PHOTONIC CRYSTAL WAVEGUIDES

# Compressing slow solitons

Time-domain measurements have confirmed the existence and compression of optical solitons in nanoscale planar photonic crystal waveguides, giving hope for the future prospects of on-chip nonlinear optical circuits.

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The simultaneous development of nanostructured optical waveguides and precise nanoscale fabrication techniques promise advances in both fundamental and applied optics on chip-scale platforms[1]. Many proposed applications of nanoscale photonic structures, such as all-optical data control and on-chip processing[2], rely on nonlinear interactions between photons. Full experimental characterization of these nonlinear effects in the nanoscale environment is notoriously difficult, however, owing to the tiny quantities of electromagnetic energy involved.

Reporting in *Nature Photonics*, Pierre Colman and co-workers from France and the USA have now conducted time-domain characterization of pico- and femtosecond pulses transmitted through a nanoscale planar photonic crystal waveguide[3]. Their time-domain measurements conclusively show that such waveguides can support and compress optical solitons — self-sustaining nonlinear pulses that have important applications in communications and optical science.

Previous studies have demonstrated spectral measurements of frequency conversion and nonlinearity-induced spectral broadening of pulses in semiconductor waveguides measuring a few hundred nanometres across[4]. Colman *et al.* now provide a detailed temporal analysis of the pulse-reshaping capabilities of on-chip nanowaveguides[3]. To make measurements feasible, the researchers carefully designed the sample such that the output signal could be characterized simply using a standard autocorrelator — a common tool for ultrashort pulse analysis.

Temporal optical solitons form in a waveguide when the natural spreading of optical pulses, caused by the group velocity dispersion (GVD) of the waveguide, is exactly compensated for by the opposing flow of energy caused by the nonlinearity. Two length scales associated with these processes are the dispersion length, $L_{dis}$, the propagation length over which pulse spreading becomes significant, and the nonlinear length, $L_{nl}$, over which the nonlinearity starts to play a role. $L_{dis}$ is proportional to the square of the pulse duration and inversely proportional to the GVD, whereas $L_{nl}$ is inversely proportional to the peak power of the pulse, $P$, and to the nonlinear parameter of the waveguide, $\gamma$. The value of $\gamma$ is related to the nonlinear change in refractive index by $\Delta n = \gamma P\lambda/2\pi$, where $\lambda$ is the wavelength of light.

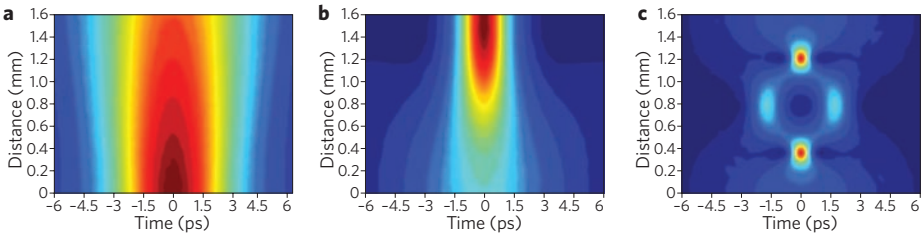


**Figure 1 |** Soliton-effect pulse compression. **a**–**c**, Evolution of the temporal profile of a pulse along the waveguide axis for different values of $L_{dis}/L_{nl}$: 0.8 (**a**), 1.5 (**b**) and 3 (**c**). Panel **a** shows the case of $L_{dis}$ being shorter than $L_{nl}$, which leads to pulse spreading. Panel **b** shows pulse compression for increased powers, and panel **c** shows the multi-soliton breather dynamics accompanied by even stronger initial compression.

Solitons have had a pivotal role in the development of optical science over the past few decades, following their first observation in telecommunications fibres[5]. They are of primary importance because they arise naturally in many optical systems. All that is needed for solitons to exist is for the waveguide to be excited with a sufficiently short and intense pulse, and to have so-called 'anomalous' GVD, which causes the shorter wavelengths within the pulse to travel faster than the longer ones. The power required for the formation of a soliton with a given duration is determined by the requirement $L_{dis} = L_{nl}$. Colman *et al.*[3] report how the properties and nanogeometry of photonic crystals impact every aspect of this simple condition.

It is well-known that a large $\gamma$ will cause solitons to appear in low-peak-power pulses. For example, solitons with 10 pJ energy and 1 ps duration, which are characteristic for the experiments of Colman *et al.*, have peak powers of around only 10 W. In contrast, typical picosecond solitons excited in telecommunications fibres have powers of hundreds to thousands of watts. The corresponding value of $\gamma$ in such fibres is six orders of magnitude less than the $\gamma \approx 1{,}000\ \mathrm{W^{-1}m^{-1}}$ reported by Colman *et al.* The difference in soliton power would be much more dramatic if the GVD of the photonic crystal waveguides in the relevant frequency range (around 1,500 nm) was not ~5,000 times higher than in telecommunications fibres.

What causes such a dramatic enhancement of the nonlinear response in photonic crystal waveguides? First, the intrinsic nonlinear response of semiconductors (GaInP in the work of Colman *et al.*) is two orders of magnitude higher than that of the silica glass used in telecommunications fibres. Also, and crucially, $\gamma$ is inversely proportional to the effective area covered by the waveguide mode, which can be estimated at around 0.1 $\mu m^2$ for the work of Colman *et al.*, compared with an area of ~50 $\mu m^2$ for standard telecommunications fibres.

In addition, Coleman *et al.* follow from previous theoretic results[6] to show that the effective $\gamma$ can be further increased by the light slow-down factor introduced by the photonic crystal. That is, the low group velocity of light in the photonic crystal waveguide leads to a greater nonlinear response than might otherwise be expected.

The nonlinearity enhancement factor is the square of the ratio of the phase velocity of light to the group velocity of the waveguide mode, and is of the order of 10 in the system of Colman *et al.* Although this slow-light nonlinearity enhancement had been proposed to have an important role in the generation of green light in silicon nanosized photonic crystal waveguides[7], its impact on soliton formation had not been experimentally confirmed until now.

When the input power is increased beyond the soliton threshold ($L_{dis} > L_{nl}$), the nonlinearity chirps the spectral content of the pulse such that the leading edge of the pulse is red-shifted while the trailing edge is blue-shifted. This develops within the first tens of micrometres of propagation — well within one dispersion length $L_{dis}$. Thus, the spectral content of the pulse is changed, while the temporal profile remains unchanged. This chirped pulse is then compressed by the GVD, which shifts the long- and short-wavelength parts of the pulse towards the pulse centre, thereby reducing its temporal width. Stronger nonlinearity-induced chirping and larger GVD values lead to stronger compression over shorter distances. This compression technique is well-known in the context of optical fibres[8], and is illustrated in Fig. 1.

In a greatly simplified theoretical picture, one can neglect the variation of GVD with wavelength and the non-instantaneous nonlinear response, which theoretically results in periodic recompressions known as multi-soliton breathers (Fig. 1). In more realistic situations, however, the dynamics of repeating breathers is inevitably destroyed, but the initial compression remains a robust, easily identifiable and usable feature of the process. Selecting an optimal waveguide length for a given power, or vice versa, results in greatly compressed pulses at the output. Colman *et al.* have demonstrated compression of 3.2 ps pulses down to 580 fs using very low input energies of just 20 pJ in ~1-mm-long photonic crystals waveguides. This was possible not only because of the enhanced nonlinear response, but also owing to the large GVD values of photonic crystal waveguides achievable in the slow-light regime. These values approach the record-large GVD values attainable in fibre Bragg gratings.

Most recent efforts with planar nanowaveguides have been focused on the silicon-on-insulator platform[2,4], which benefits from a large nonlinearity, controllable GVD and a mature fabrication technology. However, unlike GaInP, silicon suffers from substantial two-photon absorption loss under nonlinear conditions. Two-photon absorption destroys the desirable direct proportionality between nonlinear processes and pump power, because pumping more power into the silicon system introduces more loss through the two-photon process. Despite this, efficient nonlinear wave mixing[2,4] and soliton dynamics[9,10,11] have been reported in silicon nanowaveguides using spectral measurements and comparison with numerical modelling.

The experiments of Colman *et al.* highlight the urgency with which the nonlinear effects in silicon nanowaveguides must be characterized in the time domain. This work, together with other recently published and ongoing research, demonstrates decisively that soliton physics, already well-known for its importance in fibre optics[5,12], will have a central role in nonlinear chip-scale nanowaveguides, periodic structures and other miniature photonic devices. ❐

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NANOPHOTONICS

# Rewritable oxide photodetectors

The simultaneous control of photon and electron confinement at the nanoscale on an oxide platform may pave the way for optoelectronic devices measuring just a few nanometres in size.

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A critical challenge in the union of optics and electronics is overcoming the size mismatch; the micrometre scale of visible and infrared wavelengths — and therefore of the related optical devices — is significantly larger than the nanometre scale of modern electronic devices[1]. In the conversion of photons to electrons by photodetectors, this size incompatibility often leads to substantial penalties in power dissipation, chip area, latency and noise. Nanoscale photodetectors[2], such as those based on subwavelength light confinement, promise to overcome this size incompatibility. Unfortunately, it has traditionally proved difficult to fabricate and integrate nanophotonic devices intimately with nanoelectronics, as the two fields require contrasting material choices and device architectures.

Now, Patrick Irvin and colleagues describe in *Nature Photonics*[3] a rewritable and reconfigurable oxide photodetector that is just 2–3 nm across. Silicon transistors, the workhorses of mainstream electronics, currently have characteristic dimensions of ~20 nm, but are already approaching the quantum-mechanical limits of miniaturization. The tiny photodetectors of Irvin *et al.* match the size of future-generation transistors, and may therefore provide a convenient technique for seamlessly integrating photonic and electronic devices at the nanoscale.

Recent interest in the field of oxide nanoelectronics is due to progress in the growth of high-quality oxide heterostructures[4]. For example, the interface between $LaAlO_3$ and $SrTiO_3$