Why do we need slow light?

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The extreme speed at which light moves, and the fact that photons do not tend to interact with transparent matter, is of enormous benefit to mankind. It allows us to see deep into the Universe and to transmit data over long distances in optical fibres. So, why slow light down?

The first answer is, "because we can". Many advances in science and technology were achieved out of the urge to tackle hard problems. Who would have thought that atoms could be made to interact coherently in what is now known as a Bose–Einstein condensate (BEC)? Who would have expected that light could be slowed all the way down to 17 m s^{-1} (ref. 1) — the speed of a swiftly moving bicycle? Controlling what is intrinsically difficult to control bears a certain fascination and drives us to explore and extend the boundaries of knowledge. For example, the first paper on photonic crystals[2] was motivated by the desire to control the process of spontaneous emission of light, and it spawned a new field that has now given us strong coupling in semiconductor nanocavities, supercontinuum generation in optical fibres and enhanced light extraction from LEDs. The advent of research into slow light, is also anticipated to bring in a wealth of applications, especially in the fields of telecommunications and optical data processing.

The second answer is that faster is not always better, as the well-known fable of the hare and the tortoise demonstrates (see Fig. 1). Using light smartly rather than simply relying on its speed offers many opportunities. Slow light promotes stronger light–matter interaction, it offers additional control over the spectral bandwidth of this interaction and it allows us to delay and temporarily store light in all-optical memories.

Figure 1 Faster is not always better, as the fable of the hare and the tortoise demonstrates. The same is true in photonics, where slow light can outperform fast light in many aspects.

OPTICAL NONLINEARITIES

Nonlinear optics is one of those hard problems that have fascinated researchers for many years. Because photons do not naturally interact strongly with transparent matter, researchers typically use high-power lasers to overcome this limitation and induce nonlinear responses. As a consequence, the equipment required for nonlinear optics experiments is often large and expensive, sometimes filling an entire laboratory. The first step in addressing this issue is to realize nonlinear functions in miniature waveguides that have a cross-sectional area on the micrometre scale and below. This approach has already led to major advances, for instance the recent demonstration of efficient and low-power Raman amplification in silicon[3]. Adding slow light to the equation provides the opportunity for further enhancements. As shown in Fig. 2, when an optical pulse travels in a slow-light waveguide, it is compressed and its energy density is thereby increased[4]. As nonlinear effects depend on energy density, this means that the strength of the nonlinear interaction effectively scales with the slow-down factor of the waveguide. If this approach is applied to nonlinear Raman amplification with appropriately designed slow-light waveguides[5], the efficiency of the nonlinear process can be improved by a factor of more than 10,000. This highlights the spectacular advances that slow light can bring to the field of nonlinear optics, enabling sizeable effects to be realized with much lower powers and with much smaller and cheaper lasers.

Another important nonlinear device that could benefit from slow light is a regenerator — a device that cleans up optical signals that have suffered distortion and noise after long-distance propagation through optical fibre and a chain of optical amplifiers. The key feature of a regenerator is its nonlinear transfer function, which allows it to remove noise as well as restoring the data bits close to their original shape. Current versions of optical regenerators require high-power amplifiers to achieve this nonlinear transfer function and thus are very costly. As such, electronic regenerators are preferred. If the nonlinearity were to be enhanced by slow-light effects, possibly to a similar magnitude as mentioned above, much lower-power operation could be realized leading to a more cost-effective optical regenerator.

OPTICAL SWITCHING

Slow light refers to light with a low group velocity, described by a gentle slope, $d\omega/dk$, in an ω–k dispersion diagram, as shown in Fig. 3, where ω is the angular frequency and k is the wavevector of light. When the refractive index n is tuned, the dispersion curve (solid line) is shifted upwards (dashed line). In the fast-light regime, around ω_1, the gradient is steep, so the change of k (Δk_{fast}) with n is small, whereas in the slow-light regime, which has a shallow gradient, around ω_2, a large Δk (Δk_{slow}) can be achieved with the same change of n, Δn. As most optical switches are actuated by a phase change, $\Delta\varphi$, where $\Delta\varphi = \Delta kL$ and L is the interaction length, Δk is the key parameter responsible for actuating the optical switch. The large Δk available in slow-light waveguides therefore enhances the optical switching operation. A recent example of such enhancement is a 5-μm-long optical switch that was actuated with a refractive-index shift of $\Delta n = 4 \times 10^{-3}$ (ref. 6). A comparable switch, actuated with the same Δn but realized in a conventional 'fast' waveguide, required an interaction length 40 times longer[7]. This implies that a large number of switches can be combined on a small footprint, for example, in a large switch matrix, or, following redesign, switching could be realized with a lower Δn. The trade-off for this improvement is a reduced spectral bandwidth of operation, although this reduction is not as severe as for ring resonators that are commonly used for the same purpose.

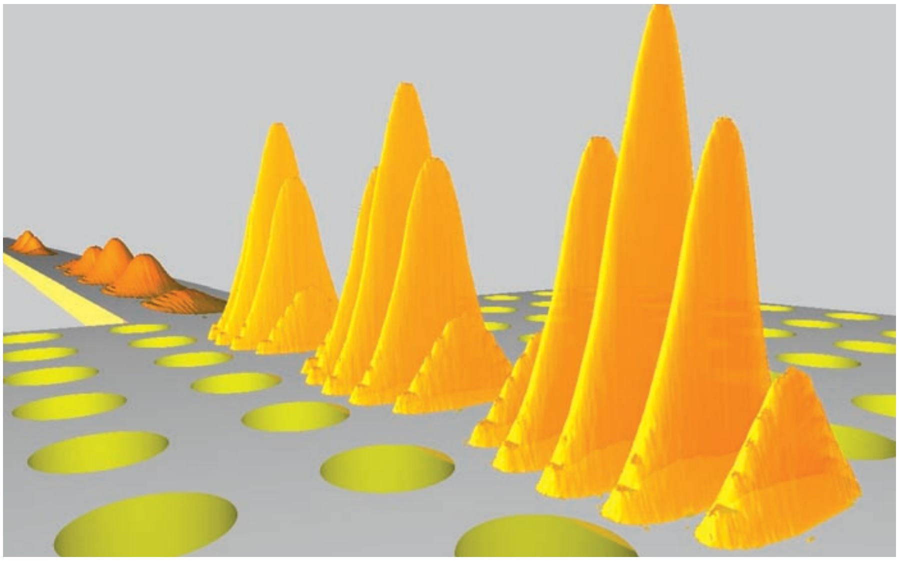
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Figure 2 Illustration of the slow-light intensity enhancement. As a light pulse (left) enters a photonic-crystal waveguide operating in the slow-light regime, the pulse length is compressed resulting in increased intensity. Reprinted with permission from ref. 4.

QUANTUM OPTICS

In quantum information processing, one of the key issues is to store the quantum state of light for a sufficiently long time to enable quantum operations. Slowing and stopping light are ways to achieve this long storage time, that is, up to the millisecond range, and pulses of light can be locked inside a Bose–Einstein condensate without loss of their quantum properties[8]. Quantum operations can also be performed in the same system by slowing down two pulses of light simultaneously. The two pulses, when propagating with slow but equal group velocities, interact very efficiently for a long time. This process creates strongly correlated (that is, entangled) states of interacting photons[9], which form the basic building blocks of a quantum processor.

OPTICAL STORAGE

The initial slow-light experiments were carried out using electromagnetically induced transparency (EIT), which is best observed in cold gases and Bose–Einstein condensates. These are excellent media for fundamental investigations, but rather unsuited for practical applications. The current trend is to study similar effects in solid-state systems, such as semiconductors and optical fibres, which, similar to EIT systems, exploit the strong dispersion available near electronic resonances (see page 474 of this issue[10]), thus creating optical storage media that may one day be used in real applications.

The target application of slow light for optical memory is an all-optical router that temporarily stores data while identifying the address of a data packet (that is, header recognition). Electronic buffers typically store megabits of data and the main argument in favour of optical schemes is that the required optical–electronic–optical conversion consumes a lot of power and limits the bandwidth of information.

All-optical buffers operate, in principle, independently of the data rate and are more efficient, as the data remain in the optical domain. Many ingenious slow-light schemes have now been demonstrated that enable the controlled delay of a few bits of information[11]. A method based on wavelength conversion by means of four-wave mixing has achieved the longest delay (around 80 pulsewidths, ref. 12), but is also one of the most complex and power-hungry solutions. Alternatively, slow-light systems based on photonic resonances, typically realized as chains of coupled cavities, are conceptually much simpler and are readily integrated with other photonic circuitry. They have now achieved delays of a few bits of information[13], a number that is expected to increase considerably as the waveguide technology and achievable cavity Q factors continue to improve.

Although the exciting vision of an all-optical buffer is a strong driver for pushing the boundaries of science and technology, optical buffers are unlikely to outperform electronic buffers for some time. Instead, tunable optical delays are much better suited to synchronizing and time-interleaving streams of data, which is easier as delays of the order of only a few bits are required. Similarly, in radiofrequency photonics, where micro- or millimetre-wave signals are transported in the optical domain, tunable delays can be used to synchronize or steer signals, such as in phased-array applications.

CHALLENGES

The two major limitations of any slow-light structure are dispersion and loss; dispersion limits the available bandwidth, that is, the information content that can be slowed down or stored, whereas loss limits the storage time and interaction length. For schemes based on photonic resonances, the loss is mainly determined by technology, whereas in EIT systems it is given by the dephasing time or the spontaneous emission time of the respective material. Unless there are major breakthroughs, neither can be expected to improve by orders of magnitude, which explains why optical buffers that may store kilobits of data will not be available for some time. In fact, if a figure of merit is constructed that includes dispersion-limited bandwidth as well as loss, simple optical fibres are difficult to beat[14].

As far as bandwidth is concerned, there is no free lunch; the longer the delay for a given device, the narrower the bandwidth, which is why the so-called 'delay–bandwidth product' is such a useful figure of merit. An interesting approach that breaks this delay–bandwidth product limitation, however, is to tune the system adiabatically, which means that its properties are changed after inserting the optical signal, consequently 'freezing' the optical signal inside[15]. Another idea is to chirp the properties of the system to broaden its response, which is done by combining several EIT or photonic resonances (see page 465 of this issue[16]).

Although many challenges remain, especially in optical storage, the slow-light enhancement of linear and nonlinear functions appears to be maturing rapidly and should bear fruit in the short term. Going back to the fable, the tortoise has the upper hand, but it has not beaten the hare just yet.

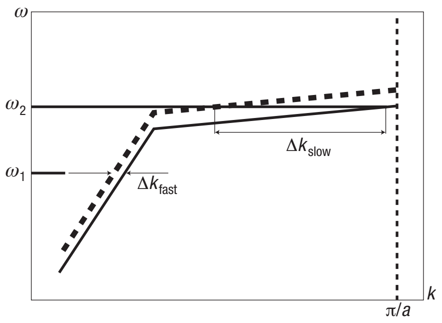

Figure 3 Dispersion (ω–k) diagram for slow light. In the slow-light regime, the phase change (proportional to Δk) is much larger for a given change in refractive index (from solid to dashed line) than in the fast-light regime.

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