However, the possible compression, given by the ratio of the two pulse velocities, is limited by the ‘optical depth’ of the medium, which is proportional to the density of the atoms in the storage medium as well as the strength of the coupling between the atoms and the optical probe field used. In vapour cells, researchers have to make sure that the atomic density (and therefore optical depth) does not become too large as this can compromise the quality of the retrieved pulse, owing to the increased influence of decoherence processes. To achieve the best possible fidelity for a limited optical depth, special optimization strategies have to be used, and even then it is not possible to approach the desired fidelity.

In a typical EIT scheme, two coherent optical fields—a probe (signal) pulse and a much stronger coupling (control or pump) laser—are tuned to interact with three quantum levels of a material. They couple to different ‘legs’ of a so-called lambda-type configuration of atomic transitions (represented in Fig. 1a). The probe pulse is tuned near resonance between two of the states, and the pump pulse is tuned near the resonance of a different transition. If the states are chosen carefully, the presence of the pump field creates a transparent spectral window that can be detected by the probe.

Camacho et al. pursue a different approach (Fig. 1b). In their scheme, the pump laser also couples to the probe-field transition. In this way a fourth field, called the idler, is coherently generated, and the process is termed resonant four-wave mixing. Because all fields propagate in the same direction, the interaction of the idler field with the three-level medium modifies the signal field. As a result, a combined signal–idler mode builds up and evolves in the medium (Fig. 1b). The authors’ experiment demonstrates that it is possible both to read and to write using four-wave mixing and two lambda resonances simultaneously, and hence record information about the input signal and generated idler waveforms for later retrieval. Remarkably, the nonlinear mixing amplifies the effective compression of the combined field mode.

After sending a probe pulse a few microseconds long into a hot rubidium vapour and switching off the control laser, Camacho and colleagues store the generated signal–idler mode in the ground-state spin transitions of the atomic ensemble for up to several hundred microseconds. Switching on the control laser after the storage period then leads to a regeneration of the signal and idler pulses. As expected, the peak amplitude of the retrieved light pulses decreases exponentially with the length of the storage time, owing to the finite lifetime of the atomic spin coherence. Surprisingly, however, the results show that the form of the retrieved pulse exactly matches that of the input pulse, proving that the information imprinted in the input pulse shape is restored.

To verify that the shape of the retrieved pulse is indeed determined by the input beam and is not the result of pure coincidence, the authors perform a storage of partial input waveforms. They switch off the control laser once different parts of the input pulse have already passed the vapour cell. By piecing together the front end of the pulse, which is not stored, and the back end of the pulse, which is stored and retrieved after a time delay of 10 μs, Camacho et al. are able to reproduce the entire input pulse shape very nicely.

Owing to the unavoidable amplification noise in the four-wave mixing process, the proposed technique may be of limited use for quantum information purposes. Nevertheless, the experiment opens an interesting new avenue in the quest for a high-fidelity, all-optical memory for light.

Michael Fleischhauer is a member of the Department of Physics and the OPTIMAS research centre at the University of Kaiserslautern, Erwin-Schrödinger Strasse, D-67663 Kaiserslautern, Germany. e-mail: mfleisch@physik.uni-kl.de

References

SILICON PHOTONICS

A chip-scale one-way valve for light

For integrated photonics to take off, light signals zooming around optical chips must be successfully isolated from one another. Scientists at Stanford University have now designed a miniature one-way valve for light that uses photonic transitions and is potentially compatible with silicon-chip CMOS fabrication processes.

S. J. Ben Yoo

Being able to isolate optical signals on-chip is a great challenge for integrated photonics, and is crucial to the success of large-scale photonic integrated circuits. Photonic integration has the potential to reduce power consumption, size and cost while improving reliability and performance. Moreover, integration of photonic components on a silicon CMOS-compatible platform brings additional scalability and functionality as a result of the experience of the vast electronics industry. However, cross-talk and interference in photonic and electronic integrated circuits ultimately limits the scalability of integration. On page 91 of this issue, Zongfu Yu and Shanhui Fan of Stanford University propose a way of achieving broadband, non-reciprocal optical isolation in a waveguide structure that is compatible with silicon CMOS-integrated photonics

As yet, the techniques that have been used to achieve on-chip optical signal isolation have relied on materials or processes that are not fundamentally compatible with silicon CMOS processes. Non-reciprocal optical isolation, which requires time-reversal symmetry breaking, is typically achieved using bulk components made from materials that show magneto-optical effects, which are incompatible with integrated photonics. Recent efforts to achieve optical isolation in integrated photonics systems have involved waveguides with magneto-optical materials bonded to or incorporated into the waveguide. Optical isolation has also been attempted using chiral structures (reciprocal structures with no inversion symmetry), but this is only successful for specific optical modes of reflected waves. Nonlinear optical processes or electro-absorptive modulators can be effective, but optical isolation occurs only at specific power ranges, or with associated modulation sidebands.

Yu and Fan propose an unusual solution to the problem of isolation that is based on the effects of photonic transitions. Using a dynamic refractive index modulation,
the authors artificially create an indirect photonic interband transition analogous to the indirect electronic transition seen in many semiconductor materials. These artificial photonic transitions were predicted theoretically in 1999 (ref. 2) and demonstrated experimentally in a silicon microresonator waveguide in 2008. Yu and Fan have now gone further and shown that by applying a dynamic modulation to a carefully designed optical structure, complete (non-reciprocal) optical isolation can be achieved.

The trick is to choose a spatially and temporally varying modulation format that simultaneously imparts frequency and wavevector shifts to light waves during the photonic transition (Fig. 1). This enables the transmission behaviour of an optical structure to become non-reciprocal: light of frequency \( \omega_1 \) travelling in the forward direction is converted to a higher-frequency mode \( \omega_2 \) by the modulation. At the same time, such a modulation has no effect on light propagating in the backward direction at any frequency, and therefore leaves the mode in the backward direction intact. Combined with an absorption filter centred at \( \omega_2 \), the structure can absorb all light incident from one direction at a frequency \( \omega_1 \) while passing all light in the opposite direction, thus producing the behaviour of a complete isolator.

This technique can be applied to a variety of waveguide structures. Yu and Fan first consider their optical isolation method in a simple silicon slab waveguide, where they apply a modulation frequency of 20 GHz to light with a wavelength of 1.55 \( \mu \)m and a modulation strength (that is, the ratio of the modulated optical refractive index to the average optical refractive index of the modulator) of about \( 5 \times 10^4 \). The resulting coherence length is about 2.19 mm, which means that a travelling-wave modulator that is 2.19 mm long can achieve essentially complete isolation. The authors design the photonic transition between the two optical waves to be between a fundamental even mode at \( \omega_1 \) and a second-order odd mode at \( \omega_2 \) so that a high-contrast mode filter can be used for selective absorption at \( \omega_2 \). This gives rise to more than a 40-dB isolation over a 1.2-THz optical bandwidth, centred at \( \omega_1 \).

Yu and Fan also devise a more attractive and extremely compact design involving a 3-\( \mu \)m-radius silicon microresonator in resonance at both \( \omega_1 \) and \( \omega_2 \). The double resonance is not a necessity, but it greatly helps in achieving the desired miniaturization of the optical isolator. The optical isolator, then, consists of a waveguide side-coupled to the microresonator, and offers external quality factors of \( Q_1 = 3,426 \) and \( Q_2 = 887 \). The authors choose a modulation strength of around \( 4.8 \times 10^4 \), which results in a coherence length of around 250 \( \mu \)m. Figure 2 shows the field distribution and frequency response of the modulated coupled ring–waveguide structure. As with the first design, the optical modulation needs to travel in one direction (anticlockwise along the ring waveguide in this case) to break the time-reversal symmetry.

This modulation-based approach suggested by the authors is attractive from a practical point of view for several reasons. First, it uses CMOS-compatible silicon waveguides, eliminating the need for special magneto-optical materials and showing that on-chip isolation can be accomplished using standard material systems that are widely used for integrated optoelectronic applications. Second, the microresonator-based design is extremely compact, and compact design is a must for CMOS-realizable photonic integrated circuits. Third, the relatively high optical isolation ratio implies the capability to support large-scale photonic integrated circuits, which is important for a whole host of applications: future computing systems with optical interconnects, optical communications, and optical signal processing, with units capable of processing \( 10^{12} \) bits per second on-chip, integrated together with CMOS electronics.

Naturally, the next step for Yu and Fan is to actually fabricate and demonstrate experimentally the performance of their optical isolator. They will need to reduce radiofrequency reflections in the travelling-wave modulator in order to maintain high optical isolation and to control the operating temperature of their waveguide structure accurately in order to avoid misalignments.

**Figure 1** Illustration of how a travelling (dynamic) modulation of a silicon waveguide’s refractive index can be used to perform optical isolation. The modulation induces a wavevector shift on light pulses (red) travelling from left to right, whereas pulses travelling right to left experience no such change. An optical filter can be used to separate the shifted and non-shifted pulses.

**Figure 2** Field distribution and frequency response of the modulated coupled ring–waveguide structure. Light is incident from the left in **a** and **b**, and the right in **c** and **d**. **a**, **b,** Distribution of electric fields with continuous wave incident at \( \omega_1 \). **b,** Output spectra. The dashed lines represent the input spectra; the solid lines represent the (analytically calculated) output spectra. The circles are from finite-difference time-domain simulations. Red and blue colours indicate spectra around \( \omega_1 \) and \( \omega_2 \), respectively.
Eavesdropping on DNA replication

The use of fluorescent tagging and nanoscale waveguides looks set to make real-time DNA sequencing a realistic proposition. Commercial devices based on nanophotonics are expected in 2010.

David Pile

Real-time sequencing of DNA is an important goal for many working in genetics, but until now it has remained elusive in practice owing to a host of difficulties. It now seems that nanophotonics may be the answer to providing fast cost-effective sequencing by commercial machines. In a recent paper in *Science*, a team of researchers from California-based Pacific Biosciences describe an optical technique for proof-of-concept single-molecule real-time sequencing.

Put simply, the approach relies on co-localizing DNA-strands and excitation light in tiny hollow optical waveguides, and reading the signal from the DNA’s fluorescently labelled bases as it replicates.

The technique relies on the same DNA replication process that occurs in our cells throughout our lives. When cells divide, the DNA is first replicated by enzymes called DNA polymerases. In essence, the enzymes sequentially read the DNA and form a complementary strand of its bases (nucleotides). The Pacific Biosciences team simply use an optical technique to eavesdrop on this base-by-base replication process, in real-time.

Steve Turner, founder and chief technology officer of Pacific Biosciences, told *Nature Photonics* that there are two key developments behind their success.

The first is the use of so-called phospholinked nucleotides—a unique scheme for fluorescent tagging of the DNA-bases. To identify the different nucleotides, different coloured fluorescent molecules are attached to each of the four nucleotide types, A, C, G and T. However, unlike other sequencing techniques, the team decided to have the nucleotides carry their fluorescent label not on their base, as is usually done, but on a terminal phosphate.

In short, this means that the natural enzyme activity removes the fluorophore, leaving behind a natural strand of DNA, making the process unlike any other DNA labelling technique. As a result, the DNA polymerase activity is not slowed down or halted by contamination, and much faster and longer reads can be conducted, with higher fidelity.

The second main development was the successful reduction of the observation volume down to the zeptolitre range. In particular, this involved localizing the excitation light to dimensions conventionally unobtainable by typical techniques such as confocal or total internal reflection microscopy. As far back as 1997, when they were in graduate school together at Cornell University, Steve Turner and his friend and now collaborator, Jonas Korlach, recognized the need for improved confinement to enable observation of individual molecules against the background of a bulk solution of fluorophores. The basis of their optical technique relies on so-called zero-mode waveguides—waveguides that the team previously developed for studying single-molecule dynamics. Each waveguide is essentially a metal-clad dielectric cylinder made from a hole (~100-nm in diameter) in a metal film. Such a waveguide exhibits a cut-off wavelength, a wavelength above which conventionally guided waves cannot propagate. When operated beyond this cut-off the waveguides are sometimes referred to as ‘zero-mode waveguides’. On illumination, incident light with a wavelength that efficiently excites the fluorophores (between 500 and 700 nm) experiences rapid exponential decay on entering the waveguide, providing localization of light within tiny volumes—in this case 20 × 10⁻²³ litres.

The trick is then to immobilize DNA polymerase in the zero-mode waveguides, and this can be achieved using novel surface chemistry. With the combination of small observation volumes and a method of immobilizing the molecules, the sequencing process can be achieved as follows. Fluorescently labelled nucleotides in solution diffuse in and out of the waveguides on a timescale of the order of microseconds. When the enzyme (DNA polymerase) encounters the matching nucleotide, the nucleotide is incorporated and a fluorescent signal is generated owing to the co-localized light. As the incorporation process takes place on the millisecond timescale, it acts as the limit for the speed of the replication and hence for the reading process.

The process repeats, creating sequential pulses of light, with colours that correspond to the base that has been incorporated at each location along the strand. In this way, the sequence of the DNA strand is revealed, step by step, alongside the progress in photonic integration.

S. J. Ben Yoo is in the Department of Electrical and Computer Engineering, University of California, Davis, California 95916, USA. e-mail: yoo@ece.ucdavis.edu

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**BIOPHOTONICS**

**Eavesdropping on DNA replication**

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