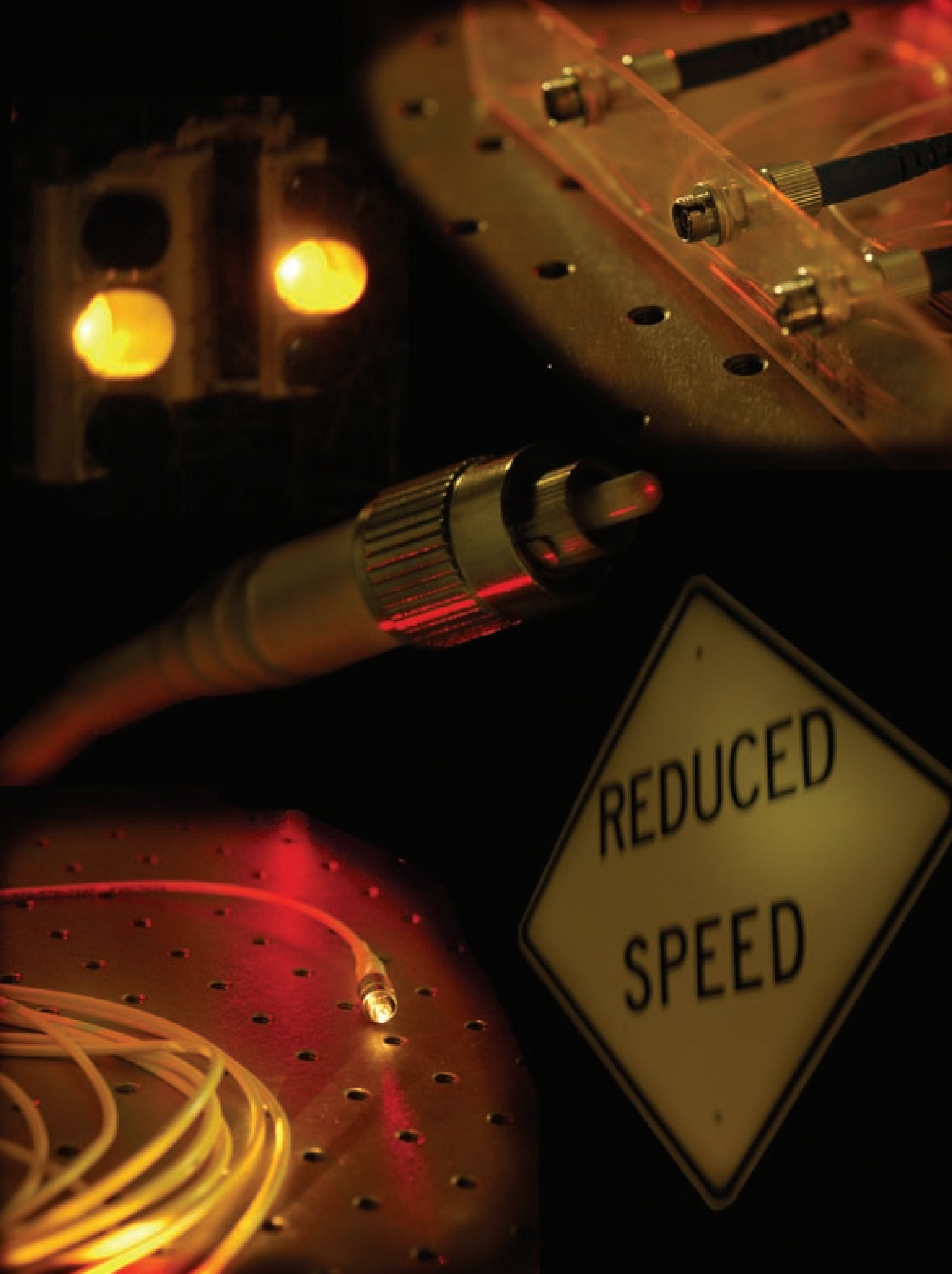
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Applications of Slow Light in Telecommunications

Robert W. Boyd, Daniel J. Gauthier
and Alexander L. Gaeta

Over the past several years, researchers have been intrigued by the possibility of using nonlinear optical methods to exercise unprecedented control over the propagation velocity of light pulses through material systems. Exotic effects such as slow light, fast light and even stored light have been observed in the laboratory. Now, optical scientists are turning their attention toward developing useful applications of slow light, including controllable optical delay lines, optical buffers and true time delay methods for synthetic aperture radar. This article reviews recent progress in developing slow-light methods for these applications.

Photo composition by Mark Foster

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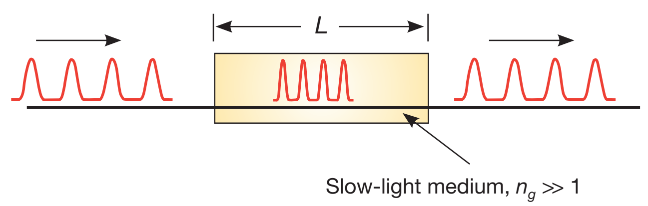
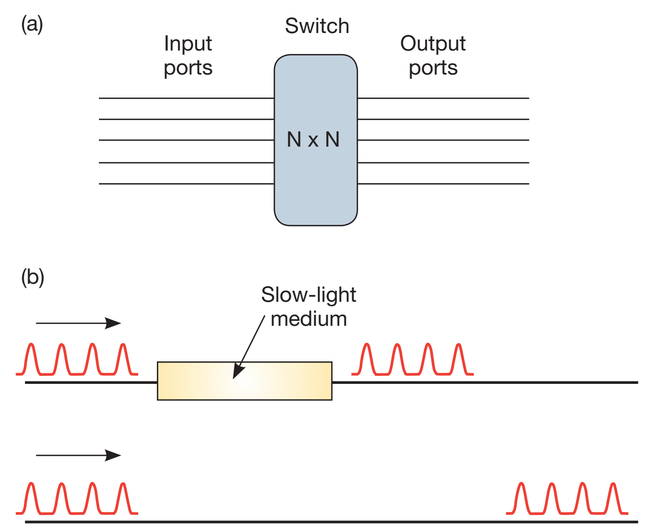
The basic idea behind slow-light methods is illustrated in the figure on the right. It shows a pulse train passing through a material designed to produce a very small value of the group velocity, which is defined roughly as the velocity at which the peak of an optical pulse propagates through a material. The group velocity can be expressed as $v_g = c/n_g$, where c is the velocity of light in a vacuum and n_g is the group index, which is related to the usual refractive index by $n_g = n + \omega\, dn/d\omega$. The time it takes for a pulse to pass through the optical material is known as the group delay, which is given by $T_g = L/v_g = Ln_g/c$.

Thus, to make the controllable delay as large as possible, one wants to make L as large as possible and to maximize the value of the group index. In practice, the effective length L of the optical material is usually limited not by its physical length but by the requirement that absorption losses and dispersion-induced pulse broadening be kept to acceptably low levels. The condition for maximizing the group delay is therefore often one of reducing the absorption and broadening experienced upon propagation through the interaction region.

[The concept of slow light]



[Optical buffering by means of slow light]



(a) An NxN all-optical switch; (b) an optical buffer can be used to ensure that two data packets are not incident simultaneously on the switch.

Optical buffering

One of the proposed applications of slow light is for the process of optical buffering, as illustrated in the figure on the right. With an N×N all-optical router, any of the input ports can be dynamically switched to any of the output ports. However, a serious problem can arise with this sort of architecture if two data packets arrive simultaneously at the router, because the switch can only deal with one packet at a time. This problem is known as data packet contention.

A solution is to build a buffer, which places one of these data packets on hold while the other clears the switch. A controllable slow-light medium can perform this function. Numerical modeling shows that the performance of a switching network under high traffic conditions can be dramatically increased through the use of such buffering.

Systems considerations

For most practical situations, the key parameter of interest for a slow-light delay line is not the total induced time delay but rather the normalized time delay—that is, the total time delay divided by time duration of the input pulse. This quantity can be thought of as a rough measure of the information storage capacity of the optical medium. The best published laboratory results to date appear to be a delay of approximately five pulse lengths reported by Kasapi et al. That configuration made use of electromagnetically induced transparency (EIT) to minimize signal absorption while retaining the large contribution to the group index associated with working close to an atomic absorption frequency.

However, data packets used in telecommunications systems would be expected to contain at least 1,000 bits of information. Thus, one needs to determine the prospects for construction of slow-light delay lines with 1,000 bits of capacity. To address this, we recently performed a detailed theoretical study of limitations to the time delay achievable through the use of slow-light delay lines (see Boyd et al., 2005).

For most practical situations, the key parameter of interest for a slow-light delay line is not the total induced time delay but rather the normalized time delay—that is, the total time delay divided by time duration of the input pulse.

A key issue in all slow-light experiments is finding the maximum modulation bandwidth (roughly the inverse of the shortest pulse) that can experience the full slow-light effect.

Our model includes the influence of group velocity dispersion and the spectral reshaping of the optical pulses. We concluded that there are no *fundamental* limitations to the maximum fractional pulse delay. However, there are some serious practical limitations, primarily associated with residual absorption. Our proposed strategy for overcoming this limitation is the careful use of EIT or other nonlinear optical methods to reduce the absorption to acceptable levels.

The approach we have adopted for our research is based on the use of room-temperature solid-state materials. While there are probably specialized situations in which other types of material systems—such as atomic vapors, collections of ultra cold atoms and cryogenically controlled solids—might be useful, we feel that the greatest opportunities for the practical use of slow-light techniques involve room-temperature solid-state materials. Within this broad framework, we are pursuing a number of approaches, some of which are described here.

Coherent population oscillations

Like EIT, coherent population oscillations (CPO) is a process that can lead to decreased absorption and rapid spectral variation of the refractive index, thus producing a strong slow-light effect. However, unlike many other quantum coherence effects, CPO is highly insensitive to the presence of dephasing collisions and thus can occur in room-temperature solids.

The process of CPO occurs when a strong pump beam and a signal-carrying beam at a slightly different frequency interact within a material that displays saturable absorption. The population of the ground state of the material will be induced to oscillate at the beat frequency between the two input waves. Mathematical analysis shows that CPO leads to a rapid frequency variation of the refractive index experienced by the signal wave, which then leads to a large value of the group index.

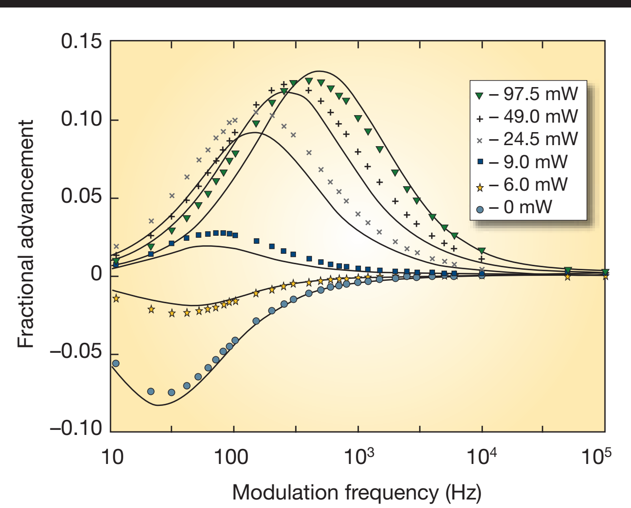
Slow light based on CPO has been studied in a variety of material systems. In a 2003 study published in *Physical Review Letters*, Bigelow and colleagues reported the results of their experiments in ruby, which established that slow light based on this effect could be observed and that the group indices could be as large as several million.

An intriguing variant of this behavior is observed in the case of alexandrite. At certain wavelengths, alexandrite acts as an inverse saturable absorber, meaning that the absorption of the material increases with rising optical intensity. At these wavelengths, the induced change in the group index has the opposite sign as for the case of a saturable absorber. Consequently, the group index can be smaller than unity or even negative. Bigelow et al. reported having made measurements of just this sort of superluminal propagation in a 2003 article in *Science*.

Modification of the group velocity by CPOs has also been observed in erbium-doped optical materials and in semiconductor structures (see Baldit et al., 2005; Schweinsberg et al., 2006; and Zhao et al., 2005). Some results showing slow- and fast-light effects in an erbium-doped optical fiber are shown in the figure below.

A key issue in all slow-light experiments is finding the maximum modulation bandwidth (roughly the inverse of the shortest pulse) that can experience the full slow-light effect. In CPO experiments, this bandwidth is set by the inverse of the population recovery time T_1. The early experiments based on ruby, alexandrite and erbium led to highly restricted bandwidths on the order of one kilohertz as a consequence of the long population relaxation times of these materials. More recent work has been aimed at the development of materials with a much faster population recovery. For instance, Zhao et al. have observed slow light with a modulation bandwidth as large as 2.8 GHz in a semiconductor laser amplifier.

[Slow light via CPO in an erbium-doped fiber amplifier]



Laboratory results showing the ability to advance or retard a waveform by a controllable amount. These results were obtained by using slow light enabled by coherent population oscillations in an erbium-doped optical amplifier. The delay is controlled by changing the power of the 980 nm pump light [Schweinsberg et al.].

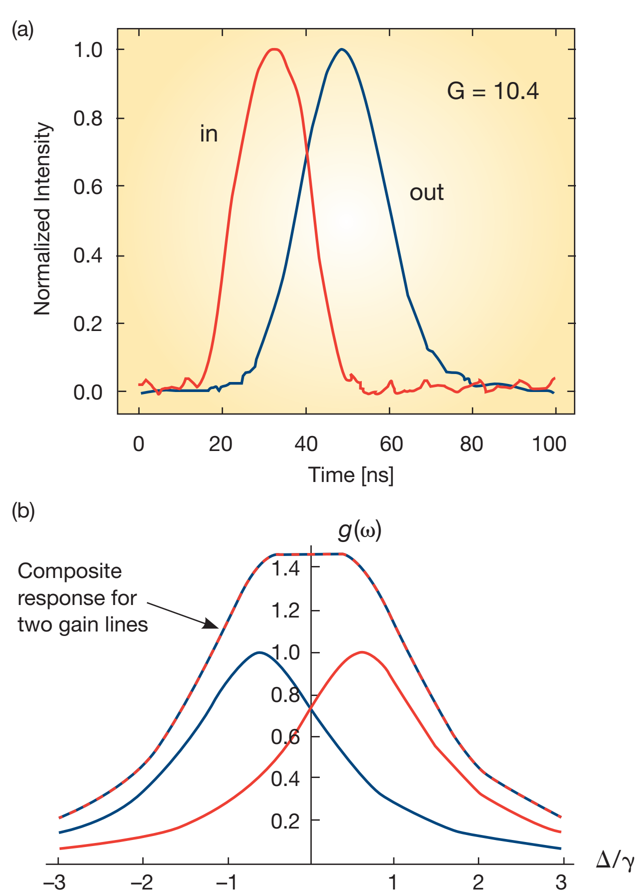
Under many conditions, the primary limitation to the achievable delay is an unacceptably large amount of pulse distortion that accompanies large time delays. The use of a flattened gain profile minimizes this distortion.

Stimulated Brillouin and Raman scattering

Stimulated Brillouin scattering (SBS) involves the coherent interaction of an intense pump field, a Stokes field at a downshifted frequency and an acoustic field at the difference frequency of the pump and Stokes fields. The SBS process can lead to a large amplification of the Stokes field over a fairly narrow bandwidth on the order of 100 MHz.

A variation of refractive index is associated with this gain feature; a rapid spectral variation of the refractive index leads to a strong slow-light effect. Slow light based on SBS has been observed experimentally by two groups: Song et al. and Okawachi and colleagues. Some of our group's results are shown in part (a) of the figure on the left.

[Slow light by stimulated Brillouin scattering]



(a) Typical laboratory results [Okawachi et al.]. (b) Recent work has shown that the distortion of the transmitted waveform can be dramatically reduced by using frequency-flattened gain profiles [Stenner et al.].

We are also working on procedures for increasing the normalized delay time achievable using the SBS process. Part of our team has found that the normalized delay can be increased dramatically by using two nearby SBS gain lines to flatten the frequency response near the signal frequency [see part (b) of the figure]. The reason behind this approach is that, under many conditions, the primary limitation to the achievable delay is an unacceptably large amount of pulse distortion that accompanies large time delays.

The use of a flattened gain profile minimizes this distortion by canceling the lowest-order contribution to group velocity dispersion. In one example, the researchers found that the normalized pulse delay could be increased by a factor of nine while maintaining a distortion no larger than 5 percent through use of a double gain line.

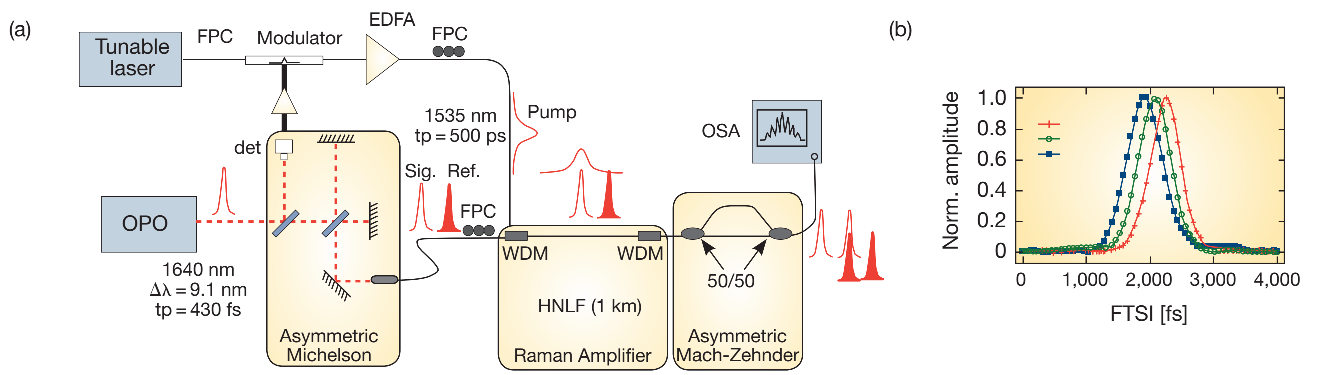
The line width of SBS of about 100 MHz is too small for certain applications of slow light. Appreciably larger line widths can be obtained by using the related process of stimulated Raman scattering (SRS). SRS involves the coherent interaction of an intense pump field, a Stokes field and the vibrational mode of a molecule or solid-state material.

The SRS line width can be as large as 3 THz (the value for silica glass), which is big enough to support the modulation bandwidth of currently proposed applications of slow light. In one result from Sharping and colleagues, which was published in *Optics Express* in 2005, an input pulse of 430 fs has been delayed by 370 fs by means of the SRS process (see figure on facing page, top).

Tunable time delays by wavelength conversion and dispersion

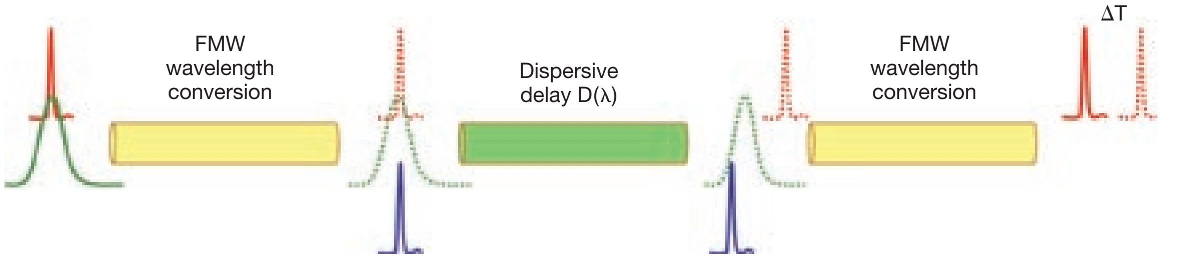
So far, the examples we have given all involve the use of small values of the group velocity to produce a tunable time delay. An alternative strategy is to use the spectral variation of the group velocity (see figure on facing page, bottom). The signal-carrying beam is first converted to a different wavelength by means of a four-wave mixing process. The wavelength-converted wave then passes through a strongly dispersive material, where it undergoes a time delay that is strongly wavelength dependent. The time-shifted beam is subsequently shifted back to the original wavelength or to any other desired wavelength by means of another four-wave mixing process.

[Slow light by stimulated Raman scattering]



(a) Laboratory setup for measuring induced slow-light time delay. (b) Laboratory results showing the ability to induce time delays for sub-ps pulses [Sharping et al., 2005].

[Method for inducing long time delays]



The wavelength of the signal wave is first converted by means of four-wave mixing, delaying the pulse in a dispersive medium such as an optical fiber; the signal is then converted back to the original wavelength [Sharping et al., 2005].

In a recent demonstration of this procedure, which was published in *Optics Express* last fall, Sharping and colleagues were able to produce tunable delays as large as 800 ps for pulses of roughly 10 ps in duration.

Conclusion

Slow-light techniques hold great promise for applications in many areas of modern photonics, including telecommunications. Good progress is being made in the development of new techniques for producing controllable time delays in optical waveguides based on slow-light methods. ◭

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