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Controlling the Velocity of Light Pulses

Robert W. Boyd[1]* **and Daniel J. Gauthier**[2]

It is now possible to exercise a high degree of control over the velocity at which light pulses pass through material media. This velocity, known as the group velocity, can be made to be very different from the speed of light in a vacuum c. Specifically, the group velocity of light can be made much smaller than c, greater than c, or even negative. We present a survey of methods for establishing extreme values of the group velocity, concentrating especially on methods that work in room-temperature solids. We also describe some applications of slow light.

For the past decade or more, the optical physics community has been fascinated by the related phenomena known figuratively as slow and fast light (*1*–*3*). These names refer to situations in which the group velocity of light v_g is very different from the speed of light in a vacuum c. The group velocity gives approximately the velocity at which light pulses propagate through a dispersive material. One refers to light as being "slow" for $v_g << c$ (*4*, *5*) or "fast" for $v_g > c$ or $v_g < 0$ (*6*–*12*). For $v_g < 0$, the pulse envelope appears to travel backward in the material (*12*), and hence it is sometimes referred to as "backward light."

Interest in slow and fast light dates back to the early days of the 20th century. Sommerfeld and Brillouin (*13*) were intrigued by the fact that theory predicts that v_g can exceed c, which leads to apparent inconsistencies with Einstein's special theory of relativity. Experimental investigations of extreme propagation velocities were performed soon after the invention of the laser (*6*, *7*).

A great impetus for much of the recent interest in slow and fast light is the experiment of Hau *et al.* (*4*), which showed that light could be slowed down to the "human" scale of 17 m/s. The result was obtained in ultracold atom clouds with the use of electromagnetically induced transparency (EIT), which induces transparency in a material while allowing it to retain strong linear and nonlinear optical properties (*14*). Slow light can also be obtained through the use of the optical response of hot atomic vapors (*5*). To date, the largest slow-light optical delay measured in pulse widths is 80 pulse widths (*15*) for 740-ps-long pulses propagating between two absorbing resonances in a cesium vapor.

More recently, extreme values of v_g were realized in room-temperature, solid-state materials, which are more suited for many practical applications. Here we review some of the physical mechanisms that can be used to induce slow- and fast-light effects in room-temperature solids (*16*–*18*), and we describe some of the exotic propagation effects that can thereby be observed. We also survey some applications of slow and fast light within the fields of quantum electronics and photonics.

Slow- and Fast-Light Fundamentals

The concept of velocity is well defined for a point particle but becomes murky for wave phenomena. For example, a light pulse tends to spread and distort as it propagates through a material system such a glass. For this reason, it is not possible to use a single definition of velocity to describe the speed at which a pulse of light propagates through a material (*2*). Nonetheless, under conditions described below, v_g gives a reasonable measure of the speed at which a pulse travels.

To understand the consequences of dispersion of the refractive index, we first consider the propagation of a monochromatic beam of light through a material. The phase velocity (v_p) describes the speed at which the wavefronts move through the material and is given by

$$v_p = c/n \tag{1}$$

Here, n is the refractive index of the material, which describes effects such as refraction at an interface between two dissimilar materials.

A pulse of light is a wavepacket that is composed of an infinite number of monochromatic component waves, where constructive and destructive interference among the waves defines the shape and location of the pulse envelope in space and time. When the pulse propagates through a material system, each monochromatic component wave travels at a different speed because of the frequency dependence of n, resulting in a shift (relative to vacuum propagation) of the regions of constructive and destructive interference. Pulse distortion can also occur. For sufficiently short propagation distances, pulse distortion is not too severe, and the motion of the pulse can be described by v_g (*2*) given by $v_g = c/n_g$, where

$$n_g = n + \omega \frac{dn}{d\omega} \tag{2}$$

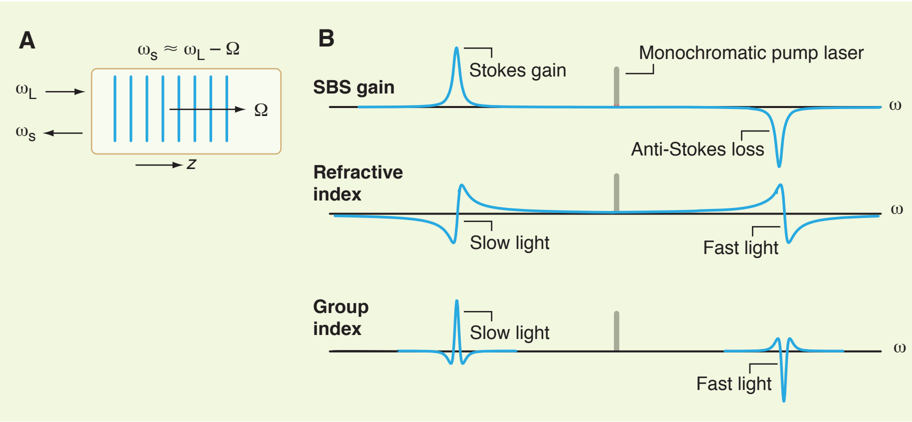

Fig. 1. Slow light via SBS. (**A**) Schematic of the SBS process. A laser beam (frequency ω_L) and a signal beam (frequency ω_S) interact to produce an ultra–high-frequency acoustic wave (frequency Ω, typically ~10 GHz for standard optical fibers) through the process of electrostriction. The acoustic wave produces an optical wavelength–scale variation in the refractive index of the material, which acts as a moving diffraction grating. For the case of $\omega_S \approx \omega_L - \Omega$, the grating travels in the same direction as the pump laser beam and scatters light coherently from the pump beam into the signal beam. This process thus gives rise to a narrow isolated amplifying resonance, known as the Stokes resonance, as shown in (**B**). For the opposite case in which $\omega_S \approx \omega_L + \Omega$, the diffraction grating moves in the opposite direction, and light from the signal beam is scattered into the pump laser beam, resulting in an anti-Stokes absorbing resonance. General considerations (the Kramers-Kronig relations) require that a peak in the gain or loss be accompanied by a rapid variation in the refractive index n. According to Eq. 2, this rapid variation gives rise to a large contribution to n_g. Thus, a large slow-light effect occurs near the center of the Stokes gain, or a fast-light effect occurs near the center of the anti-Stokes absorption resonance. The SBS process is noteworthy in that the resonances can be created at any frequency by adjusting the pump laser frequency, and the time delay can be adjusted continuously by adjusting the laser intensity.

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[1] The Institute of Optics and Department of Physics and Astronomy, University of Rochester, Rochester, NY 14627, USA. [2] Department of Physics, Duke University, Box 90305, Durham, NC 27708, USA.

*To whom correspondence should be addressed. E-mail: boyd@optics.rochester.edu

is known as the group index, where ω is the light's frequency. A fascinating result of recent investigations is the extreme range of values of n_g that can be observed in the laboratory. For example, one can readily observe extremely slow light with $n_g \sim 10^8$ or can observe backward light with $n_g < 0$. These values should be put in the context of the refractive index, which lies in the range of ~1.4 to ~3 for typical materials in the visible part of the electromagnetic spectrum. As can be seen from Eq. 2, n_g can be adjusted either by modifying n or by modifying $dn/d\omega$ (the dispersive contribution to n_g). Most demonstrations of extreme values of n_g rely on the dominance of the dispersive contribution to n_g. However, recent developments in the field of metamaterials have led to the demonstration of negative values of n (*19*).

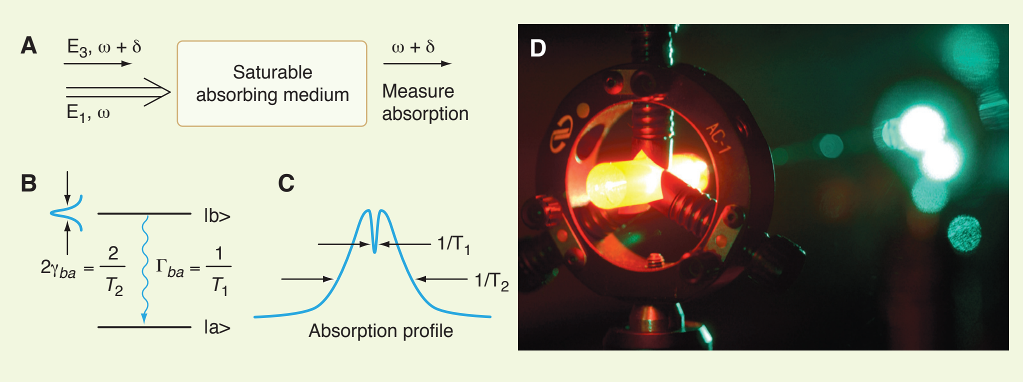

Fig. 2. Origin of slow light due to CPO. (**A**) A strong pump laser beam (E_1, frequency ω) copropagates with a weak probe beam (E_3, frequency ω + δ) through a saturable absorber. (**B**) Energy-level diagram of a typical saturable absorbing medium. The width of the resonance is governed by the inverse of the dipole dephasing time T_2. Here $2\gamma_{ba}$ is the resonance linewidth and Γ_{ba} is the spontaneous emission rate of $|b\rangle$. (**C**) Absorption profile in the presence of CPO. The pronounced dip is created by the following process: A beat note is induced at the frequency difference of the two input beams. When the beat-note period is so long that the atomic population can follow the beat frequency (the time scale for atomic population to respond is the T_1 relaxation time), the resonance is more easily saturated, resulting in smaller signal-beam absorption. When the beat-note period is much shorter than the T_1 lifetime, the material senses only the average of the field (that is, the beat notes are washed out), resulting in lower saturation of the resonance and larger signal-beam absorption. If T_1 is much greater than T_2, a well-defined hole is thus induced in the absorption profile of the saturable absorber, even if the absorption profile is homogeneously broadened in the conventional sense. This spectral hole then leads, through the usual Kramers-Kronig relations, to a rapid spectral variation of the refractive index and thus to a strong slow-light effect. Detailed calculation (*25*) shows that the resulting n_g scales linearly with the intensity of the pump laser, as long as the pump intensity is not too large. Thus, the slow-light delay via CPO can be tuned continuously by adjusting the pump beam intensity. (**D**) Part of the experimental setup.

Slow Light in Room-Temperature Solids

Many applications of slow light require the use of room-temperature solids, rather than crystals at cryogenic temperatures (*8*), hot atomic vapors (*5*, *15*), or ultracold atomic ensembles (*4*, *20*). In our view, three methods involving room-temperature solids have emerged as being particularly well suited for use in applications of low light. These methods are reviewed below.

Slow light via stimulated Brillouin scattering. Stimulated Brillouin scattering (SBS) is a nonlinear optical process that occurs readily in any transparent material. It results from the mutual interaction of applied pump and signal laser beams with an acoustic wave that is itself created by the laser beams through the process of electrostriction (*21*). For the case in which the signal beam has a slightly lower frequency than the pump beam, the mutual interaction gives rise to a narrow gain resonance (Fig. 1). There will be a large slow-light effect near the center of this gain line. For the case in which the signal beam has a slightly higher frequency than the pump, the opposite happens, giving rise to an absorption resonance and a fast-light effect. The induced time delay for the slow-light situation is proportional to the intensity of the pump beam, allowing v_g to be readily controlled. Slow light based on this process was first observed in standard telecommunication optical fibers at a wavelength of 1550 nm (*17*, *18*).

A limitation to the usefulness of the SBS process, however, is that the Brillouin linewidth for typical optical fibers is only 30 to 50 MHz. This linewidth sets the characteristic frequency bandwidth over which slow-light effects can be observed. Data transmission rates are hence limited to this value, which is much too small for many applications in optical telecommunication. Several procedures have been introduced to broaden this linewidth, such as broadening the linewidth of the laser that pumps the SBS process. This method was used to achieve a 12-GHz bandwidth (*22*) and to delay 100-ps-long pulses by up to three pulse widths (*23*). More details on recent advances in SBS slow light can be found in a recent review (*24*).

Slow light via coherent population oscillations. Another method for producing slow light is based on the process of coherent population oscillation (CPO). The CPO process has been studied since the 1960s and has successfully been exploited for slow- and fast-light research (*12*, *16*, *25*–*27*). The idea behind CPO (see Fig. 2) is that, when pump and probe beams of slightly different frequencies interact inside a saturable absorbing material, the atomic population is driven coherently between the ground and excited states at the beat frequency of the light beams. These population oscillations lead to a dip in the absorption spectrum that is experienced by the probe beam, which then leads to a greatly reduced v_g over a spectral region surrounding the dip.

In the first reported experimental study of slow light based on CPO (*25*), saturation of the strong green absorption band of ruby was used to produce the slow-light effect. Group velocities as low as 60 m/s, corresponding to an n_g of 5×10^6, were observed for waveforms with time scales on the order of 16 ms.

A follow-up experiment made use of the nonlinear optical properties of the crystal alexandrite (*16*). Alexandrite is a saturable absorber at some frequencies but an inverse saturable absorber at others. At frequencies at which alexandrite is an inverse saturable absorber, it displays fast and backward light as a result of the CPO effect. In one situation, a velocity of −800 m/s was measured. The implications of a negative v_g are described in the following section. CPO typically produces a maximum delay or advance of about 0.25 pulse widths. However, by careful choice of material parameters and by cascading more than one CPO delay element, greater delays can be obtained. In one study, a delay of approximately 1.3 pulse widths was achieved (*28*).

Tunable time delays based on v_g dispersion. The simplest method for controlling the velocity of light is to make use of a medium with a large dispersion in v_g (*29*). By varying the frequency of the carrier wave of the signal, the time delay can be controlled directly. In practice, this method is often implemented by starting with a signal at a prescribed carrier frequency, shifting the carrier frequency with a nonlinear optical conversion method, passing this frequency-shifted signal through a highly dispersive medium, and finally converting the carrier frequency back to the original frequency. This method is often called the conversion/dispersion (C/D) method for this reason.

Fast Light and Its Interpretation

As mentioned above, v_g can become greater than c or can even become negative (Fig. 3). Fast light is sometimes taken to constitute a highly exotic phenomenon, perhaps because of some fear that superluminal propagation constitutes a violation of relativity theory. However, slow light occurs when $dn/d\omega$ is positive, and fast light occurs when $dn/d\omega$ is negative. Thus, there is nothing fundamentally different between slow light and fast light. Here we show that fast light is entirely consistent with accepted physical laws.

Experimental studies of fast-light propagation include those of (*7*–*10*). More-recent work was motivated by a suggestion (*30*) to make use of a Raman gain doublet to induce a spectral region within which v_g exceeds c and pulse distortion effects are minimized. This idea was successfully implemented (*10*) by using a gain doublet produced in a laser-pumped cesium vapor. Soon thereafter, an experiment directly measured the speed at which information propagates through a fast-light material (*11*). Figure 3A shows an example for the case of a smooth Gaussian-shaped pulse propagating through the fast-light medium in comparison to the same pulse propagating through vacuum.

Causality implications. It is well established that the superluminal transfer of information is inconsistent with the concept of Einstein causality. In particular, if information could be transmitted from one observer to another in a superluminal fashion, then there is always some other inertial reference frame in which the information reaches the receiver before it leaves the sender. Because causality is believed to be a universal property of nature, it is commonly thought that the superluminal transfer of information is therefore impossible.

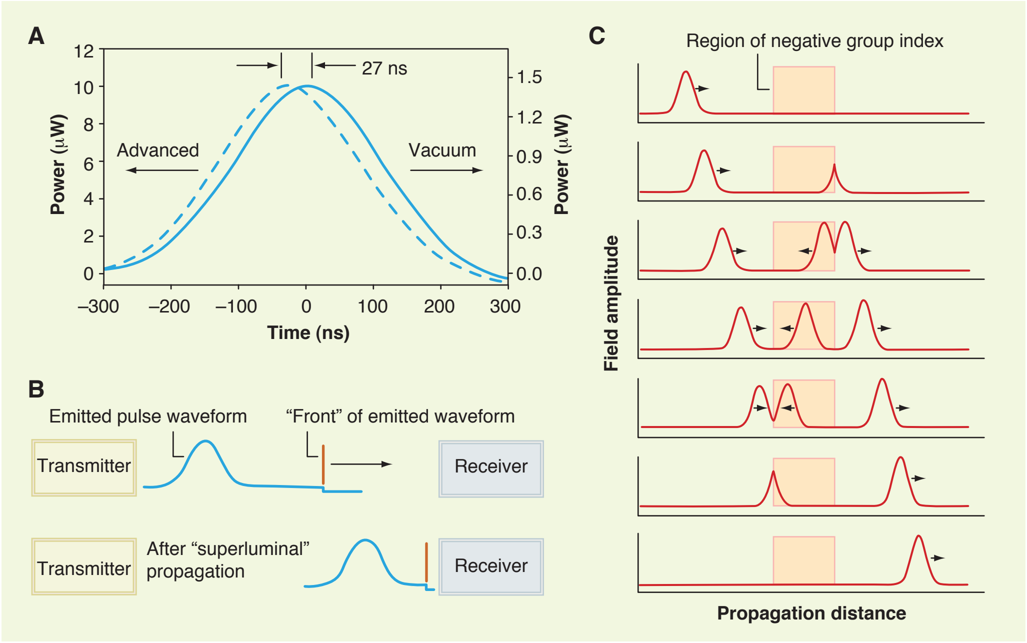

Fig. 3. Some exotic propagation effects can occur when light pulses pass through a dispersive material. One of these is superluminal pulse propagation. In (**A**), a 260-ns-long (full width at half maximum) pulse propagates through a laser-pumped potassium vapor with n_g of approximately -20 (dashed line). The peak of the pulse is seen to be advanced by 27 ns with respect to vacuum propagation (solid line) (*11*). Such superluminal propagation effects may appear to violate principles of causality, but in fact they do not for reasons illustrated in (**B**). Any real pulse has a "front": the first moment in time at which the intensity becomes nonzero, as indicated by the vertical line. In superluminal propagation experiments, the peak of the pulse moves at a superluminal velocity, but the front of the pulse moves at velocity c. Because the information content of the pulse is contained in the front, no information is transmitted at a velocity exceeding c. For propagation distances longer than those shown here, for which the pulse peak begins to overtake the pulse front, severe pulse distortion always occurs and no pulse energy ever precedes the pulse front. (**C**) Another exotic propagation effect is backward pulse propagation. This effect occurs for a sufficiently long material with a negative n_g and leads to the result that the peak of the transmitted pulse appears to emerge from the material medium before the peak of the incident pulse enters the medium. Backward propagation has been observed in the laboratory (*12*). The plots are based on a simple model that assumes that all spectral components of the pulse propagate without loss at the same v_g.

So why do laboratory results of fast light not necessitate the superluminal transfer of information? It is believed that the explanation lies in the distinction between v_g and the information velocity. The group velocity can take on any value. However, the information velocity can never exceed c and, according to many models, is always equal to c (*2*, *13*, *31*). To understand why this is so, we note that the encoding of information onto an optical waveform necessarily entails impressing points of discontinuity onto the waveform. New information is encoded at each discontinuity. In concept, no information is carried by the smooth portions of the waveform, because, in principle, the future behavior can be predicted in terms of the past behavior for any analytic function. Points of discontinuity propagate at the speed of light in a vacuum c because no physical material can respond instantaneously to a change in the waveform (*13*).

Backward light. Under certain extreme conditions, v_g can actually become negative. Numerical simulations of the sort shown in Fig. 3C (*32*, *33*) demonstrate that the peak of the pulse leaving a slab of material appears to exit before the peak of the input pulse enters the slab. Moreover, the pulse envelope appears to propagate backward inside the material (although the flow of power is still from the entrance to the exit of the slab), justifying the name backward light. These predictions were verified experimentally (*12*) using the highly dispersive response of an erbium-doped fiber amplifier. When driven into saturation, an amplifier shows fast light by means of the CPO effect (*12*) for the same reason that an absorber shows slow light (Fig. 2C). The peak of the pulse did propagate in the backward direction within the fiber, in agreement with the standard meaning of v_g.

Applications of Slow and Fast Light

Telecommunication. Slow-light methods have direct applicability to the field of optical telecommunication for applications such as buffering and regeneration. Figure 4A shows how a slow-light delay line acting as a buffer might be used to increase the throughput of an optical telecommunication system.

To implement this idea, the delay line needs to be able to store as many bits of information (data pulses) as are contained in a data packet. This number is determined by the system architecture. In most implementations, a typical packet has at least 1024 bits of data (or 1024 pulses in the return-to-zero data format). In fundamental terms, the number of stored pulses is known as the delay-bandwidth product of the delay line. There have been a number of analyses of the theoretical limit to how large the delay-bandwidth product of a slow-light delay line can be (*34*, *35*). The general conclusion of these analyses seems to be that there is no fundamental limit to the size of the delay-bandwidth product, although there can be serious practical problems involved in obtaining large values of this quantity. One important implementation of slow-light methods in optical telecommunication is the demonstration of optical data packet synchronization and multiplexing based on the C/D method (*36*).

By careful selection of the slow-light mechanism and operating conditions, delays of many pulse lengths have been obtained in laboratory

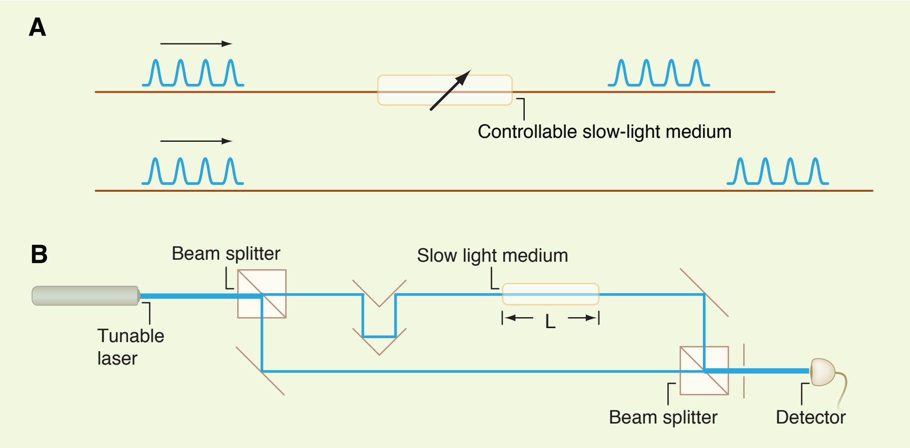

Fig. 4. Two applications of slow and fast light. (**A**) A slow-light buffer for use in a telecommunication system. If two optical data packets arrive simultaneously at an optical switch, a problem occurs because the switch cannot handle the two data packets simultaneously. In the worst case, one of the data packets is simply dropped and must be retransmitted at a later time. This procedure, of course, simply makes the problem of system overload worse, because the data packet has to be transmitted more than once. This problem can be avoided by constructing a controllable delay line that can act as a buffer for a complete data packet, as shown. In this scenario, one data packet is directed into the buffer and is released only after the other data packet has cleared the switch. (**B**) Slow-light–enhanced optical interferometer. By placing a slow-light medium of length L in one arm of the interferometer, the spectral resolution can be increased by a factor as large as the n_g of the slow-light material. This procedure holds great promise for the development of spectrometers with extremely high spectral resolution or for miniaturizing the size of spectrometers of more modest resolution.

measurements. By combining slow-light methods with self-phase modulation, a total advancement/delay bandwidth product of ~10 for 370-fs-long optical pulses has been obtained using a semiconductor optical amplifier (*37*). Recently, using the C/D method, delays of 20,000 pulse widths have been obtained at a data rate of 40 Gb/s (*38*). These delays are large enough to prove useful in actual communication systems.

Microwave photonics. Microwave photonics is an emerging field in which high-frequency electrical signals in the radio-frequency or microwave-frequency bands are impressed onto a light beam using amplitude or phase modulators and are subsequently processed using all-optical methods. These all-optical methods tend to have very high bandwidth, fast reconfiguration speeds, and low loss. Already, microwave photonic devices are being integrated into broadband wireless access networks, phased-array antennas, and high-speed signal processing engines.

At the heart of many of these devices is a unit that gives a true time delay (as opposed to mechanisms that would delay some spectral components but not others) of an optical waveform (*39*). For device reconfigurability, it is important that the time delay be continuously tunable. Thus, slow- and fast-light methods are well suited to the development of microwave photonic devices. In fact, only modest delays are needed (a delay-bandwidth product of unity is often sufficient) in comparison to what is needed for data buffering in telecommunication systems described above. One example of a microwave component based on slow light is a phase shifter with a continuously tunable phase shift of ~240° at a microwave frequency of approximately 19 GHz (*40*).

Interferometry. The performance of many types of interferometers can be dramatically improved by placing a highly dispersive material within the interferometer. One example is the slow-light Mach-Zehnder interferometer shown in Fig. 4B. One finds by direct calculation (*41*) that the spectral sensitivity of the interferometer, defined as the change in phase difference between the two arms per change in input frequency, is proportional to the product of the length L and n_g of the slow-light material. Thus, dramatic increases in the spectral sensitivity of the interferometer are enabled by using large values of n_g. A slow-light spectrometer of this sort was constructed (*41*) and was found to achieve an increase in spectral sensitivity by a factor of approximately 2; more recent work has demonstrated a 100-fold enhancement of the sensitivity.

Summary and Outlook

Slow- and fast-light methods have advanced dramatically in recent years. Many of the fundamental aspects of slow and fast light are currently well understood. Thus, research has turned to the equally exciting task of developing applications of this new technology.

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