

Fiber-Based Slow-Light Technologies

George M. Gehring, *Member, OSA*, Robert W. Boyd, *Member, IEEE, Fellow, OSA*, Alexander L. Gaeta, *Fellow, OSA*, Daniel J. Gauthier, *Fellow, OSA*, and Alan E. Willner, *Fellow, IEEE, Fellow, OSA*

Abstract—A review of current fiber-based technologies capable of producing slow-light effects is presented, with emphasis on the applicability of these technologies to telecommunications. We begin with a review of the basic concepts of phase velocity, group velocity, and group delay. We then present a survey of some of the figures of merit used to quantify the engineering properties of slow-light systems. We also present a description of several of the physical processes that are commonly used to induce a slow-light effect. Finally, a review of some recent advances in this field is presented.

Index Terms—Fibers, slow light.

I. INTRODUCTION

SLOW-LIGHT technologies are at the forefront of the current drive for potential replacements of electronic delay lines in telecommunications. Such tunable optical delays can enable various digital signal processing functions that are useful in various types of communication systems. Specifically, accurate and fine control of an optical delay is important for high-bit-rate systems, in which it is difficult to temporally control the light to within a fraction of a bit time; this small time could correspond to less than 1 mm in optical path length. Applications of optical tunable delays include synchronization of time-division-multiplexers, data equalization using tapped-delay-lines, and optical correlation [1]. While slow light has been demonstrated in atomic vapors, Bose–Einstein condensates [2], and cryogenic crystals, room-temperature solids provide the most feasible solutions for optical buffer production [3]. Fiber-based slow-light technologies in particular show great promise for practical applications, as they are easily integrated with existing telecommunications equipment.

A. Basics of Slow Light

The term “slow light” describes a broad class of technologies that alter the propagation of pulses through a medium to

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G. M. Gehring and R. W. Boyd are with the Institute of Optics, University of Rochester, Rochester, NY 14627 USA (e-mail: gehring@optics.rochester.edu; boyd@optics.rochester.edu).

A. L. Gaeta is with the School of Applied and Engineering Physics, Cornell University, Ithaca, NY 14853 USA (e-mail: a.gaeta@cornell.edu).

D. J. Gauthier is with the Department of Physics, Duke University, Durham, NC 27708 USA (e-mail: gauthier@phy.duke.edu).

A. E. Willner is with the Department of Electrical Engineering—Systems, University of Southern California, Los Angeles, CA 90089-2565 USA (e-mail: willner@usc.edu).

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create exotic effects, including time delays that suggest abnormally slow propagation velocities. Related effects include “fast light,” which refers to superluminal or even negative propagation velocities, and “stopped” or “stored” light, where the information contained in a pulse is encoded in a medium or cavity and released after a controllable storage time. Before discussing the processes that lead to these effects, we will briefly review the fundamentals of pulse propagation.

The *phase velocity* $v_p = c/n$ is the speed at which the phase front of a monochromatic wave propagates through a medium with real refractive index n . A pulse of light, however, is created by the interference of a large number of component sinusoidal waves, each of which travels at its own phase velocity. If the phase velocities of the individual component waves are equal, as they are in a perfect vacuum where $n = 1$, then the pulse subsequently travels at that velocity and experience no distortion. In dispersive materials, n varies with wavelength, and each component wave travels at a slightly different phase velocity. This will cause the individual components to be “out of synch” and interfere in a different way, resulting in some degree of pulse distortion (for example, pulse broadening or reshaping).

In the special (and unphysical) case where n varies linearly with frequency, to first order, the pulse “distortion” preserves the pulse’s shape but shifts the peak of the pulse temporally. Here, we use distortion in the very general sense of the word: we take it to mean any change in shape of the pulse that is different from vacuum propagation. Thus, a pure translation of the pulse is considered a distortion. This effect implies that the pulse travels at a velocity that’s different from the phase velocity, and depends on the amount of dispersion. This speed is termed the *group velocity* of the pulse.

More generally, the group velocity is defined mathematically for a pulse with center frequency ω_0 as

$$v_g = \left. \frac{d\omega}{dk} \right|_{\omega_0} = \frac{c}{n_g} \quad (1)$$

where we have introduced the *group index* n_g as a proportionality constant reminiscent of the refractive index. To prevent ambiguity, the terms *phase index* and *group index* are used to refer to n and n_g , respectively, when discussing slow-light effects. Since $k = n\omega/c$ for media that responds linearly to the applied field, we can rewrite the group index as

$$n_g(\omega_0) = c \left. \frac{dk}{d\omega} \right|_{\omega_0} = n + \omega_0 \left. \frac{dn}{d\omega} \right|_{\omega_0}. \quad (2)$$

Here, we see that the group index reduces to the phase index for a dispersionless material ($dn/d\omega = 0$), and the pulse propagates at the phase velocity as expected. If instead we consider

our special case of linear dispersion over the pulse bandwidth, the group index is nearly constant over the region of the pulse spectrum that contains most of the spectral energy, leading to the behavior described above.

However, if the frequency dependence of n deviates significantly from linearity, the group velocity will begin to vary noticeably with frequency over the pulse bandwidth—an effect that is known as group velocity dispersion (GVD). Physically, this means that the pulse will begin to experience distortion effects due to higher-order dispersion that may degrade or change the pulse's shape. Generally, the concept of group velocity is used as long as the pulse distortion is not too great, though there is no agreed-upon quantitative benchmark for this limit. Most slow- and fast-light experiments attempt to minimize this ambiguity by limiting the bulk of the pulse's spectral energy to regions of linear dispersion, or by employing distortion compensation methods such as those described in later sections.

Nonetheless, the group index (also sometimes referred to as the *slowdown factor* [4]) is a common metric used to describe or evaluate a slow-light system. For a pulse whose bandwidth is considerably smaller than the region of linear dispersion, the group index is directly proportional to the delay experienced during propagation [5]. If such a pulse traverses a slow-light material of length L , the delay experienced by a pulse is

$$\tau_g = \frac{n_g L}{c} \quad (3)$$

which is also called the *group delay*. Note that (3) is only valid for narrowband pulses, though it serves as an upper bound to the delay if higher order distortion becomes important. Group indexes as large as 10^8 have been observed experimentally in a Bose–Einstein condensate (BEC) [6] and as large as 10^{12} in a room-temperature photoreactive crystal [7]. In fibers, group indexes on the order of 10^3 have been achieved using erbium-doped fiber amplifiers [8]. It should be noted that, while we have listed some of the largest experimentally demonstrated values, it is possible to achieve appreciable pulse delay with group indexes as low as 2 or 4 [9], [10].

It is clear from (2) that the group index can be made significantly different from the phase index by changing the dispersive properties of a material. According to the *Kramers–Kronig* relations, the dispersion and the absorption of a material are related through a Hilbert transform [11]. An isolated gain peak will therefore create a region of large normal dispersion, as shown in Fig. 1. Within this region, $dn/d\omega$ is large and positive, and the group velocity will be small, resulting in slow-light propagation. This is not only true for a gain peak, but for any similar spectral structure, such as a narrow dip in a broad background absorption profile. The amount of dispersion introduced will depend on the strength, bandwidth, and shape of the gain feature.

As an example, consider a simple Lorentzian gain feature of the form

$$g(\delta) = \frac{g}{1 + \delta^2/\gamma^2} \quad (4)$$

where $\delta = \omega - \omega_0$ is the detuning from the resonance frequency ω_0 , γ is the linewidth of the resonance, and g is the value of the

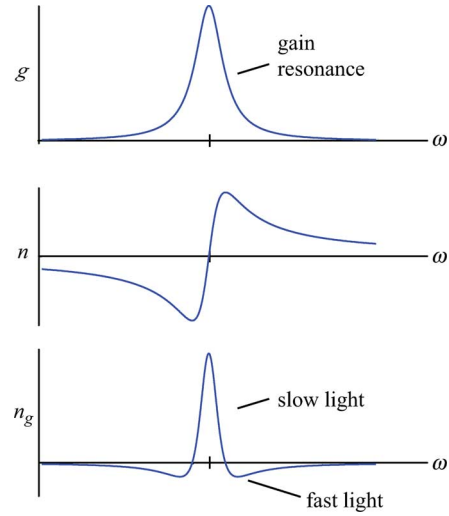


Fig. 1. Lorentzian gain peak and the dispersion profiles of the refractive index n and group index n_g associated with this gain spectrum by the *Kramers–Kronig* relations. It is clear from the figure that a very large and positive group index occurs in the region of strong linear dispersion in n . This region of slow-light propagation is accompanied by fast-light regions due to strong normal dispersion in the wings of the refractive index dispersion profile.

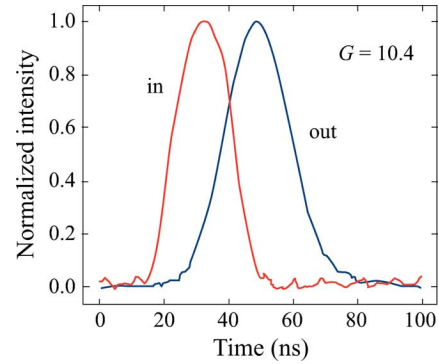


Fig. 2. Input (red) and output (blue) pulse data for a fiber SBS system, from [13]. The gain parameter $G = g_0 I_p L$ was 10.4 in this experiment.

intensity gain coefficient at line center. The refractive index in this region is then

$$n(\delta) = n_0 + \left(\frac{gc}{2\omega_0} \right) \frac{\delta/\gamma}{1 + \delta^2/\gamma^2} \quad (5)$$

where n_0 is the real frequency-independent background index, and we have ignored other sources of dispersion. The group velocity is then calculated by (2) to be

$$n_g(\delta) = n(\delta) + \left(\frac{gc}{2\gamma} \right) \frac{1 - \delta^2/\gamma^2}{(1 + \delta^2/\gamma^2)^2} \quad (6)$$

and, at line center ($\delta = 0$), the corresponding group delay predicted by (3) is

$$\tau_g = \frac{n_0 L}{c} + \frac{gL}{2\gamma}. \quad (7)$$

We define the *pulse delay* τ_d to be the additional delay introduced by the gain feature, since that is often the quantity of interest. The first term in (7) is the group delay in the absence of the gain feature, so the pulse delay is simply

$$\tau_d = \frac{gL}{2\gamma}. \quad (8)$$

The terms group delay and pulse delay are sometimes used interchangeably in cases where the first term of (7) is much smaller than τ_d .

In theory, it is possible to specify a dispersion profile exactly and determine the gain structure necessary to elicit that profile [12], [13], but such a scheme is difficult to implement experimentally except in certain special situations. In practice, a slow-light medium is designed by choosing an appropriate gain or loss profile to create the desired dispersive qualities [14].

The group delay can be obtained from pure time-domain measurements of slowed (signal) and reference pulses, though this method is obviously not predictive. There are a number of ways to perform this measurement, and no universally agreed-upon standard for doing so, as different algorithms are better suited to specific pulse shapes and sequences.

For single pulses, the simplest way is to simply measure the time delay between the peak point on the signal and reference traces. However, in cases of moderate to large pulse distortion or broadening, the value obtained by this method may be misleading. More sophisticated methods include calculating the shift of the pulse centroid or measuring the peak shift of the intensity cross-correlation function of signal and reference pulses. If the input is a pulse sequence, the maximum opening of the eye diagram is another possibility [15], [16]. For a sufficiently narrow pulse spectrum, all of these measurements give the same delay as the Kramers–Kronig group delay prediction.

B. Metrics

We have already mentioned the group index as a metric for describing a slow-light medium. However, when given by itself, the group index is not sufficient to fully characterize a slow-light system. The best solution for a given application often depends highly on other factors, including bandwidth (or bit rate), pulse distortion due to higher-order dispersion, and power requirements. Comparing different slow-light techniques often requires several measures of performance covering a broad range of operational details. A few common measures of slow-light performance that will be used throughout the rest of the discussion are given here.

1) *Group Index, Group Velocity, or Group Delay*: As discussed above, the group delay is often given as a measure of performance; the group velocity or group index are equivalent measures. Unfortunately, they can be the least useful measures for some applications. A delay of 10 ns is large for a pulse of 1-ns duration, but insignificant for a pulse of 10 μ s. As a result, the group delay time is usually accompanied by a measure of the achievable bandwidth or bit rate in order to present a more complete assessment.

2) *Fractional Delay*: *Fractional delay* refers to the pulse delay divided by a measure of the pulse duration, i.e.,

$$T_{\text{frac}} = \frac{\tau_d}{T_0}. \quad (9)$$

T_0 is most commonly defined as the pulse full-width at half-maximum (FWHM), though authors occasionally use other measures of the pulse duration. Conceptually, the fractional delay combines a measure of the delay with a measure of the pulse duration to give a more accurate representation of the amount of “slowing” present. In the above example, quoting the fractional delay would clearly differentiate between the two scenarios, which would have $T_{\text{frac}} = 10$ and $T_{\text{frac}} = 0.001$ respectively. Unfortunately, it also cannot stand alone as the sole metric for a slow light system; quoting a fractional delay of 10 does not give the reader any information as to *either* the pulse delay *or* the pulse width, only their ratio. It is usually accompanied by a bandwidth measurement to show a more complete assessment.

3) *Delay-Bandwidth or Delay-Bit-Rate Product*: Very similar to the fractional delay, the *delay-bandwidth product* or *delay-bit-rate product* (DBP) combines a delay measurement with a frequency or bit rate measurement. In general, “bandwidth” refers to the optical spectral width of a data channel, whereas bit rate refers to the bits/s of transmitted data. The DPB is a valuable parameter since large absolute time delays might accompany a fairly low-bit-rate channel, but this might correspond to only an insignificantly small fractional delay. Moreover, higher-bit-rate channels are presently of high interest in terms of potentially performing digital signal processing. Therefore, small delays for extremely small bit times might be of significance.

The expression for DPB product is

$$\Delta_{\text{DBP}} = \tau_d B \quad (10)$$

where B is the bit rate of the signal being slowed and is identical to (9) if one defines T_0 to be the temporal width of the bit slot rather than the pulse duration. While at first glance it appears that Δ_{DBP} differs from T_{frac} only by a constant (usually ≈ 2), the difference is more subtle. The delay τ_d in (10) is the amount of delay achievable for each pulse in a *sequence* of pulses at a bit rate B (pulse temporal width $\leq 1/B$), whereas the fractional delay usually refers to the delay of a single pulse.

To elaborate, if one can slow an entire sequence of pulses by τ_d , then one can slow an individual pulse by τ_d and $\Delta_{\text{DBP}} \approx T_{\text{frac}}$ (ignoring the constant factor). However, the converse of this statement is *not* necessarily true. A slow light system may be able to slow a single pulse of width $1/B$ by τ_d , but nonlinearities, distortion constraints, or transient effects may make it incapable of slowing the second pulse of the sequence by the same amount. Thus, the bit rate is effectively lowered or the amount of delay reduced to recover the “lost” bandwidth. In either case, the DBP for such a medium may be orders of magnitude smaller than the fractional delay.

Thus, the DBP is capable of conveying different (though not necessarily more) information about a slow-light system than

the fractional delay. In particular, the DBP is the number of bits that can be stored in a delay line, which is a very useful metric for telecommunications. Subsequently, the inverse of the DBP (also known as the normalized bit length $L_{\text{bit}}/L_{\text{medium}} = 1/\Delta_{\text{DBP}}$) gives information about the miniaturization potential of a particular device [17]–[19]. There appears to be an upper limit on the delay-bandwidth product that scales with the length of the material and the contrast in the refractive index of the medium [20], [21].

As with the other measures, DBP is rarely cited alone, since it fails to convey the pulse duration or bit rate directly. Most of the time, DBP is accompanied by the bit rate B in bit/s. Occasionally the pulsewidth and fractional delay are also given, to clearly differentiate between T_0 and $1/B$.

4) *Q-Delay Product*: Given that data might be distorted after passing through a slow-light element, it might be useful to employ a data integrity-delay product. The data distortion can be quantified by using the data Q factor, which is related to the signal-to-noise ratio and the eye diagram opening. Moreover, if the digital data bits are distorted or broadened after passing through a slow-light medium, then the eye diagram opening and Q factor will decrease. A Q -delay product provides insight into optimal design guidelines [22]. Consider Q -delay product as a function of signal bandwidth relative to the slow light resonance bandwidth. For signals much narrower than the resonance bandwidth, there is little distortion and negligible induced delay. Conversely, for signals much wider than the slow-light resonance, high delay and high distortion result. Therefore, there exists an optimal operating point for a given signal data rate and slow-light element [23].

5) *Other Metrics*: There are a host of other metrics that can be used to evaluate slow-light systems. Many familiar figures of merit can be applied seamlessly, including *bit error rate* (BER) [24], *power penalty* [24], and *eye opening* [15], [25]. More obscure metrics are often applied or invented for specific research topics, such as integrating absorption into one of the common metrics [3], [26], [27] or characterizing distortion of the pulse after propagation [15], [28].

II. PHYSICAL PROCESSES LEADING TO SLOW LIGHT

Here, we review some of the more important mechanisms through which slow-light propagation can be achieved in a fiber system.

A. Stimulated Scattering

Normally, stimulated light scattering processes are considered detrimental to fiber communications, placing an upper limit on the power or transmission distance of an optical signal [29]. However, in a carefully designed system, processes such as stimulated Brillouin scattering (SBS) or stimulated Raman scattering (SRS) can be harnessed to generate slow light effects. Slow light via stimulated scattering in fibers was first demonstrated experimentally by Song *et al.* [30] and Okawachi *et al.* [13] for SBS and by Sharping *et al.* for SRS [31].

Stimulated Brillouin scattering occurs when a pump field applied at frequency ω interacts with a vibrational (acoustic) wave at frequency Ω . This interaction causes some light from the pump field to be scattered into a counterpropagating Stokes

sideband at frequency $\omega_S = \omega - \Omega$. The beating between the pump and the Stokes fields enhances the acoustic wave through a process called electrostriction, or the tendency of a material to compress in the presence of an applied electric field. The enhanced acoustic wave causes stronger scattering of the pump into the sideband, reinforcing the effect. As a result, the Stokes wave experiences exponential gain upon propagation through the material. It should be noted that the same effect causes exponential loss (absorption) for the anti-Stokes sideband at frequency $\omega_{aS} = \omega + \Omega$ [11]. In most cases, amplification of the Stokes wave can only occur when the pump and probe wave are counterpropagating, though in certain rare circumstances forward-scattered Stokes light can be generated [32].

While this effect can grow out of noise, it is usually seeded by applying a probe field near ω_S . The gain and absorption features are narrowband and Lorentzian, with a Brillouin linewidth of $\Gamma_B = \tau_{\text{phonon}}^{-1}$, where τ_{phonon} is the phonon lifetime in the material. As long as the probe field falls within the Brillouin gain bandwidth, it will experience both exponential gain and strong normal dispersion, leading to a slow light effect. Fast-light effects are possible by detuning the probe to the anti-Stokes resonance, though then one must contend with absorption of the probe [10]. For optical fibers near the telecommunication wavelength, the Brillouin frequency shift $\Delta\nu_B = \Omega_B/2\pi$ is typically around 10 GHz and the Brillouin linewidth $\Gamma_B/2\pi$ is typically around 35 MHz.

Since the Brillouin gain feature is Lorentzian, we can use the formalism in Section I-A to calculate the group velocity. For SBS, the parameters g and γ are

$$g = g_0 I_p \quad \gamma = \frac{\Gamma_B}{2} \quad (11)$$

where g_0 is the gain factor at line center, I_p is the applied pump intensity, and δ is the detuning of the probe from the Stokes frequency ω_S . Substitution of (11a) and (11b) into (8) yields a pulse delay of [13]

$$\tau_d = g_0 I_p L / \Gamma_B. \quad (12)$$

As with (3), this result serves as an upper bound reachable only under appropriate conditions. It is clear from (12) that the amount of delay can be continuously controlled by adjusting the pump intensity I_p [13].

Unfortunately, there are also limitations imposed by the SBS process. Spectral reshaping and GVD cause pulse broadening upon propagation. Gain saturation can occur if the input probe field intensity is too large [33]. In addition, when the gain parameter $g_0 I_p L$ becomes too large (greater than ≈ 25), spontaneous Brillouin scattering can seed the SBS process, saturating the pump field even in the absence of an applied probe [11]. Finally, if τ_{in} becomes too short, higher-order dispersion and frequency-dependent gain can cause further pulse distortion [13], [19], [34]. These experimental difficulties limit single-stage SBS elements to single-digit group indexes and fractional advancements [9], [10]. Some of these limitations can be overcome by the methods described in Section III.

Stimulated Raman scattering works in much the same way as SBS. In SRS, the pump scatters off of a vibrational mode of an atom, leading to gain for a probe at $\omega - \Omega$. For SRS, Ω can be as large as several THz. Four-wave mixing in the medium can offset the loss at the anti-Stokes frequency if proper phase matching is achieved, allowing for gain at both sideband frequencies [11]. Equation (12) correctly describes SRS slow light propagation with the substitution of the Raman linewidth Γ_R for Γ_B [31]. Raman slow light has also been demonstrated on a silicon microchip [35].

Raman scattering can also be used in conjunction with optical parametric amplification (OPA) to achieve slow- and fast-light effects in fiber systems [36]. Though the theory of Raman-assisted OPA is too extensive to detail here, OPA provides a narrow gain resonance that can produce slow-light effects [37], [38]. The SRS process reshapes the gain spectrum and allows the delay to be controlled delicately with applied pump power.

B. Coherent Population Oscillation

Coherent population oscillation (CPO) is a technique for creating slow light that works in a variety of materials, including crystals [39], [40], semiconductor waveguides [41], quantum dots [42], [43], and erbium-doped fibers [8], [44]. While we will use the density matrix formalism in this text, CPO can be developed in an entirely equivalent fashion using rate equations describing saturable absorption [45].

In CPO, a pump wave at frequency ω and a weaker probe wave at frequency $\omega + \delta$ are applied to a medium near an allowed transition. For the moment, we will assume the broadened linewidth of the transition is sufficiently broad that both fields are nearly resonant. If the pump is strong enough, the interaction will cause the atomic population to oscillate between the ground and excited states at the beat frequency δ . This temporally modulated ground state population can scatter light from the pump into the probe, leading to decreased absorption of the probe wave. In the frequency domain, this leads to a sharp spectral hole in the absorption profile, and the probe field will experience slow light propagation.

The population oscillations are appreciable only for detunings such that $\delta \leq 1/T_1$, where T_1 is the excited state lifetime of the transition. This effectively means that both pump and probe must fall within the lifetime-broadened linewidth of the transition for the effect to work; if the probe is detuned too far, the oscillations become too weak to efficiently scatter light from pump to probe. In spectral terms, this is equivalent to the probe frequency falling outside the spectral hole created by the pump, and therefore not experiencing the rapid index variation and enhanced group index in the region of the spectral hole.

In practice, the pump and probe need not be separate beams; a single beam with a temporal modulation can experience the effect, and a single (strong) pulse can self-delay, acting as both pump and probe. In the case of single pulses, the bandwidth of the pulse should be narrow enough to fit within the spectral hole for the slow light effect to be appreciable. This effectively limits the maximum bit rate for this technique to $\approx 1/T_1$ by the material parameters. Attempting to transmit data at higher bit rates will lead to a reduction of the total delay and distortion of the signal via spectral reshaping and GVD.

Since a constant gain or absorption factor has no effect on the formalism of Section I-A, we can use it to model a Lorentzian transparency dip in a broad background absorption feature. If the background absorption coefficient is α_0 and we let $g = \alpha_0 f$, the frequency dependent absorption can be expressed as

$$\alpha(\delta) = \alpha_0 \left[1 - \frac{f}{1 + \delta^2/\gamma^2} \right] \quad (13)$$

where f is a parameter describing the depth of the transparency window, such that $0 \leq f \leq 1$. This expression is valid for CPO when the dephasing rate $1/T_2$ is much faster than both the population relaxation rate $1/T_1$ and the Rabi frequency $\Omega = 2\mu E/\hbar$, often referred to as the rate equation limit. In this limit, the transparency depth f and power-broadened linewidth γ have the form

$$f = \frac{I}{(1+I)^2}, \quad \gamma = \frac{1}{T_1}(1+I) \quad (14)$$

where $I = \Omega^2 T_1 T_2$ is the saturation parameter $I_{\text{pump}}/I_{\text{sat}}$. Equation (8) then gives a pulse delay at line center of

$$\tau_d = \frac{\alpha_0 L T_1}{2} \frac{I}{(1+I)^3}. \quad (15)$$

As can be seen from (15), there is no theoretical limit to the amount of delay achievable via CPO, since L is unbounded. In practice the residual absorption, as well as GVD and spectral reshaping imposed by the physical medium, limit the achievable fractional advancement to around 10% [46].

While we have focused in this discussion on slow light via CPO in an absorbing medium, it is also possible to induce CPO in an amplifying medium. In this case, a spectral hole is created in a gain feature, and the resulting anomalous dispersion can lead to superluminal or negative group velocities. Working in a gain medium also reduces problems caused by residual absorption but introduces new difficulties caused by amplified spontaneous emission. As seen in Fig. 3, both slow- and fast-light effects can be obtained for 1550-nm pulses in erbium-doped fiber, since the background absorption or gain can be controlled by an applied 980-nm pump beam [8], [44]. In this case, (14) need to be modified slightly to include power broadening induced by the 980-nm pump. Unfortunately, the response time T_1 of erbium is approximately 10 ms, making it unsuitable for use at high bit rates. However, experiments utilizing semiconductor quantum wells [4] and quantum-dot semiconductor optical amplifiers [47] have managed to produce similar results at much higher signal bandwidths.

C. Electromagnetically Induced Transparency in Hollow-Core Photonic-Bandgap Fibers

Electromagnetically induced transparency (EIT) is another technique that creates a narrow transparency window in an atomic absorption profile. It was first proposed in 1990 by Harris *et al.* as a method to access the large resonant nonlinear response near an atomic transition that is normally obscured by large amounts of absorption [48]. EIT has been demonstrated

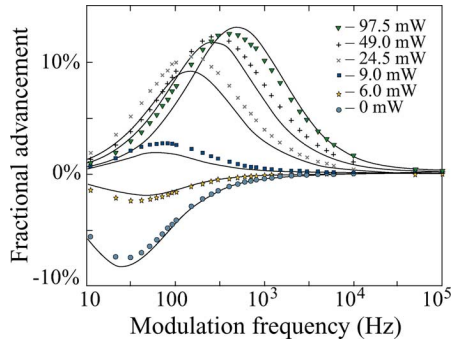


Fig. 3. Plot of pulse fractional advancement as a function of modulation frequency for an erbium-doped optical fiber CPO system [8]. The amount of advancement or delay is controlled by the amount of applied 980-nm pump power, given in the inset.

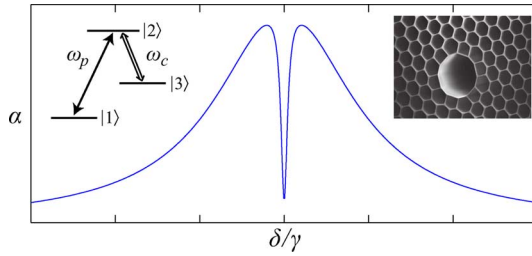


Fig. 4. EIT probe absorption spectrum, calculated from [46] using $\gamma_{31}/\gamma_{21} = 5 \times 10^{-3}$ and $\Omega_c/2\gamma_{21} = 0.4$. The left inset shows a three-level lambda EIT system, while the right inset is a cross section of the hollow-core PBGF used in [56].

in BECs [2], atomic vapors [49], [50], solid crystals [51], and semiconductor quantum wells and quantum dots [52], [53]. Schemes to achieve EIT-based slow light in fiber systems have been proposed [54], and both EIT as well as EIT-based slow-light propagation have recently been demonstrated experimentally in hollow-core photonic-bandgap fibers (PBGF) filled with rubidium [55] and acetylene [56], [57].

EIT is usually performed in a three-level Λ system such as the one in Fig. 4. A strong control field at ω_c between states $|2\rangle$ and $|3\rangle$ induces a coherence between ground states $|1\rangle$ and $|3\rangle$. Quantum mechanical interference between the $|1\rangle - |2\rangle$ and $|3\rangle - |2\rangle$ transitions results in a cancellation of the probability amplitude for absorption of a photon resonant with the $|1\rangle - |2\rangle$ transition, creating a sharp transparency resonance in the absorption profile. It is this resonance that provides the dispersion necessary to create the slow light effect.

Under appropriate conditions [46], the transparency window created by EIT is approximately Lorentzian, and can be described by (13) with f and γ given by

$$f = \frac{|\Omega_c/2|^2}{\gamma_{31}\gamma_{21} + |\Omega_c/2|^2} \quad \gamma = \frac{|\Omega_c/2|^2}{\gamma_{21}} \quad (16)$$

where γ_{21} is the coherence dephasing rate of the $|1\rangle - |2\rangle$ transition, $\Omega_c = 2\mu_{23}E_c/\hbar$ is the Rabi frequency of the strong coupling field at ω_c , and γ_{31} is the dephasing rate of the ground

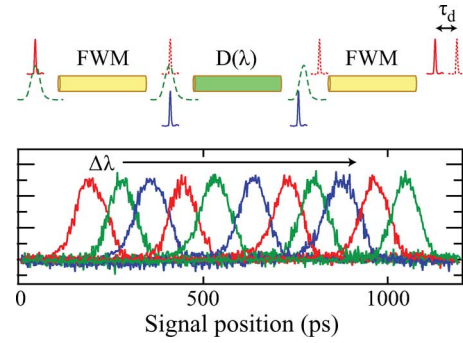


Fig. 5. Schematic diagram (top) and signal delay data (bottom) for a conversion-dispersion system based on FWM. In the schematic, the signal pulse (red solid line) and FWM pump pulse (green dashed line) first enter a conversion stage, during which the signal is wavelength-shifted (blue solid line). The signal pulse at the new wavelength travels through the dispersion stage, acquiring a dispersive delay ΔT compared with propagation at the original wavelength (red dotted line). The signal is then converted back to the original wavelength in a final conversion stage. The lower plot shows delay of a single signal pulse for eleven different $\Delta\lambda$ values, demonstrating the tunability and dynamic range of conversion-dispersion [58].

state coherence. In the same fashion as before, we can substitute (16a) and (16b) into (8) to find the pulse delay at line center

$$\tau_d = \left(\frac{\alpha_0 L}{2} \right) \frac{\gamma_{21}}{\gamma_{31}\gamma_{21} + |\Omega_c/2|^2}. \quad (17)$$

Again, from (17), we see that there is no theoretical upper limit to the amount of delay, and EIT has the clear advantage over CPO that the transparency depth f can approach 1, eliminating residual absorption. However, spectral reshaping limits the fractional advancement to approximately

$$T_{\text{frac}} = \frac{3}{2} \frac{|\Omega_c/2|^2 T_0}{\gamma_{21}}. \quad (18)$$

Third-order dispersion imposes an additional limitation on the transmission bandwidth, limiting operation at high bit rates [18]. Further complicating matters is the fact that the EIT medium must be able to preserve quantum coherence [48], often making EIT difficult to achieve experimentally.

D. Conversion-Dispersion

Conversion-dispersion refers to a novel technique that generates tunable delay without relying on absorption or gain resonances. In this technique, the original pulse is wavelength-shifted (hence conversion) by an amount $\Delta\lambda$ using a highly nonlinear fiber (HNLF). The converted pulse then travels through a length of dispersion-compensating fiber (DCF) possessing a large group-velocity dispersion parameter D that can be of the order of -100 ps/nm \cdot km. This introduces a delay proportional to the product of the wavelength shift $\Delta\lambda$ and the GVD parameter D . After propagation through the DCF, the pulse is then sent through a second HNLF to convert the pulse back to the original wavelength. The conversion process can be accomplished via four-wave mixing (FWM) in either HNLF [58], or a periodically

poled lithium-niobate (PPLN) waveguide [59], or by broadening due to self-phase modulation (SPM) followed by a narrowband filter [60]. Another alternative is to exploit the soliton self-frequency shift, which simultaneously produces a frequency shift and a delay proportional to the square of the input pulse peak power [61].

We can express $\beta(\omega = \omega_0 + \delta)$, the waveguide mode propagation vector within the DCF, as a Taylor series expansion around the input pulse frequency ω_0

$$\beta(\delta) = \beta_0 + \beta_1\delta + \frac{\beta_2}{2}\delta^2 + \dots \quad (19)$$

Ignoring higher order dispersion, substitution into (2) gives a group index of

$$n_g(\delta) = c \frac{d\beta}{d\omega} = c(\beta_1 + \beta_2\delta). \quad (20)$$

The effective delay a pulse experiences through the DCF is then the difference between the group delay at the shifted frequency and the group delay at the original frequency

$$\begin{aligned} \tau_d &= \frac{L}{c} (n_g(\delta) - n_g(0)) \\ &= L\beta_2\delta \\ &= -LD\Delta\lambda \end{aligned} \quad (21)$$

where L here is the length of the DCF.

Conversion-dispersion has several major advantages over slow-light methods that rely on gain or absorption resonances. Perhaps the most noticeable advantage is the large amount of controllable delay possible; fractional delays of up to 1200 have been demonstrated experimentally for 3.5-ps pulses [60]. Since the method is not tied to a resonance feature, it can accommodate much broader bandwidth input pulses, resulting in excellent operation at data rates exceeding 10 Gb/s with minimal pulse broadening [60]. Finally, the output signal wavelength and bandwidth can be made identical to the input wavelength and bandwidth, which is of importance for practical application in a telecommunications-grade device [58].

There are a few disadvantages to the conversion-dispersion method, however. The reconfiguration rate in the SPM variation is dependent on the speed with which the bandpass filters can be adjusted, though recent advances in filters indicate that this can be reduced to less than 90 μ s [62]. For the FWM variant, the reconfiguration rate should depend only on the speed at which the lasers can be tuned, though stimulated Raman effects limit the wavelength shift to about 40 nm. In addition, dispersive pulse broadening, nonuniformity of the GVD profile of the DCF, and the gain profile of the FWM process can make operation with pulses shorter than 1 ps difficult [58].

E. Fiber Bragg Gratings

Fiber Bragg gratings (FBGs) may soon be able to add optical buffering to their already robust list of pulse propagation and control applications [63]. The transmission profile of a FBG leads to dispersion in an analogous fashion to an absorption or

transmission peak [64]–[66]. Slow-light effects can be observed near the band edge in the transmission region, while fast-light effects occur within the photonic bandgap. Recent experiments utilizing superstructure periodic Bragg gratings have demonstrated fractional delays of ~ 1 for 760-ns pulses in a 20-cm Moiré grating [67]. While tunability and reconfiguration rate are limited, the construction of active fiber Bragg gratings for controllable delay with fast tuning speeds holds great promise [68].

One can also achieve “dispersionless” slow light in FBGs by exploiting gap solitons [69], [70]. Gap solitons occur when the pulse intensity causes a change in the refractive index through Kerr nonlinearity, which subsequently shifts the location of the photonic band edge of the grating. An appropriately shaped pulse whose bandwidth falls within the bandgap of the unmodified grating but outside the shifted bandgap can in this way propagate through the grating as a gap soliton with any velocity between 0 and c/n . The delay is continuously tunable by varying the input intensity of the signal pulse [71].

III. RECENT ADVANCES IN THE FIELD

Now that we have discussed the physical mechanisms that can lead to slow light in fibers, we will conclude with a review of recent work undertaken in these systems.

A. Slow-Light Propagation of Phase-Shift-Keyed Signals

While most slow-light discussions focus on pulses or other amplitude modulations of a signal, the phase properties of the transmitted signal are also subject to slow light effects. Optical delay of phase-modulated signals has been demonstrated experimentally [24]. A 10.7-Gb/s signal encoded in a differential-phase-shift-keying (DPSK) format was delayed by up to 42 ps using SBS slow light, and pattern dependency was reduced via a novel detuning mechanism. In addition, NRZ and RZ formats were compared at 2.5 Gb/s, with the RZ format showing as much as 2 dB less power penalty than the NRZ format, primarily due to reduced pattern dependence.

B. Distortion Management

Much of the current slow-light research focuses on minimizing the large amounts of distortion that can occur when trying to stretch the bandwidth of slow-light systems to accommodate current telecommunication bitrates. Often this requires mitigation of limitations imposed by the physical system employed to create the slow-light effect.

1) *Multiple Gain Lines*: A major factor that limits the bandwidth available to slow light systems is pulse distortion due to GVD. In an SBS system, GVD can be reduced by using a superposition of two Lorentzian gain resonances instead of a single resonance [72]. Stenner *et al.* demonstrated that the lowest order GVD term k_2 can be expressed as

$$k_2 = -\frac{4ig_0\gamma^2}{z} \frac{3\delta^2 - \gamma^2}{(\delta^2 + \gamma^2)^3} \quad (22)$$

where g_0/z is the line-center amplitude gain coefficient, γ is the linewidth for each line, and 2δ is the separation between the two lines. From this, it is clear that, when $\delta = \gamma/\sqrt{3}$, $k_2 = 0$,

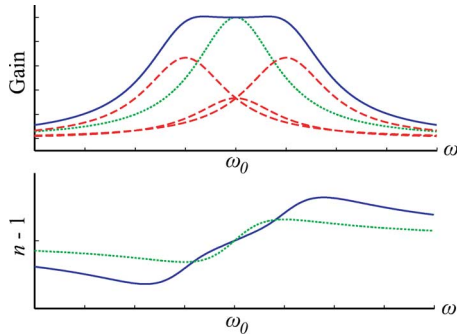


Fig. 6. Gain spectrum and associated refractive index illustrating the multiple-gain-line concept. The green dotted lines are calculated for a single gain line, while the blue solid lines are calculated for the summation of three individual gain lines, illustrated by red dashed lines. The triple-gain line exhibits strong dispersion over a larger bandwidth than the single-gain line, reducing GVD-based distortion for high bit rate signals.

eliminating lowest order GVD while having only a small effect on the overall amount of delay.

One can extend this idea to three or more gain lines, which increases both the maximum achievable fractional delay and signal bandwidth [73], [74]. It has recently been demonstrated that a triple-gain-line structure, such as that shown in Fig. 6, can provide almost twice the delay of a single gain line while accommodating three times the bandwidth, with no loss of fidelity as measured by the eye-opening penalty [15]. Two absorption lines have also been used effectively to reduce pulse level changes while increasing the bandwidth [75].

2) *Modulated Pumps*: Another technique to enhance the bandwidth available to SBS slow light schemes is to modulate the pump beam to broaden the Lorentzian gain linewidth. *Herréiz et al.* were the first to demonstrate this effect, broadening a 35 MHz SBS gain line to 325 MHz [76]. *Zhu et al.* extended this broadening technique to 12.6 GHz, allowing for 10-Gb/s transmission rates [77]. Further broadening proved ineffective, as it exceeded the Brillouin frequency $\Delta\nu_B$ of the optical fiber, causing the Stokes gain peak and anti-Stokes absorption feature to overlap significantly and introduce distortion. This is illustrated in Fig. 7(a).

To get around this limitation, Song and Hotate introduced a second SBS pump, separated from the first by twice the Brillouin frequency [78]. In this arrangement, shown in Fig. 7(b) and (c), the Stokes gain feature of the second pump coincides with the anti-Stokes absorption of the first pump, increasing the available bandwidth to $2\Delta\nu_B$. Using this technique, they demonstrated SBS slow-light bandwidths of 25 GHz. They also noted that the addition of a third, fourth, and subsequent pumps at $3\Delta\nu_B$, $4\Delta\nu_B$, and so forth extend the gain bandwidth identically, potentially making an enormous amount of bandwidth available to SBS when appropriate pumps are used.

Chin et al. [79] and *Schneider et al.* [80] have also explored slow light in SBS systems where the anti-Stokes loss is compensated via Stokes gain from additional pump waves in order to increase the available bandwidth. In addition, delay with reduced distortion can be achieved using AM pump modulation [81] and programmed chirping of the pump frequency [82].

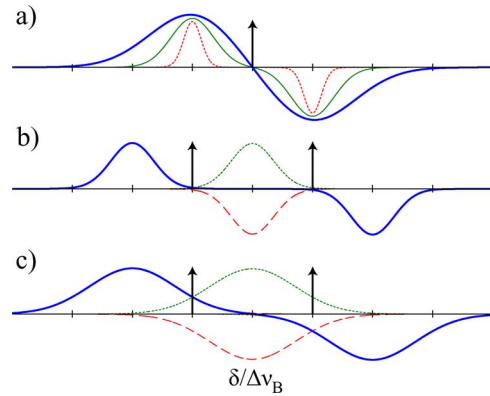


Fig. 7. SBS gain spectra for various pump configurations. Black arrows indicate the location of applied pump fields, and the gain spectra have been arbitrarily normalized for clarity. (a) The single-pump configuration is shown for pump broadenings of $0.4\Delta\nu_B$ (dotted red line), $\Delta\nu_B$ (thin green line), and $2\Delta\nu_B$ (thick blue line). The asymmetry of the Stokes gain line can be clearly seen in the $2\Delta\nu_B$ case. (b) and (c) The addition of a second pump is illustrated for pump broadenings of $\Delta\nu_B$ and $2\Delta\nu_B$, respectively. The second pump's Stokes gain line (green dotted line) exactly offsets the Anti-Stokes loss line of the first pump (red dashed line), resulting in the solid blue curve.

3) *Decreasing Distortion by Detuning*: Pattern dependence of NRZ-encoded signals is another important form of distortion encountered in high-speed SBS slow-light systems. A consecutive series of “1” bits occupies the central components of the signal bandwidth, while an isolated “1” or an alternating series of ones and zeroes will have stronger sideband components, detuned slightly from the center frequency. Since the center frequency is often chosen to coincide with the resonance frequency of the gain peak, where the slow-light effect is the greatest, the sideband components experience less gain and lead to strong pattern dependence of the output signal.

One technique to reduce this pattern dependence that has recently been demonstrated is to detune the center frequency enough to equalize the gain experienced by the center frequency and one of the sidebands. An improvement of 3 dB in the Q factor of a 10-GB/s NRZ-DPSK signal has been demonstrated by this technique [24], [83], [84].

4) *Pulse on a Background*: For slow-light systems using CPO in erbium-doped fiber, a major concern is pulse-width distortion due to pulse broadening or compression. It was recently reported that the addition of a continuous-wave control field, or “background,” applied at the signal frequency can reduce pulse-width distortion by balancing the different mechanisms that control broadening and compression, so that they counteract each other [28].

C. Independent Control of Multiple Channels

The delay and handling of wavelength-division multiplexed (WDM) signals is a vital concern for telecommunications device design. While it is possible to de-multiplex a WDM signal and use a separate narrowband optical delay line for each [WDM] channel, it would be more desirable to design a single optical delay element capable of controlling each channel independently. Such a delay element has recently been demonstrated for multiple 2.5-Gbit/s data channels within a single SBS-based delay device by using individually-tunable pump

lasers for each data channel [85]. With this technique, controllable, independent delays of up to 112 ps were demonstrated with error-free transmission for three NRZ-OOK channels.

IV. CONCLUSION

Fiber-based slow-light technologies hold great promise for a wide variety of applications. In addition to telecommunication, these techniques should prove useful in the areas of microwave photonics, laser radar, and all-optical steering of light beams.

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George Michael Gehring received the B.S. degree (with honors) in physics from Juniata College, Huntingdon, PA, in 2003. He is currently working toward the Ph.D. degree at the University of Rochester's Institute of Optics, Rochester, NY.

His current research focuses on slow- and fast-light propagation and microscale photonic resonators.

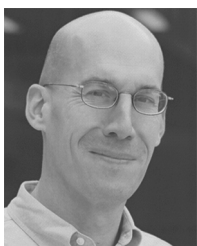


Robert W. Boyd was born in Buffalo, NY. He received the B.S. degree from the Massachusetts Institute of Technology, Cambridge, and the Ph.D. degree from the University of California, Berkeley, in 1977, both in physics. His Ph.D. thesis was supervised by Prof. Charles H. Townes and involved the use of nonlinear optical techniques in infrared detection for astronomy.

He joined the faculty of the Institute of Optics, University of Rochester, Rochester, NY, in 1977 and, since 1987, has held the position of Professor

of Optics. He also holds the positions of the M. Parker Givens Professor of Optics and Professor of Physics. His research interests include studies of slow- and fast-light propagation, quantum imaging techniques, nonlinear optical interactions, studies of the nonlinear optical properties of materials, the development of photonic devices including photonic biosensors, and studies of the quantum statistical properties of nonlinear optical interactions. He has written two books, coedited two anthologies, published over 270 research papers, and been awarded seven patents.

Prof. Boyd is a Fellow of the Optical Society of America and of the American Physical Society and is the past chair of the Division of Laser Science of the American Physical Society.



Alexander L. Gaeta received the B.S. and Ph.D. degrees from the University of Rochester, Rochester, NY, 1983 and 1991, respectively, both in optics.

In 1992, he joined the faculty at the School of Applied and Engineering Physics, Cornell University, Ithaca, NY, where he is currently a Professor. His research interests include ultrafast nonlinear optics, all-optical processing, the development and application of photonic crystal fibers, nanophotonics, and quantum effects in nonlinear optics. He has participated in the organization of various meetings

including serving as Chair of the 2003 OSA Annual Meeting, Program Chair of the 2007 Nonlinear Optics Topical Meeting, and the Program and General Chair of the 2005 and 2007 QELS Conferences, respectively.

Prof. Gaeta is a Fellow of the Optical Society of America and the American Physical Society.



Daniel J. Gauthier received the B.S., M.S., and Ph.D. degrees from the University of Rochester, Rochester, NY, in 1982, 1983, and 1989, respectively. His Ph.D. research on "instabilities and chaos of laser beams propagating through nonlinear optical media" was supervised by Prof. R. W. Boyd and supported in part through a University Research Initiative Fellowship.

From 1989 to 1991, he developed the first continuous-wave two-photon optical laser as a Postdoctoral Research Associate under the mentorship of Prof. T.

W. Mossberg at the University of Oregon. In 1991, he joined the faculty of Duke University, Durham, NC, as an Assistant Professor of physics and was named a Young Investigator of the U.S. Army Research Office and the National Science Foundation in 1992 and 1993, respectively. He is currently the Anne T. and Robert M. Bass Professor of Physics and Biomedical Engineering with the Department of Physics and the Fitzpatrick Center for Photonics and Communications Systems, Duke University. His research interests include applications of slow light in classical and quantum-information processing and controlling and synchronizing the dynamics of complex electronic, optical, and biological systems.

Prof. Gauthier is a Fellow of the Optical Society of America and the American Physical Society.



Alan E. Willner (S'87-M'88-SM'93-F'04) received the Ph.D. degree in electrical engineering from Columbia University, New York, NY, in 1988.

He has worked at AT&T Bell Laboratories and Bellcore. He is currently a Professor of electrical engineering with the University of Southern California (USC), Los Angeles. He has authored or coauthored 650 publications, including one book and 23 patents. His research is in the area of optical communications.

Prof. Willner is a Fellow of the Optical Society of America (OSA) and was a Fellow of the Semiconductor Research Corporation. His professional activities have included the following: President of the IEEE Lasers and Electro-Optics Society (LEOS), Editor-in-Chief of the IEEE/OSA JOURNAL OF LIGHTWAVE TECHNOLOGY, Editor-in-Chief of the IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS, Co-Chair of the OSA Science and Engineering Council, General Co-Chair of the Conference on Lasers and Electro-Optics (CLEO), Editor-in-Chief-elect of OSA OPTICS LETTERS, Chair of the IEEE TAB Ethics and Conflict Resolution Committee, General Chair of the LEOS Annual Meeting Program, Program Co-Chair of the OSA Annual Meeting, and Steering and Program Committee Member of the Conference on Optical Fiber Communications (OFC). He has received the National Science Foundation (NSF) Presidential Faculty Fellows Award from the White House, the Packard Foundation Fellowship, the NSF National Young Investigator Award, the Fulbright Foundation Senior Scholars Award, the IEEE LEOS Distinguished Traveling Lecturer Award, the USC University-Wide Award for Excellence in Teaching, the Eddy Award from Pennwell for the Best Contributed Technical Article, and the Armstrong Foundation Memorial Prize for the highest ranked EE graduate student.