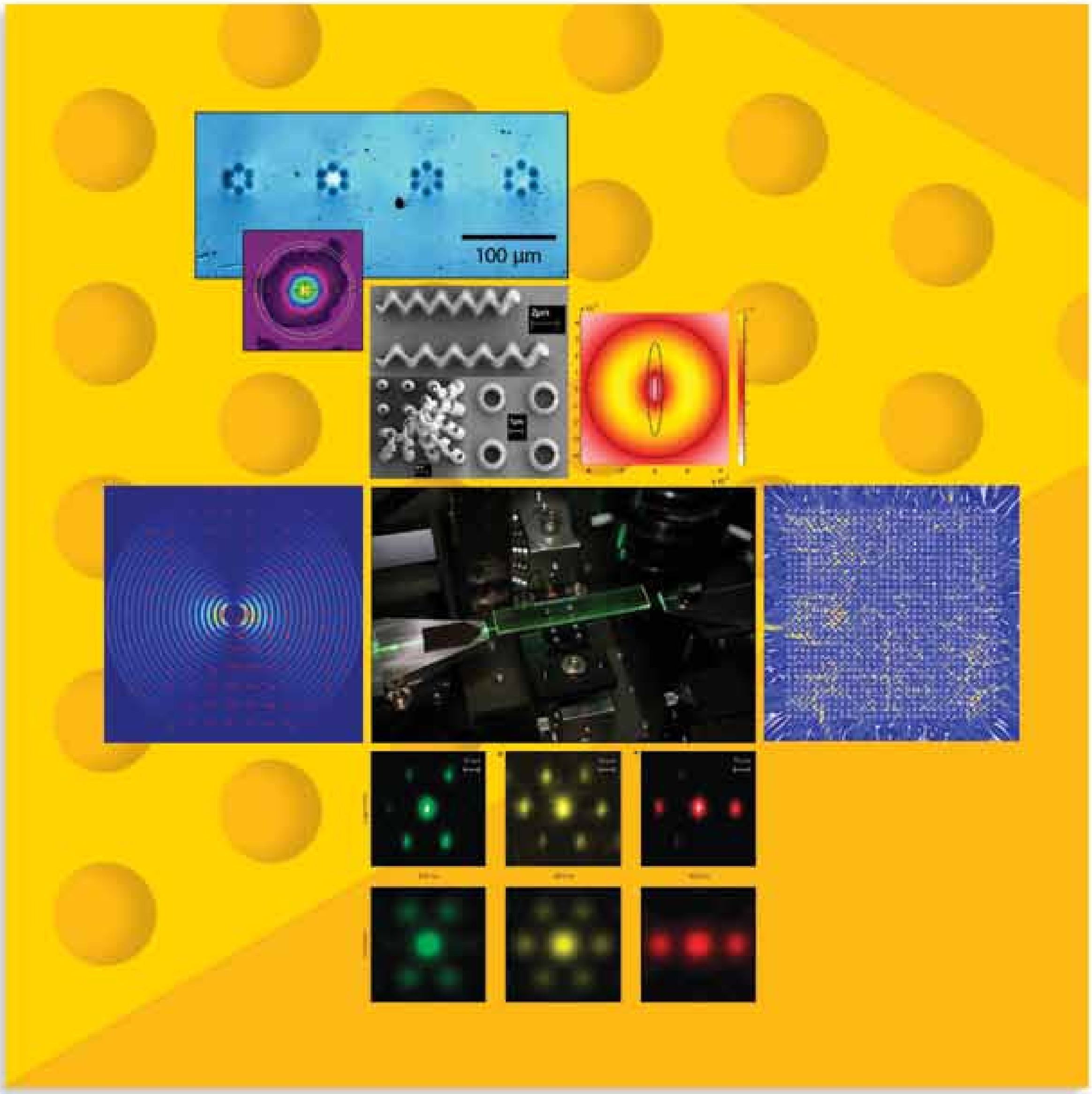
ANNUAL 2009 REPORT



CUDOS

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

SLOW LIGHT

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Long term goal and motivation

Apart from its intrinsic scientific interest, slow light can lead to strongly enhanced interactions with the optical medium, increasing, for example, gain and losses. More importantly for CUDOS, the magnitude of nonlinear interactions increases more strongly, thus ultimately leading to the lowering of the intensity requirements for nonlinear effects, with obvious advantages for the operation of nonlinear signal processing devices. Slow light is unlikely to provide commercialization opportunities in its own right, but will act as an enabler for other flagship projects.

CUDOS approach/competitive advantage

CUDOS's approach is to combine a nonlinear medium with a periodic structure for slowing light down. This has a dual benefit. First, the use of slow light enhances the efficiency per unit length of nonlinear effects through exploiting strong slow light–matter interaction occurring in these structures. The second advantage arises from the fact that most linear slow-light research suffers from the effect of dispersion, which leads to a broadening of the slow-light pulses. Through our use of the nonlinear response of the medium, we can prevent this broadening from occurring and balance dispersion, thereby generating solitons.

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 also actively developing, 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). Dr. Jacob Scheuer (Tel-Aviv University) visited ANU/NL with the support of the European Cooperation in Science and Technology (COST) Reciprocal Pilot Programme with Australia. Collaborative research has been engaged with him on the topic of "Light propagation in nonlinear slow-light polymeric

Slow light team.

photonic structures". As part of the continuing collaboration with Prof. Conelia Denz's group at Munster University, Mr Sebastian Kroesen (student from Munster University) spent four months at ANU/NL to study theoretically slow-light dynamics in nonlinear periodic structures (DAAD travel grant).

Goals for 2009

The aims for 2009 were threefold. The first goal was to improve our fundamental understanding of slow light effects, including the coupling into the slow light regime, and the demonstration of slow light enhancement of a wide range of nonlinear effects in periodic structures. The second goal aimed to solve the fabrication issues associated with chalcogenide Bragg grating waveguides to demonstrate the formation of slow gap solitons, i.e. low power pulses that can be delayed with limited distortion. The third objective was to exploit slow light to realise nonlinear devices with low power consumption and small footprint. This includes the construction of devices for the manipulation of slow light.

Achievements and highlights for 2009

Efficient coupling into a slow light photonic crystal waveguide without transition

Photonic crystals are a popular geometry for the study of slow light since the velocity of light pulses can be delicately controlled. An issue which was thought to be a problem is that of the coupling of light into a slow mode from a waveguide where the light travels faster. Because of the large difference in velocities this coupling was thought to be inefficient, making it necessary to include tapers or other transition regions. However, in 2007 it was pointed out that the coupling can in fact be efficient (close to 80%), and one of our aims has been to investigate why this is so [1]. We found that the coupling can be so efficient because of the presence of evanescent modes. These are modes which grow or decay exponentially, and which do not carry energy in the steady state in semi-infinite media. While not carrying energy, they help match the fields in the fast and the slow waveguide. In fact, at the interface evanescent modes can be as strong as the guided modes, though they decay rapidly away from the interface (see Figure 1). We found that the strong evanescent field arises because the propagating modes in the two waveguides have quite different shapes (see Figures 1(c) and 1(g)). If the modal shapes match better then the coupling is necessarily poor.

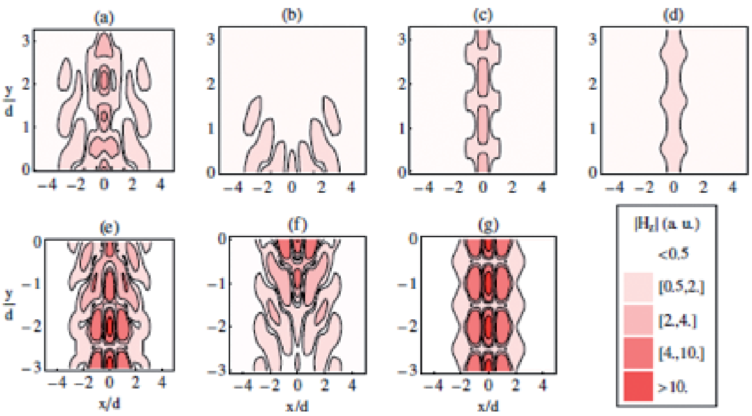

Fig 1. Magnetic field versus position when light is incident from a fast waveguide onto a slow one. The top row (a-d) refers to the field in the fast medium while the bottom (e-g) refers to the slow medium. Shown are: the total field (first column a,e), the evanescent field (second column b,f), field of the forward propagating modes (third column c,g), field of the backward propagating mode (fourth column d).

Slow light in chalcogenide waveguide Bragg grating

Among different schemes to control the speed of optical pulses, the one which is based on gap soliton formation in nonlinear periodic medium is very promising. The main reason for this is that solitons are high-intensity pulses which retain their shape in a dispersive medium. Unlike low-intensity pulses, they therefore do not suffer from dispersive broadening when they propagate. Solitons form naturally from a wide range of input conditions, and their velocity can be easily tuned. The main drawback of using gap solitons is a high peak power requirement in conventional optical fibers [Mok *et al* Nature Physics 2 2006]. Our approach is to use a highly nonlinear chalcogenide glass, the nonlinear refractive index of which is two orders of magnitude larger than in conventional silica fibre. Additionally, this glass exhibits a strong photosensitivity (about ten times larger than in silica) which enables Bragg grating fabrication via photo-inscription techniques. Figure 2 shows the transmission spectrum of an apodized Bragg grating, 15 mm long, induced in a rib As_2S_3 waveguide with an effective mode area of less than 4 µm2. The small mode area of the waveguide, combined with a high nonlinear refractive index of chalcogenide is an effective way to significantly reduce the power requirement for gap soliton formation. The grating in Fig. 2 was fabricated in our laboratory by transverse holographic technique in modified Sagnac interferometer. It has a high reflection at the Bragg wavelength (T ~-30 dB) and a width of the stop band of approximately 2 nm, which corresponds to a photo-induced refractive index contrast of 0.005. Such grating is a perfect starting point for further experiments with ultra-short pulses and demonstration of slow light in a chalcogenide waveguide.

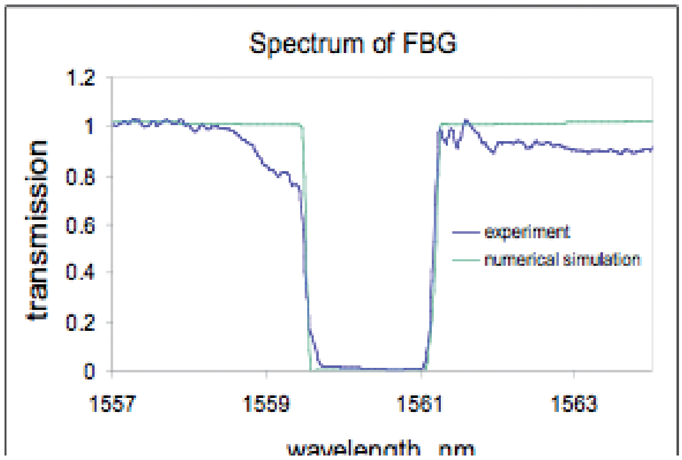

Fig 2. Transmission spectrum of an apodized FBG written in a chalcogenide As_2S_3 rib waveguide.

Slow light enhancement of nonlinear effects in silicon photonic crystal waveguides and its application to nonlinear devices

After the demonstration of the slow light enhancement of nonlinear effects in 2D silicon photonic crystal waveguides [2-4] in early 2009, the USyd's team in collaboration with Prof. T. Krauss' group has started exploiting it for realizing nonlinear devices. The first implementation, which was initiated by Dr. Dominik Pudo's visit, consisted of realising an optical limiter based on slow-light increased nonlinear losses. The latter induce a clamped transmission of the short device towards high input powers. We used this nonlinear transfer function to reduce the slow amplitude distortion imposed on a train of 10 Gbit/s data [5]. We have demonstrated the resulting decrease in the bit-error-rate and the associated noticeable improvement in the degree of signal eye opening. Because the nonlinear losses in silicon consist of combined two-photon and free carrier absorption, we have studied the role of free carrier dynamics in this device, and the associated limitations of this material for fast nonlinear devices.

In another application of slow light photonic crystal waveguides, we have demonstrated that the generation of visible light through third-harmonic generation [3] could be used for monitoring the quality of optical signals, as degraded by noise and dispersion. The concept is illustrated on Fig. 3a where the amount of green light emitted off the photonic crystal chip increases with the degree of eye opening of the near-infrared input signal. The cubic transfer function associated with this process makes the average power of visible light relatively sensitive to variations in signal impairment. In addition, we took advantage of the large bandwidth (~10nm) of the slow light feature provided by the dispersion engineered photonic crystal waveguides to demonstrate the operation of the device with ultra-fast data rates. Critically, Fig. 3b shows that the device efficiency (green light power versus coupled near-infrared peak power) is constant at all bit-rates from 40Gb/s to 640Gb/s, attesting that the bandwidth of the device is wide enough to accommodate ultra-fast data rates. This method has been applied to monitor the residual dispersion and optical signal to noise ratio (OSNR) of intentionally degraded optical data. Some of these results are shown on Fig. 3c with the green light average power clearly varying with signal OSNR at three different bit rates. The decrease in the dynamic range when increasing the bit rate (from 40Gb/s to 640 Gb/s) is due to the associated increase in the duty cycle (from 8% to 33%) and is common to all performance monitoring techniques that rely on a nonlinear transfer function. These results, which have been presented as postdeadline papers to OFC [6] and MOC Conferences, represent the first application of photonic crystal for all-optical signal processing.

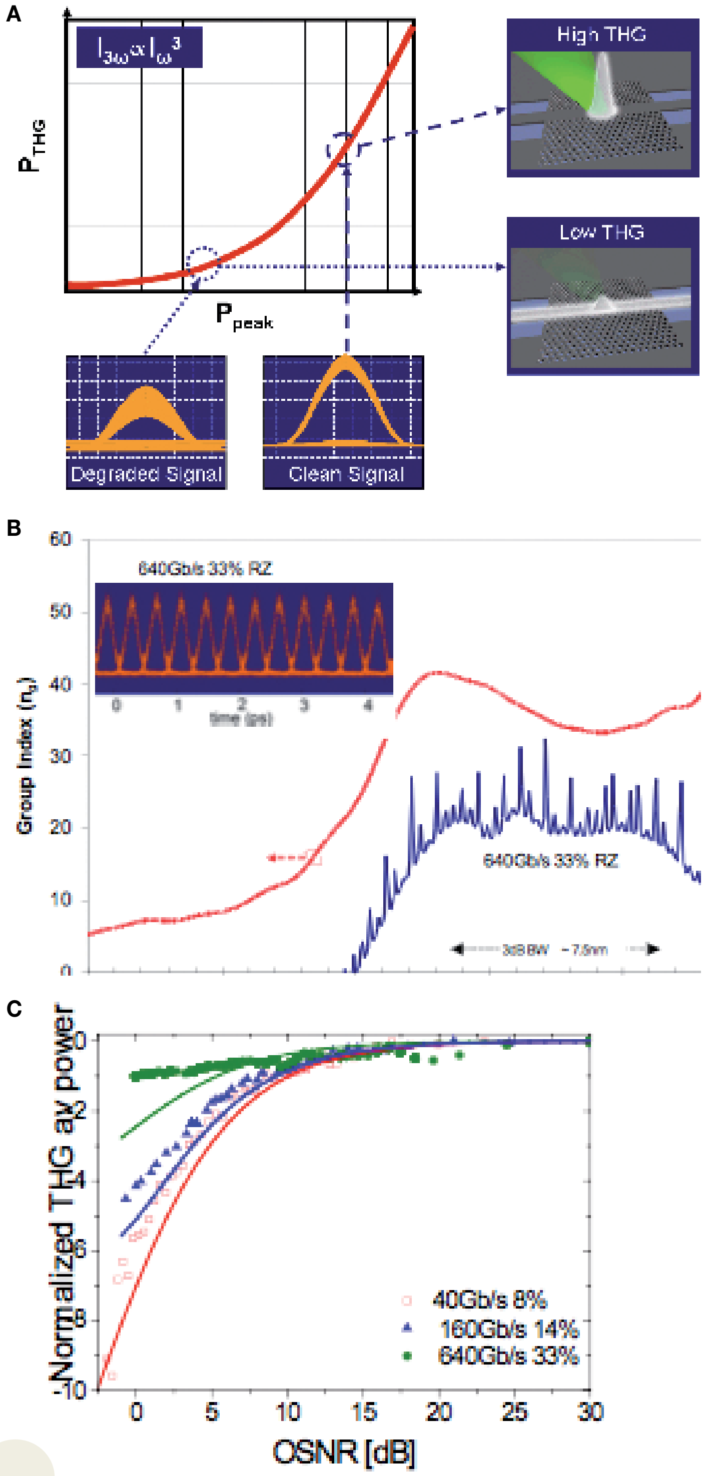

Fig 3. (a) Concept of the optical performance monitoring device based on third-harmonic generation in a slow photonic crystal waveguide. The associated cubic transfer function between the average visible light and the peak power of the near-infrared input signal allows us to monitor the quality of the optical signal through measuring the average power of the green light. (b) Average visible light power emitted from the device versus coupled peak power of the near-infrared signal at different bit-rates; all curves are scaled to include the difference in the duty cycle. (c) Measured (dots) average green light versus OSNR for different bit rates along with simulations (solid lines).

We investigated theroretically and numerically the potential of short (80 µm) silicon slow light photonic crystal waveguides for generating optical parametric processes such as four-wave mixing [7]. While slow light is essential for increasing the efficiency of this nonlinear process, the capability of engineering the group velocity dispersion of 2D photonic crystal waveguides, due to their flexible geometry, is critical as well. We have numerically shown that this approach can provide a compact solution for 2R and 3R regeneration of optical signals.

Slow-light in coupled periodic waveguides and control of cavity modes

Optical cavities created in periodic photonic structures have a remarkable capacity to confine light in very tight volumes. A problem which is a subject of active studies is the coupling between the cavities, since such structures offer benefits for various applications including nonlinear interactions and opto-mechanical effects. In our work, we demonstrate that the mode properties of coupled cavities created in periodic waveguides are determined by the slow-light dispersion at the photonic band-edge, which in turn is linked to the vortex-type structure of energy flows [8,9].

We show that the slow-light dispersion can be controlled through the shift along the direction of periodicity, providing a simple means to tune the cavity modes. In the absence of shift [Figure 4(a)], the slow-light occurs at the single maximum of dispersion dependence, the modes feature symmetric or antisymmetric profiles and their frequency splitting increases as the cavities are brought closer [Figure 4(a), bottom]. We show that the longitudinal shift enables flexible control over the fundamental modes, which frequency detuning can be reduced down to zero [Figure 4(b), bottom]. We illustrate our approach through direct numerical modeling of cavities created in arrays of dielectric rods, and confirm our predictions with experimental observations.

The proof-of-concept experimental observations were performed at the metamaterial laboratory at the Australian National University. We have developed original method for extraction of slow-light dispersion from the measured electric field profiles [10,11], and confirmed the predicted relation between mode tunability and transformation of slow-light dispersion [12,13].

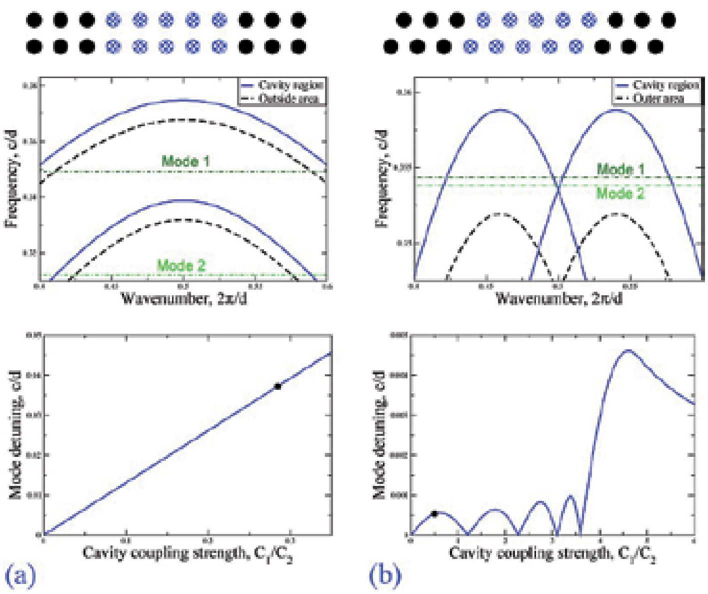

Fig 4. Tuning of coupled-cavity modes in with (a) zero lateral displacement and (b) half-period shift. Middle row: wave dispersion inside and outside the cavity region, and the frequencies of fundamental cavity modes. Bottom row: dependence of the mode detuning on the transverse coupling strength.

Direct laser written couplers with shifted Bragg gratings

We have previously predicted that the slow-light dispersion in coupled periodic waveguides fundamentally depends on the lateral shift [14]. For the first time, researchers at Macquarie University have fabricated with direct laser-writing in glass a directional waveguide coupler, where each waveguide contains a Bragg grating. Most importantly, the lateral shift between the Bragg gratings was precisely controlled.

We observe a clear difference between the symmetric and antisymmetric couplers near the Bragg resonance around the 1537.1 nm wavelength. For antisymmetric coupler, the light is always primarily transmitted to the second waveguide at the output, whereas the first waveguide output remains low, see Figure 5(b), right. On the other hand, for symmetric coupler we observe the varying transmission ratio between the first and second waveguides, and an increased transmission to the first waveguide at the central wavelength, see Figure 5(b), left. These results are in good agreement with theoretical predictions [Figure 5(c)], confirming the high quality of fabricated structures. As a next step, we plan to fabricate such structures in nonlinear and active glasses, exploring further opportunities for tunable and all-optical control of light.

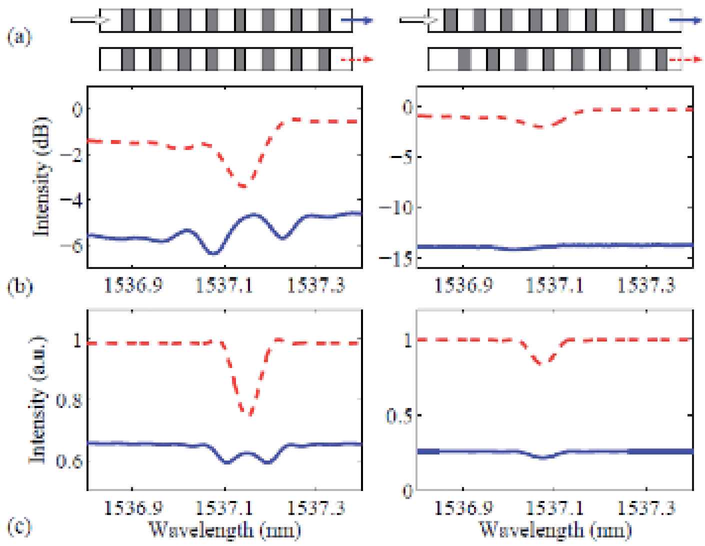

Fig 5. (a) Schematics of symmetric (left column) and antisymmetric (right column) Bragg-grating couplers. (b) Measured and (c) calculated transmission spectra from first (solid) and second (dashed) waveguides when the light is coupled to the first waveguide.

Targets for 2010

For 2010 we will continue to investigate both the fundamental properties and device applications of slow light in architectures combining a periodic geometry and nonlinear media; these will include gratings in chalcogenide waveguides, fiber Bragg gratings in highly nonlinear glass and two-dimensional photonic crystals in chalcogenide and silicon. We will employ AMOLF's heterodyne NSOM to expand our fundamental understanding of slow light. In particular, this technique should allow us to directly observe the critical role of evanescent modes for ensuring efficient coupling into slow light photonic crystal waveguides. Another interesting application of this tool will be the visualization of the interplay between dispersion and nonlinear effects that govern the propagation of slow light pulses along nonlinear slow light photonic crystal waveguides. In parallel, we will continue to investigate experimentally and theoretically how other nonlinear effects (such as Raman, Four-wave mixing) may benefit from slow-light periodic structures. On a more fundamental level, we plan to develop a general description of cavity modes in waveguides with engineered slow-light dispersion, consider effects of nonlinearity on light transmission in such structures, and explore all-optical tunability of dark states for light trapping. Another major goal for 2010 will be the progression towards the demonstration of slow gap solitons in chalcogenide gratings, following the recent improvement in the quality of these structures. Finally, we will make further use of the slow-light nonlinear enhancement to realise nonlinear devices requiring low power and small 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.

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