse must go up in order to conserve the total energy flow. This increased intensity leads to increased nonlinear effects and hence lower input intensities for nonlinear photonic signal processing. A possible longer term application of slow light is as an optical buffer, an all-optical component that will be required in future optical telecommunications networks.

CUDOS strategy/competitive advantage

CUDOS researchers are considering slow light in one-dimensional periodic media (gratings) and two dimensional ones (photonic crystal slabs). Though many groups are pursuing this line of research, we are the only ones in the world to exploit nonlinear effects for the control of slow light propagation in these structures. The nonlinearities allow us to eliminate dispersion-related pulse broadening which leads to the scrambling of information if adjacent pulses start to overlap. The combination of dispersion and optical nonlinearity leads to the formation of solitons which do not broaden upon propagation.

Collaborative links

This is a collaborative project between researchers at the University of Sydney, the Australian University and Macquarie University. Theoretical work is carried out at the ANU and at the University of Sydney. The experimental work is a truly collaborative effort, with chalcogenide samples fabricated at the ANU, grating writing carried out at the University of Sydney and at Macquarie University, while photonic crystal slabs are fabricated at the ANU. The group is also collaborating with Dr Morten Ibsen at Southampton on the production of long silica gratings.

Goals for 2006

The aims for 2006 were the experimental demonstration of slow light in one-dimensional periodic structures (gratings) in silica fibre, and the first demonstrations of the complex gratings written in chalcogenide glass that are needed for slow light experiments in this geometry. We also aimed to explore novel possibilities for controlling slow light pulses and their propagation direction in periodic photonic structures.

Achievements and highlights for 2006

The key experimental result during 2006 was the experimental observation of slow gap solitons in gratings written in the core of silica fibres [1]. The solitons travelled, without broadening, at a velocity of 0.23 v where v is the propagation velocity in the fibre in the grating's absence, giving a total delay of approximately 1.5 ns, as shown in Figure 1. Since the incident pulses had a width of 0.68 ns, this corresponds to a fractional delay of well over 2 pulse widths. This large fractional delay illustrates the key advantage of using solitons, rather than low intensity pulses. We also showed that the delay is tunable, both by varying the intensity (see Figure 1) and by varying the strain on the grating. This work was published in Nature Physics and was featured in Nature itself.

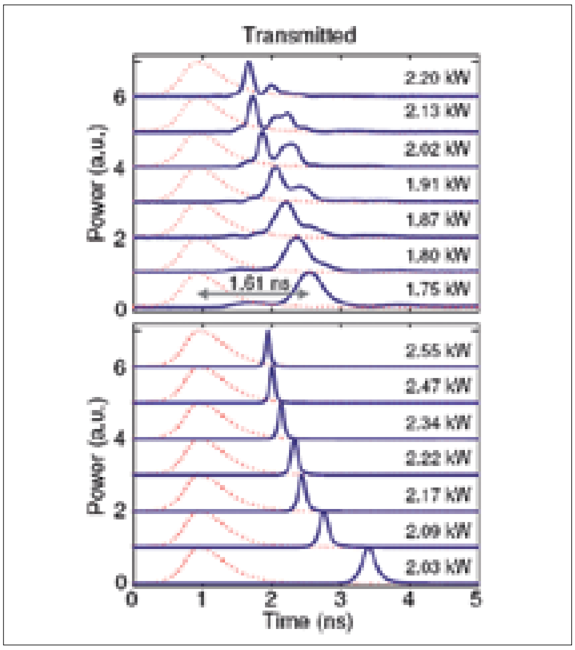
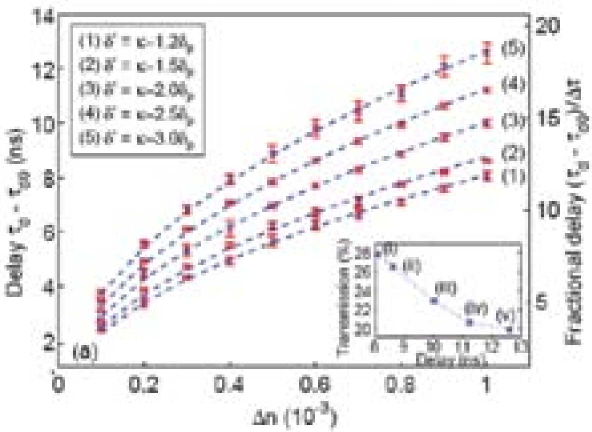


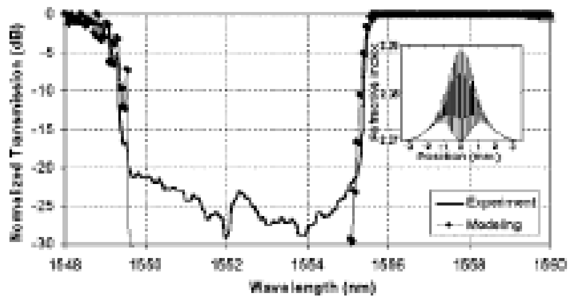
Figure 1. Measured nonlinear transmission versus input power (top) and associated simulations (bottom). The dotted curve gives the transmission in the absence of the grating. The delay is 1.61 ns at an input power of 1.75 kW, and can be tuned by varying the input power.

What limits the delay that can be achieved? Using a theoretical and numerical approach we studied the delay that can, in principle, be achieved in fibre gratings [2]. As illustrated in Figure 2, we found that the observed delay is at the lower end of the range of possibilities and that significantly larger delays should be observable in stronger gratings, although the transmission would be lower.



▲ **Figure 2. Calculated delay in nanoseconds (left-hand side) and fractional delay (right-hand side) versus the grating strength for different values of the strain on the fibre. For strong gratings the delay can in principle be well over 10 pulse widths. The inset shows the power transmission versus the strain.**

With the weak nonlinearities in silica, high peak power pulses are required (1.5-2 kW) to generate gap solitons. For this reason we are preparing for experiments in chalcogenide glass, which is a hundred to a thousand times more nonlinear than silica glass. This should reduce the peak power of the incident pulses to about 10 W. Much stronger gratings can be written in chalcogenide glass compared to silica, and this should lead to very large delays. As a first step we fabricated complex gratings in a chalcogenide waveguide [3]. The spectrum of this grating (Figure 3) clearly demonstrates the very deep gratings that can be written in these glasses.



▲ **Figure 3. Experimental and theoretical normalized transmission spectra of a strong grating fabricated in a 5 cm long As_2S_3 rib waveguide (W=4 m, H=2.37 m, h=1.25 m). Inset: the grating profile used for modeling.**

We demonstrated [4] that the propagation direction and velocity of optical pulses can be independently controlled in structures with multi-scale modulation of refractive index in the transverse and longitudinal directions (see Figure 4a). In arrays of waveguides with phase-shifted Bragg gratings, the refraction angle does not depend on the speed of light, allowing for efficient spatial steering of slow light. In this system spatial diffraction and temporal dispersion can be designed independently, and it is possible for slow light to be self-collimated when diffraction is suppressed for some propagation directions (see Figure 4b). Moreover, the broadening of pulses in space and time can be completely eliminated in nonlinear media, supporting the formation of slow light bullets that remain localized irrespective of propagation direction, as illustrated in Figure 4c. Efficient all-optical switching of slow-light pulses can be realized in nonlinear Bragg-grating couplers.

Targets for 2007

Some of the immediate goals for 2007 are direct extensions of the work in 2006: we aim to increase the delay in the silica fibres by using longer gratings. We will also investigate the effects of strong gratings and commence experiments in the chalcogenide waveguides. We will also commence experimental work in two-dimensional geometries, and devise geometries in which the slow light effects can be clearly observed and exploited. We will investigate the potential for spatial-temporal control and all-optical switching of slow light in a broad spectral range, which is essential for manipulation of short optical pulses. For this purpose, we will design photonic structures with special dispersion characteristics, and explore their operation in the nonlinear regime.

New collaborations will commence in this area in 2007. Prof Kuipers in Amsterdam, an expert in near-field optics, has joined CUDOS as a Partner Investigator, as has Prof Thomas Krauss in St Andrews, a photonic crystal expert.

From 2007 onwards, the work of Dr Andrei Sukhorukov in this area will be supported by an ARC QEII Fellowship. We also welcome Dr Christelle Monat who will commence slow light research supported by an Australian Postdoctoral Fellowship. Christelle will take up the Project Manager's role upon her commencement.

References

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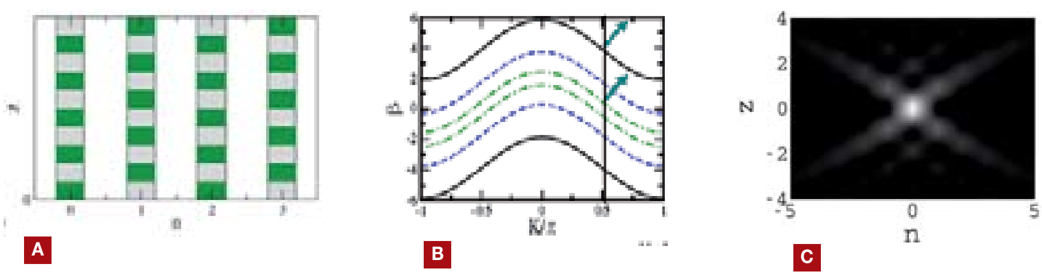
[3] Baker NJ, Lee HW, Littler ICM, Choi D, Madden S, Luther-Davies B, de Sterke CM, Eggleton BJ, Sampled Bragg gratings in chalcogenide (As2S3) rib-waveguides, OPTICS EXPRESS 14, 9451-9459 (2006)

[4] Sukhorukov AA, Kivshar YS, Slow-light optical bullets in arrays of nonlinear Bragg-grating waveguides, PHYSICAL REVIEW LETTERS 97, 233901(1-4) (2006)



▲ **Figure 4. (a) Waveguide array with phase-shifted Bragg gratings; integer n counts the waveguides; (b) Iso-frequency contours featuring wavelength independent refraction indicated by arrows; (c) Example of a slow light bullet exhibiting nonlinear self-trapping in space and time**