Stimulated Brillouin scattering slow light in optical fibers [Invited]

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Stimulated Brillouin scattering (SBS) has become a favorable underlying mechanism in many demonstrations of all-optical variable delay in standard fibers, often referred to as *slow and fast light*. Over 100 journal papers and numerous conference sessions have been dedicated to SBS slow light since 2005. In this paper, recent research in this area is reviewed. Following a short introduction to the topic, several specific trends in contemporary work are highlighted: the optimization of the SBS pump spectrum for extended slow light delay and reduced pulse distortion; SBS slow light demonstrations in nonstandard, highly nonlinear fibers; applications of SBS slow light to the delay of analog waveforms; and the role of polarization. Finally, a brief concluding perspective is provided. © 2011 Optical Society of America

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1. Introduction

The group velocity of light pulses in optical media can become significantly slower, and even faster, than the expected speed of light. These phenomena, which are referred to as *slow and fast light*, respectively, have been demonstrated in a broad variety of materials and propagation conditions [1,2]. Interest in the field increased substantially following the ground-breaking demonstrations of ultra-slow light in cold atomic vapors [3,4], in quantum well material using population oscillations [5], and in photonic crystal structures [6]. Slow and fast light propagation carry several technological promises, such as the buffering and synchronization of data in high-capacity optical communication networks, the delay and processing of microwave photonic waveforms, the enhancement of nonlinear interactions, and many others. Over the last decade, the photonics engineering community has been searching for ways to implement the principles of slow light in more practical media [2]. Slow light techniques employing standard fibers at room temperature have been drawing particular attention due to their potential incorporation in optical communication and microwave photonic systems [7,8]. The key performance metric of slow light demonstrations, with respect to potential applications, is the product of the achievable group delay variations times the bandwidth of pulses that are delayed without excessive distortion [9]. Slow and fast light in standard fibers has been demonstrated using Raman scattering [10], Raman-assisted parametric amplification [11], and a combination of four-wave mixing and dispersion [12] as well as stimulated Brillouin scattering (SBS) [13–17], which is the subject of this paper.

In SBS, a relatively intense pump wave interacts with a counterpropagating, typically weaker, signal wave, which is detuned in frequency [18]. The combination of the two waves generates, apart from a stationary intensity term, a slowly traveling intensity wave whose frequency equals the difference between the frequencies of the pump and signal waves and whose wavenumber is the sum of their wavenumbers. Through electrostriction, the intensity wave introduces traveling density variations, namely an acoustic wave, which in turn leads to a traveling grating of

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refractive index variations due to the photoelastic effect. Much like a fiber Bragg grating, the traveling grating can couple optical power between the counterpropagating pump and signal waves. Effective coupling, however, requires that the difference between the two optical frequencies should closely match a particular fiber-dependent value known as the *Brillouin frequency shift* $\Omega_B \sim 2\pi \cdot 11$ GHz (for standard single-mode fibers at ~1550 nm wavelength). The power of a signal wave whose optical frequency is Ω_B below that of the pump is exponentially amplified by SBS, whereas a signal of frequency Ω_B above that of the pump is attenuated. The amplification (or attenuation) bandwidth achieved with continuous wave (CW) pumping is rather narrow: on the order of 30 MHz, as decreed by the relatively long lifetime of acoustic phonons [18].

The SBS interaction complies with the Kramers–Kronig relations [18], which link the magnitude response of the SBS gain/loss medium to its phase response. Within the SBS amplification bandwidth, there lies a region where the frequency dependence of the signal optical phase delay is nearly linear, thereby providing an effective added group delay. Depending on the sign of the added group delay, SBS can introduce slow/fast light behavior to the propagation of pulses in standard fibers. The extent of the delay is continuously variable through changing the pump power. Amplified signal pulses are slowed by SBS, whereas SBS-attenuated pulses experience an increased group velocity. SBS has become a favorable mechanism in *slow light over fiber* demonstrations due to its low threshold power levels of only a few milliwatts, robustness, and simplicity. Initial experimental demonstrations of SBS slow light were provided in 2005 [13–17], and over 100 journal papers on this topic have followed since.

SBS slow light was thoroughly reviewed in a book chapter by Thévenaz in 2009 [19]. Over the last three years, research efforts in this area have continued and diverged, exploring new aspects and potential applications of the phenomenon. The objective of this paper is to provide an overview of the recently obtained progress and achievements in SBS slow light research. Several trends clearly stand out. First, much effort has been dedicated to the continuing optimization of the SBS pump profiles for improving the delay times bandwidth product figure of merit and reducing pulse distortions. Multiple pump frequencies and pump broadenings have been introduced to overcome the inherent linewidth limitations of SBS as early as 2005 [20–23], and several gigahertz-wide pulses were successfully delayed by 2006 [24,25]. Nonetheless, numerous groups continue to report further improvements in performance. A second significant line of research is the implementation of SBS slow light in highly nonlinear, nonstandard fibers. The SBS gain coefficient in such media is orders of magnitude higher than that of silica fibers. The stronger interaction allows for a more dramatic reduction of the group velocity, resulting in an extended range of achievable delays along relatively short fiber spans. Following earlier demonstrations in chalcogenide glass and bismuth-oxide fibers [26–28], SBS slow light was also introduced to tellurite glass and photonic crystal fibers (PCFs) [29–32]. A third research direction follows the SBS slow light delay of analog waveforms, such as radar signals, with the potential applications in optical antenna beam forming. An early example of SBS delay of radar pulses was provided in 2007 [33]. More recent studies address the more efficient slow light delay of RF signals characterized by a relatively small fractional bandwidth (= [Information bandwidth]/[Carrier frequency]) [34–36]. Finally, the role of signal and pump states of polarization (SOPs) in SBS slow light was examined. It is long known that the SBS-induced delay is polarization dependent and might therefore drift with time. A double-pass configuration using a Faraday rotator mirror was devised to overcome this drawback [37]. On the other hand, polarization was found to introduce additional pulse distortion, which could become worse than that induced by the bandwidth limitations and dispersion, as predicted by the scalar treatment of SBS [38]. The above trends are discussed in the following sections and a brief concluding perspective is provided at the end.

2. Slow Light Via SBS: The Principle

Let A_p denote the amplitude of a continuous pump wave of frequency ω_p and A_s denote the amplitude of a counterpropagating signal wave, whose frequency ω_s is lower than ω_p by a difference Ω. We assume that the pump power is sufficiently high so that it is undepleted. Subject to the above assumption, the signal magnitude at the fiber output is exponentially amplified [18]:

$$A_s(L) = A_s(0)\exp[g(\omega_s)L_{\text{eff}}]e^{-\alpha L/2}. \tag{1}$$

In Eq. (1), L is the physical length of the fiber, α is the linear loss coefficient in the fiber, $L_{\text{eff}} \equiv [1 - \exp(-\alpha L)]/\alpha$ denotes the fiber's effective length, and $A_s(0)$ and $A_s(L)$ are the signal wave magnitude at the input and output ends of the fiber, respectively. The complex SBS gain coefficient $g(\omega_s)$ is of Lorentzian line shape [39]

$$g(\omega_s) = \frac{\frac{1}{2}g_0|A_p|^2}{1 - j2(\omega_p - \omega_s - \Omega_B)/\Gamma_B}. \tag{2}$$

Here, $\Gamma_B \sim 2\pi \cdot 30$ MHz is the SBS linewidth and g_0 is the line center SBS gain coefficient. g_0 is related to the inherent material SBS gain coefficient g_B according to: $g_0 = g_B/A_{\text{eff}}$, where A_{eff} denotes the effective area of the optical mode in the fiber. In standard single-mode fibers, $g_B = 5 \cdot 10^{-11}$ m/W, and g_0 in standard fibers is of the order of 0.2 $[\text{W} \cdot \text{m}]^{-1}$.

The real part of $g(\omega_s)$ determines the frequency-dependent amplitude gain of the signal, whereas its imaginary part governs the corresponding phase delay. Equation (2) also indicates that the SBS gain and phase delay both scale with the pump power $|A_p|^2$. The real and imaginary parts are illustrated in Fig. 1. As seen in the figure, the amplified signal within the SBS bandwidth acquires a spectral phase, quite a sizable part of which can be closely approximated by a linear frequency dependence. Such linear phase dependence represents an additive group delay [19]

$$\tau = \frac{g_0 |A_p|^2 L_{\mathrm{eff}}}{\Gamma_B}. \quad (3)$$

Note that the real and imaginary parts of $g(\omega_s)$ are linked by the Kramers–Kronig relations

$$\mathrm{Im}[g(\omega_s)] = \frac{2}{\pi} \int_0^\infty \frac{\omega' \mathrm{Re}[g(\omega')]}{\omega'^2 - {\omega_s}^2} \mathrm{d}\omega'. \quad (4)$$

The bandwidth of delayed pulses is restricted to the linewidth Γ_B: broader pulses are subject to both magnitude distortion due to gain variations and dispersive broadening (see Fig. 1). Early works on SBS slow light demonstrated the delay of pulses that were tens of nanoseconds long [13–17]. The application of the technique to the delay of digital and analog waveforms of broader bandwidths, which are more relevant to modern day optical communication and processing, requires significant spectral broadening of the SBS interaction. This broadening has been at the focus of many research efforts since 2005, and it is addressed in the next section.

3. Spectral Broadening of SBS Slow Light

Two main strategies for extending the usable bandwidth of SBS slow light beyond Γ_B have been proposed and demonstrated. One approach relies on broadening of the pump wave power spectral density (PSD) using direct or external modulation. The other technique combines several CW pump lines of different, discrete frequencies. The SBS coefficient for a generalized pump PSD can be expressed in terms of a convolution [19] (see also [40] for a generalization)

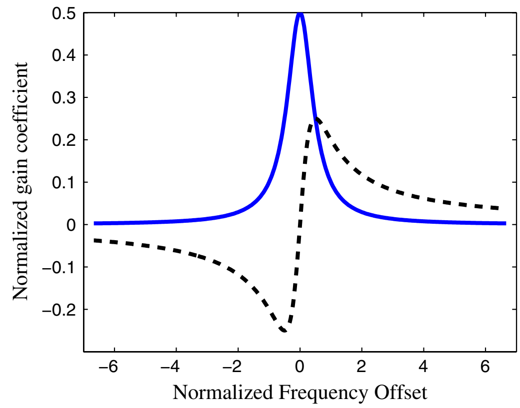


Fig. 1. (Color online) Real (solid) and imaginary (dashed) parts of the SBS gain coefficient $g(\omega_s)$ as a function of normalized frequency detuning $(\Omega - \Omega_B)/\Gamma_B$ for a continuous pump wave. The gain coefficient is normalized to $g_0|A_p|^2$.

$$g(\omega_s) = \int \frac{\frac{1}{2} g_0 |A_p(\omega_p)|^2}{1 - j2(\omega_p - \omega_s - \Omega_B)/\Gamma_B} \mathrm{d}\omega_p, \quad (5)$$

where $|A_p(\omega_p)|^2$ denotes the PSD of the pump wave.

A large number of implementations of both strategies, and even combinations of the two, have been reported since 2005. Stenner *et al.* [20], Song *et al.* [21], and Shumakher *et al.* [23] used two discrete SBS pump lines to broaden the process bandwidth and reduce the distortion of delayed pulses. When the frequency separation between the two pump lines is comparable to Γ_B, the resulting gain coefficient $g(\omega_s)$ includes a spectral region of relatively uniform magnitude gain and reduced dispersion [20,21]. The approach has been since extended to three lines [41–43] and five lines [44]. In a more recent extension of the technique, Sakamoto *et al.* used over 20 discrete SBS gain lines, which were generated from a CW source using an external phase modulator and an external intensity modulator in series [45]. Both modulators were overdriven by sine waves of frequency Γ_B and magnitude that was larger than their V_π [45]. Figure 2 shows the pump spectrum and the resulting SBS power gain as a function of frequency. A nearly uniform gain was achieved over a spectral width of 200 MHz. Figure 3 shows examples of delayed signal pulses. The 5.5 ns long pulses were delayed by as

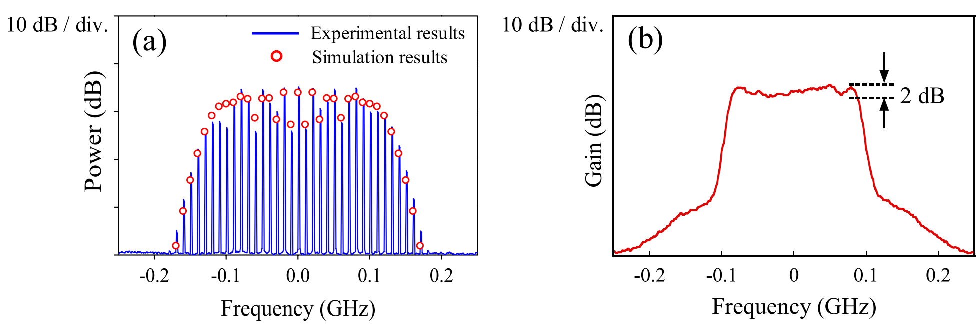


Fig. 2. (Color online) Spectrum of (a) pump wave frequency comb and (b) corresponding SBS gain as a function of frequency offset [45].

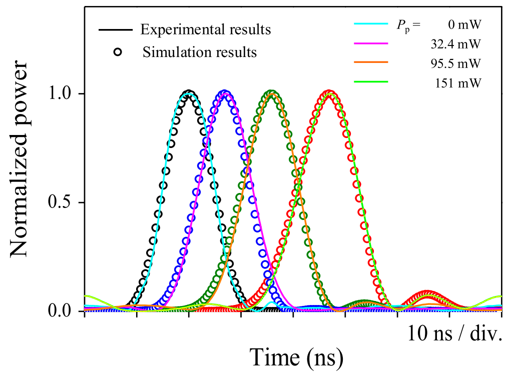


Fig. 3. (Color online) Measurements of delayed signal pulses. The SBS pump spectrum consisted of 20 discrete lines separated by Γ_B [45].

much as 13.4 ns. At the same time, the width of the pulses increased by only 19%.

Despite the above progress, the broadening of the SBS linewidth beyond a few hundred megahertz using discrete pump lines remains challenging. González Herráez *et al.* had recognized that a continuous spectral broadening of a single SBS pump line, via proper modulation, could provide a broader usable bandwidth. In their initial work of 2006 [22], an electrical pseudorandom bit sequence was used to directly modulate the drive current of a pump laser diode. The spectral width of the resulting SBS amplification process reached 325 MHz, and 2.7 ns long pulses were successfully delayed. Shortly afterwards, Zadok *et al.* [24] reported the delay of 5 Gigabit/s pseudorandom bit data by 120 ps using a synthesized pump spectrum, and Zhu *et al.* successfully delayed 75 ps long pulses [25] using a 12 GHz wide SBS gain line broadened by random noise modulation. Willner *et al.* continued to demonstrate the delay of 10 Gigabit/s differential phase shift keying (DPSK) data [46] (Fig. 4). Broadening of SBS beyond Ω_B is fundamentally restricted by the spectral overlap between the amplification and attenuation windows of the process. Song *et al.* overcame this limitation using multiple high-power broadened pumps [47], reaching a record bandwidth of 25 GHz.

The spectral broadening of the SBS slow light process is not without cost: since the pump power is spread over a broader width, the signal power gain and additive group delay are reduced accordingly. Tight trade-offs prevail between the attainable delay and distortion-free bandwidth, which call for a careful optimization of the pump PSD. Khurgin pointed out that a broadened gain line with sharp edges could provide a longer slow light delay than that of a gain line with equal width and gradual spectral transitions [48]. The analysis was corroborated by the work of Zadok *et al.* [24], which compared the delays obtained by pumps with spectral widths of 3 GHz and different shapes in both simulations and experiments. Figure 5 contrasts the imaginary parts of $g(\omega_s)$ corresponding to Gaussian and truncated Gaussian pump PSDs [24]. The imaginary parts were calculated using the Kramers–Kronig relations

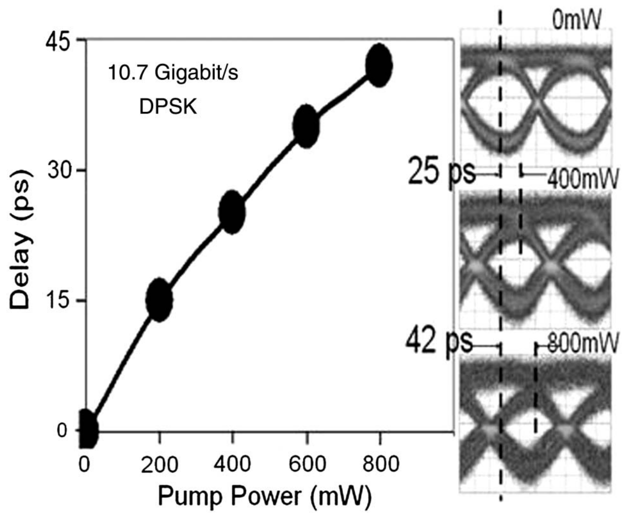


Fig. 4. (Color online) Experimental results of DPSK slow light. Continuous delay up to 42 ps for a 10.7 Gigabit/s DPSK signal is achieved [46]. © 2008 IEEE

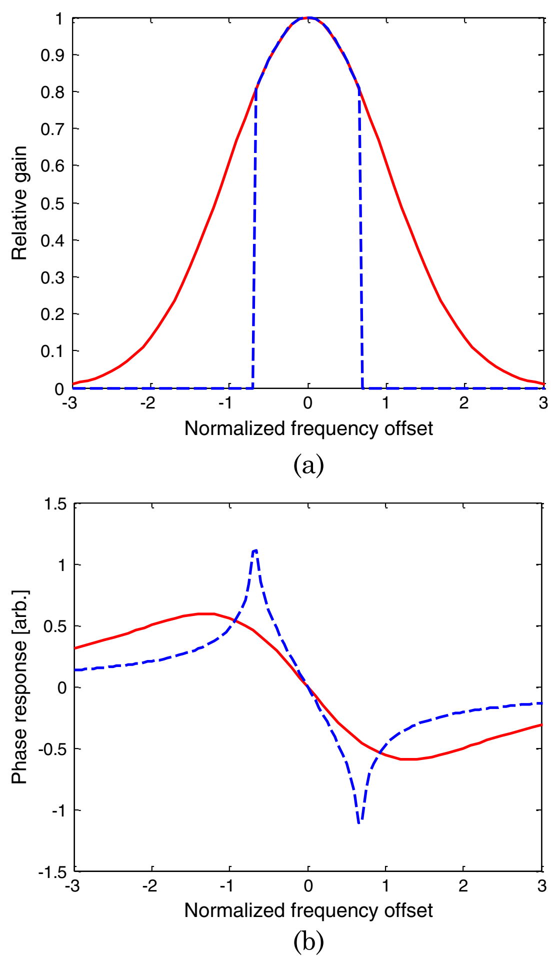


Fig. 5. (Color online) (a) Gaussian and truncated Gaussian spectral gain curves $\mathrm{Re}[g(\omega_s)]$. (b) Corresponding spectral phase responses $\mathrm{Im}[g(\omega_s)]$ calculated using the Kramers–Kronig relations [24].

of Eq. (4). The results suggest a significantly longer delay using the sharper pump spectrum. A 30–40% increase in the delay of 5 Gigabit/s digital data was observed in agreement with the prediction. The sharp pump spectrum was achieved using a synthesized, deterministic direct modulation of the pump laser diode current [24,49].

Over the last four years, the spectral profile of the pump wave has been further optimized. The role of the third-order dispersion, associated with SBS slow light delay, was carefully studied by Zhang *et al.* [50]. Yi *et al.* used a super-Gaussian-shaped pump PSD to process 10 Gigabit/s data signals of different formats [51]. DPSK data was successfully delayed by 80 ps without errors [51]. Careful synthesis of the pump PSD was also performed in a series of papers by Gauthier, Neifeld and others [52–54]. Their analysis suggested that an optimized pump PSD could provide a 50–80% increase in slow light delay, subject to pump power and acceptable distortion constraints [52]. The analysis was supported by an experimental demonstration using an optimized 7.2 GHz wide pump PSD [53]: 10 Gigabit/s data signals were delayed by three pulse widths. In a recent work [54], Zhu *et al.* proposed a scheme for optimizing the pump PSD based on noise current modulation rather than using periodic, deterministic current waveforms. Improvements in the signal-to-noise ratio and eye diagram opening of delayed signal data were obtained [54] (see Fig. 6).

Performance improvement using a combination of SBS amplification and either one or two SBS absorption lines was investigated by Chin *et al.* [55], and by the group of Schneider *et al.* [56,57]. The combination of a narrow amplification and broader absorption could eliminate the overall magnitude gain experienced by the delayed signals, leading to so-called 'zero gain' slow light [55,57]. The addition of two narrow SBS absorption lines at the spectral wings of a broader amplification window was shown to provide an extended delay with reduced distortion [57]. Similar conclusions were drawn by Pant *et al.*, who optimized the pump PSD using a combination of amplification and absorption, subject to distortion constraints [52]. The combination of two broadened SBS pumps was also studied by Wang *et al.* [58]. Shi *et al.* realized a continuously varying slow and fast light delay at constant signal frequency, alternating between a single and dual pump lines [59].

Recent years have witnessed many other novel developments in the SBS slow light delay of broadband signals. In addition to pump optimization, the delay performance of SBS slow light may be improved through a careful design of the signal pulses as well. Chin and Thévenaz [60] demonstrated that exponentially shaped isolated pulses undergo longer delays than Gaussian-shaped or rectangular pulses. Shi and Boyd [61] described a method for overcoming the delay times bandwidth product limitation by slicing the spectrum of the signal pulse and separately delaying each component using a narrowband process. While the vast majority of works thus far relied on modulation of narrowband pump laser diodes for the broadening of the SBS process, Zhang *et al.* demonstrated the delay of 2.5 Gigabit/s data using an incoherent, spectrally sliced amplified spontaneous emission (ASE) pump source [62]. The independent delay and relative synchronization of several 2.5Gigabit/s wavelength division multiplexed channels, copropagating on a single fiber, was demonstrated as well [62,63]. Both multiple broadened laser diode pumps [63] and multiple slices of an ASE source [62] were employed. In a recent study, a frequency-swept source was used as the SBS pump [64]. The technique is particularly attractive to the introduction of a relative delay between the signal and reference arms of an optical coherence tomography setup [64]. A signal from a 10 GHz wide swept source was delayed by 10 ns over a 10 m long PCF [64]. Clearly, research dedicated to the broadening of SBS slow light continues to provide new innovations and address new potential applications.

4. SBS Slow Light in Nonstandard Fibers

The vast majority of SBS slow light demonstrations were based on standard silica fibers, which provide potential integration of the technique into optical telecommunication applications. The SBS coefficient in such fibers, however, is rather modest. Consequently, only moderate changes in group velocity are typically achieved using SBS in standard fibers, and relatively long fibers spans are required unless the pump power level is raised considerably. In one of the

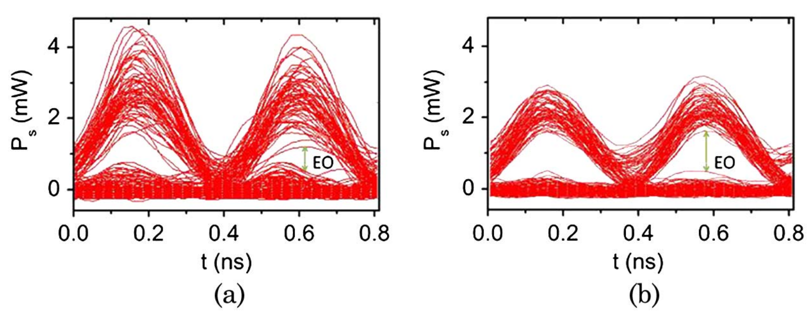


Fig. 6. (Color online) Comparison between the measured eye diagrams of delayed 2.5 Gigabit/s pseudorandom data signals: (a) pump PSD broadened using an optimized low-rate deterministic current modulation; (b) pump PSD broadened using an optimized high-rate noise current modulation. [54].

earlier experiments by Okawachi *et al.* [16], for example, a 25 ns long slow light delay of signal pulses was achieved along 500 m of Corning SMF-28e fiber. The results represent a change of about 1% to the group velocity of the signal pulses. In another early experiment by González Herráez *et al.* [13], a group velocity as slow as $c/4.26$ was achieved in a section of standard fiber that was only 2 m long. However, pump pulses having a peak power level of the order of 10 W were required [13]. The high power levels and long fiber spans restrict the application of SBS slow light techniques in practical systems.

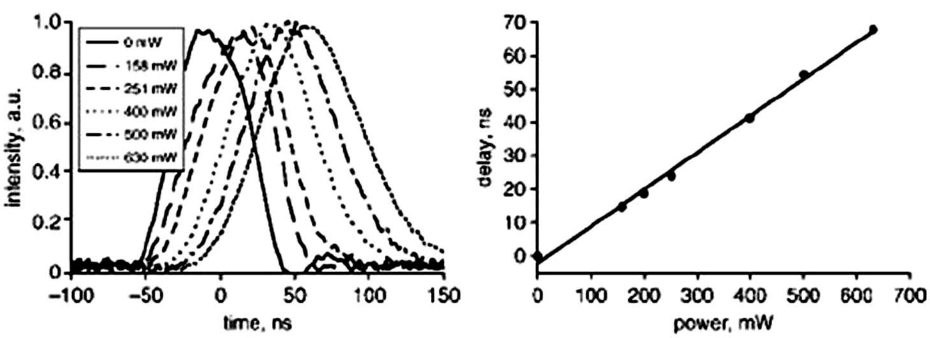
Nonstandard fibers made of nonlinear glass materials could provide SBS interaction that is 2–3 orders of magnitude stronger than that obtained in standard silica fibers. Chalcogenide glasses, such as As_2S_3 or As_2Se_3, possess an inherent material SBS gain coefficient g_B of the order of $5\cdot10^{-9}$ m/W, which is 100 times higher than that of silica [65]. In addition, the modal effective area in nonlinear fibers is often smaller than that of standard fibers. Florea *et al.* characterized the SBS amplification in chalcogenide fibers [26]. Their results suggested that the SBS slow-light delay in these fibers could be over 100 times longer than that observed in standard fibers of equal length with equal pump power [26]. Song *et al.* proceeded to demonstrate a delay of 37 ns over a 5 m long As_2Se_3 fiber [27]. In contrast with the aforementioned earlier experiment over 2 m of standard fiber, a pump power level of only 60 mW was required [27]. Bismuth oxide nonlinear fibers were used in an SBS slow light demonstration in 2007 by Jáuregui Misas *et al.* [28]. A group velocity of $c/10$ was obtained over a 2 m long fiber using a pump power level of 400 mW [28].

Over the last three years, SBS slow light has been investigated using additional types of highly nonlinear fibers. Slow light in tellurite glass fibers was demonstrated in two papers by Abedin *et al.* [31,32]. The linear loss coefficient of single-mode tellurite glass fibers can be as low as 0.02 dB/m [66], a value much lower than those of chalcogenide or bismuth oxide fibers [31]. At the same time, the material SBS coefficient g_B is an appreciable $1.47\cdot10^{-10}$m/W [67]. Because of their lower losses, the SBS slow light performance of tellurite fibers is expected to surpass that of chalcogenide and bismuth oxide fibers when the section length exceeds a few tens of meters [29]. In one experimental example, 60 ns long pulses were delayed by 67 ns over a 2 m long fiber using a 630 mW pump [31] (see Fig. 7). In a second example, fast light pulse advancement with a group velocity of $c/0.84$ was achieved in a 2 m long tellurite fiber [32]. A combination of three pump lines with an overall power of 340 mW was used [32]. Finally, PCFs could also provide an enhanced SBS interaction due to their small modal areas. Yang *et al.* demonstrated a delay of half-pulse length in a 50 m long PCF [30]. As mentioned earlier, Zhang *et al.* also used a PCF in the delay of frequency-swept signals [64]. SBS slow light over relatively short fiber spans using only moderate pump power levels is advantageous in potential applications such as all-optical signal processing in microwave photonic systems. The delay of analog waveforms is discussed next.

5. SBS Slow Light Delay of Analog Waveforms

Variable delay of analog signals in radar systems is a promising potential application for photonic processing [68]. In these systems, the directional stirring of the transmitted beam is achieved through control of the relative delay between the signals feeding the different elements of the antenna [69]. The delay lines used must accommodate broadband signals with stringent distortion tolerances. Photonic processing implementations are appealing due to their very large usable bandwidth, low frequency-independent loss, immunity to electromagnetic interference, and parallelism through wavelength multiplexing [68]. Several techniques for discrete photonic true time delay have been proposed using multiwavelength sources in conjunction with discretely reconfigurable dispersion [70,71] or a tunable laser feeding wavelength demultiplexers [72]. Continuously variable delay has been achieved using chirped Bragg gratings [73], but the accompanying nonzero dispersion can distort the modulated signals [74].

The continuous, all-optical delay capabilities of slow light techniques are highly attractive for optical antenna beamforming applications [75,76]. The necessary delay times bandwidth product in antenna beamforming is considerably smaller than that



(a) (b)

Fig. 7. (a) Delayed signal pulses and (b) slow light delay as a function of pump power in a 2 m long tellurite glass fiber [31]. © 2008 IET

required in the buffering of digital communication data [77]. While most slow light delay-related research has been dedicated to the delay of pulses, several works did examine the prospects of slow light phenomena in semiconductor devices in the processing of analog waveforms [78,79]. However, the treatment of analog waveforms using slow light techniques remains relatively limited.

The processing of analog radar waveforms using SBS slow light was demonstrated in 2007 by Zadok *et al.* [33]. A broadened SBS process was applied to delay a linear frequency modulated (LFM) waveform, which is characteristic of many radar systems. The instantaneous radio frequency of an LFM signal is linearly swept across a broad bandwidth B during a sweep time T, which is much longer than $1/B$. Subject to proper postdetection processing, LFM waveforms provide high-ranging resolution of $\sim 1/B$ while alleviating the need for transmitting short, high-peak power pulses [69,74]. In the reported experiment, 1 GHz wide LFM waveforms having a central radio frequency carrier of 5 GHz were delayed by 230 ps. The figures of merit of the processed signal, such as its width, peak-to-sidelobe ratio, and integrated sidelobe ratio, remained of sufficient quality [33]. Figure 8 shows the measured delay of the LFM signals as a function of SBS power gain along a 3.5 km long silica highly nonlinear fiber [33].

Over the last two years, significant advances in the delay of broadband analog waveforms using SBS slow light have been achieved. First, it has been recognized by Morton and Khurgin that the delay of single-sideband analog waveforms could benefit from piecewise spectral treatment [34]. Unlike most digital data, which occupy a continuously populated spectral width B surrounding an optical signal carrier at $\omega_s = \omega_c$, many analog waveforms carry information of bandwidth B centered around an RF carrier $\Omega_{\mathrm{RF}}^{\mathrm{Carrier}}$, such that $B \ll \Omega_{\mathrm{RF}}^{\mathrm{Carrier}}$. Thus, while for single-sideband modulation, the optical spectrum of the modulated optical signal occupies two spectral regions $\{\omega_s | [\omega_c], [\omega_c + \Omega_{\mathrm{RF}}^{\mathrm{Carrier}} - B/2, \omega_c + \Omega_{\mathrm{RF}}^{\mathrm{Carrier}} + B/2]\}$, we are interested only in delaying the contents of the second one, provided we can also control the phase of the first (see Fig. 9). This feature considerably relaxes the bandwidth requirement in delaying waveforms of high $\Omega_{\mathrm{RF}}^{\mathrm{Carrier}}$. In order to avoid angular dispersion of the transmitted radar beam, the optical phase of the modulated signal component at $\omega_s = \omega_c$, $\phi(\omega_s = \omega_c)$ must be adjusted to obey [34]

$$\phi(\omega_s = \omega_c + \Omega_{\mathrm{RF}}^{\mathrm{Carrier}}) - \phi(\omega_s = \omega_c) = \Omega_{\mathrm{RF}}^{\mathrm{Carrier}} \cdot \frac{\partial \phi(\omega_s)}{\partial \omega_s}\bigg|_{\omega_s = \omega_c} = \Omega_{\mathrm{RF}}^{\mathrm{Carrier}} \cdot \tau, \qquad (6)$$

where τ is the slow light optically controlled group delay.

The above principle of separate carrier tuning [34] was demonstrated recently in a couple of papers by Sancho *et al.* and Chin *et al.* [35,36]. First, a microwave photonic filter was implemented in which the phase of a single-sideband signal was modified using SBS and that of the optical carrier was adjusted with a fiber Bragg grating [35]. The work was later extended to implement a 100 MHz wide SBS slow light delay across a sideband that was centered at $\Omega_{\mathrm{RF}}^{\mathrm{Carrier}} = 2\pi \cdot 6$ GHz [36]. The carrier phase in this example was adjusted through a second SBS process [80]. Figure 9 shows the measured phase response of the obtained SBS delay line. A variable group delay with proper phase adjustment of the signal carrier is obtained [36]. The processing of analog waveforms remains an important potential application of slow light in general, and of SBS-based implementations in particular, a potential yet to be fully explored.

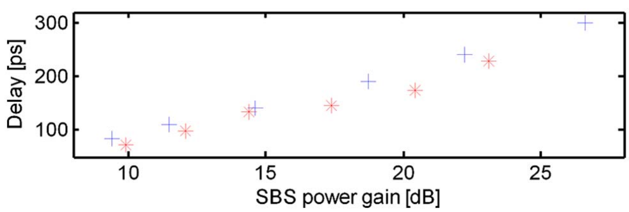


Fig. 8. (Color online) SBS slow light delay of a 1 GHz wide LFM radar waveform as a function of SBS power gain in a 3.5 km long highly nonlinear silica fiber. The pump power level was varied between 16 and 21 dBm. Asterisks denote the delay of LFM waveforms; pulse signs indicate the predicted delay based on a measurement of the SBS complex response using a vector network analyzer [33]. © 2007 IEEE

6. Role of Polarization in SBS Slow Light

In SBS slow-light setups, pulse distortion due to the limited bandwidth and the dispersion associated with the scalar frequency dependence of SBS has been thoroughly documented [39]. However, polarization considerations can distort the pulse even further.

Since SBS originates from optical interference between the pump and signal waves, the SBS interaction, at a given point along the fiber, is most (least) efficient when the electric fields of the pump and signal are aligned, i.e., their vectors trace parallel (perpendicular) ellipses and in the same (opposite) sense of rotation. Consequently, in the presence of birefringence, both the local and the overall signal gain (or loss in the anti-Stokes case) depend on the birefringent properties of the fiber, as well as on the input SOPs of both pump and signal [81].

Recently, the pioneering work of van Deventer and Boot [81] has been analytically substantiated and extended using a vector formulation of the SBS amplification process in the presence of birefringence [82]. Vector differential equations, combining SBS and birefringence effects, were derived in both the Jones and Stokes spaces. The analysis is valid in the undepleted pump regime and currently neglects polarization-dependent loss. It is important to note that unlike [81], the analysis of [82] assumes the *same* right-handed coordinate system $\{x, y, z\}$ for both

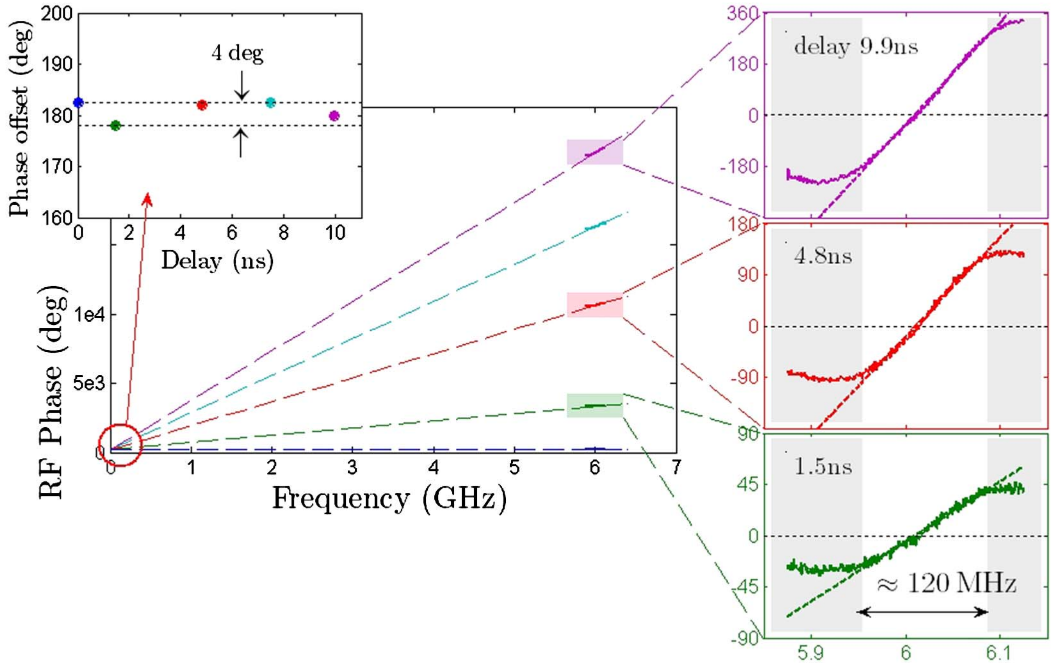


Fig. 9. (Color online) Measured phase response of SBS-based slow light delay line with separated tuning of the signal carrier frequency [36].

signal and pump, where the signal propagates in the positive z direction while the pump propagates in the negative z direction. Thus, if both $\vec{E}_{\text{sig}}(z)$ and $\vec{E}_{\text{pump}}(z)$ equal the 2×1 Jones vector $[1 \quad j]^T$ (T stands for transpose), they represent a right-handed circularly polarized signal and a left-handed circularly polarized pump wave, respectively [83,84].

One important result of the analysis is that the signal propagation through the fiber can be represented (in the Jones calculus) by $\vec{E}_{\text{sig}}(L) = \mathbf{H} \cdot \vec{E}_{\text{sig}}(0)$, where $\mathbf{H}$ is a 2×2 matrix that depends on the fiber birefringence, the fiber length L, and, of course, on the pump power and SOP. Based on this relationship and the powerful singular value decomposition theorem, there exist two orthogonal SOPs for the input signal, $\vec{E}_{\text{sig}}^{\text{inmax}}$ and $\vec{E}_{\text{sig}}^{\text{inmin}}$, that, respectively, experience maximum and minimum gains as they propagate through the fiber. Serving as a convenient vector base, an arbitrarily polarized *input* signal at $z = 0$ can be decomposed as

$$\vec{E}_{\text{sig}}^{\text{in}} = \alpha_0 \vec{E}_{\text{sig}}^{\text{inmax}} + \beta_0 \vec{E}_{\text{sig}}^{\text{inmin}}, \tag{7}$$

resulting in an output at $z = L$ of the form ($\vec{E}_{\text{sig}}^{\text{inmax}}$, $\vec{E}_{\text{sig}}^{\text{inmin}}$, $\vec{E}_{\text{sig}}^{\text{outmax}}$, and $\vec{E}_{\text{sig}}^{\text{outmin}}$ are all assumed to be of unit power)

$$\vec{E}_{\text{sig}}^{\text{out}} = \alpha_0 G_{\max} \vec{E}_{\text{sig}}^{\text{outmax}} + \beta_0 G_{\min} \vec{E}_{\text{sig}}^{\text{outmin}}. \tag{8}$$

Clearly, the SBS-amplifying fiber behaves as a polarization-dependent gain medium, where $G_{\max}$ and $G_{\min}$ are the respective (amplitude) gains of $\vec{E}_{\text{Sig}}^{\text{inmax}}$ and $\vec{E}_{\text{Sig}}^{\text{inmin}}$. Furthermore, since normally $|G_{\max}|^2$ is many decibels larger than $|G_{\min}|^2$, Eq. (8) suggests that unless α_0 is negligible, an arbitrarily polarized input signal will be pulled toward the SOP of $\vec{E}_{\text{Sig}}^{\text{outmax}}$. For a sufficiently long standard fiber [82], the analysis also shows that $\vec{E}_{\text{Sig}}^{\text{outmax}}$ has an SOP identical to that of $\vec{E}_{\text{pump}}^{*}(z = L)$. Thus, to obtain maximum delay in an SBS slow light setup, light should be launched parallel to $\vec{E}_{\text{pump}}^{*}(z = 0)$. Better yet, Walker *et al.* [37] have proposed an elegant setup that uses a Faraday mirror [85] to ensure maximum and stable delay.

The differential SBS gain experienced by the components of an arbitrarily polarized input SOP also predicts that SBS-related polarization-induced distortion may also contribute to pulse broadening in slow light setups. Since the delay increases with the gain, a signal pulse with its SOP aligned for maximum amplification undergoes a delay longer than that experienced by a pulse whose SOP is adjusted for minimum gain. Thus, it turns out that this SBS-related polarization-induced distortion is analogous to that of linear birefringence, where the orthogonal SOPs of maximum and minimum gain have a role similar to that of the principal axes in linear-birefringence-induced polarization mode dispersion [86]. The experimental results of Fig. 10 clearly indicate that SBS slow light implementations may introduce polarization-induced distortion, which is inherent to the vector nature of SBS [38].

The research interest in the polarization attributes of SBS in optical fibers and their applications is on the rise. The quantitative analysis of the strength of polarization pulling over relatively short

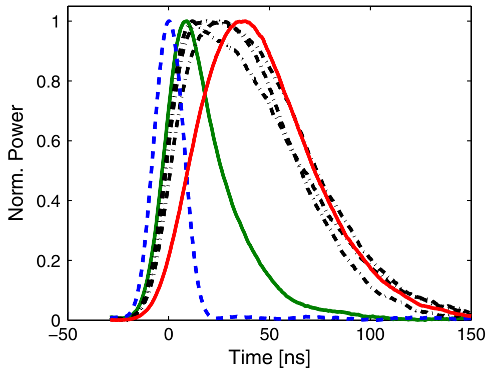


Fig. 10. (Color online) Measured, normalized signal power as a function of time. Dashed curve, input Gaussian pulse (FWHM 17 ns); solid curves, output pulses with input SOP aligned for minimum gain (left, green) and maximum gain (right, red); dash–dot curves (black), examples of output pulses with intermediate input polarization alignments. Fiber length was 140 m and pump power was 560 mW [38].

spans of standard fibers was found to provide information regarding the beat length and polarization coupling length of a specific fiber under test [87]. Frequency-selective polarization pulling based on SBS was recently applied in the generation of orthogonally polarized, optical single-sideband modulation formats [88]. Finally, nonlinear polarization pulling based on stimulated Raman scattering amplification [89] and the Kerr effect [90,91] were also demonstrated over the last two years.

7. Concluding Remarks

In this paper, we have presented a review of recent research on the topic of slow light using SBS in fiber media. Since the initial demonstrations of 2005, intense efforts have been dedicated to this subject and much progress has been made covering many of its aspects. The long reference list below, emphasizing progress made after 2008, provides one indication to the breadth and scope of the research efforts. Even this list, however, is not exhaustive: we found it impossible to relate to the entire wealth of literature on the topic within the scope of a single discussion. Instead, we have chosen to highlight several aspects of the accumulated body of research. One such aspect, the optimization of broadened SBS processes, remains the objective of a large number of studies. Others emphasize additional potential applications beyond the 'traditional' delay of pulses, like all-optical processing in specialty fibers or the delay of analog waveforms. Finally, certain aspects of the treatment of SBS slow light could provide new insights into the phenomenon, such as the role of polarization.

In spite of the intensive efforts to extend SBS-induced slow light delay and reduce the associated pulse distortion, it is now widely acknowledged that the attainable delay would be insufficient for the buffering of digital data on any relevant scale [9,77]. Khurgin pointed out that an SBS slow light delay longer than a few pulse widths would require unrealistically high power amplification [48]. Similarly, Boyd and Narum showed that subject to power gain limitations, the variable delay associated with a Lorentzian-shaped spectral gain coefficient is restricted to the order of four pulse widths by excessive pulse broadening [92]. Indeed, the longest delay times bandwidth product achieved by an SBS slow light demonstration is 3.75 [15]. Although a few claims for a so-called 'zero broadening' SBS slow light delay were made, González Herráez and Thévenaz proved that the root mean squared width of a delayed pulse is bound to increase [93].

Alternatives to SBS slow light, such as the combination of wavelength conversion and dispersive propagation, have been established as more feasible approaches for all-optical data buffering [94]. Nevertheless, ongoing efforts aimed at improving SBS slow light bring up other potential applications, a few of which have been briefly addressed in previous sections. In particular, it has been our opinion that microwave photonics is a suitable potential application for SBS slow light principles [33,36]. Another promising direction is the SBS slow light delay of a frequency-swept source within an optical coherence tomography configuration [64]. Such nontelecommunication applications can take advantage of the enhanced efficiency of SBS in specialty, highly nonlinear fibers [27–32]. More research is needed to evaluate the full impact of the relatively high spontaneous noise levels associated with the Brillouin amplification process [95].

On a broader context, the research interest in slow and fast light has drawn the attention of the photonics research community to further investigate the phenomenon of SBS in optical fibers. Recent contributions include the realization of stored light based on SBS [96], the introduction of dynamic gratings based on SBS in high-birefringence fibers [97,98], and the more complete understanding of the vector nature of SBS in weakly birefringent standard fibers [82,99–101]. Concepts rooted in slow light research could have profound implications on the field of Brillouin optical time domain analysis [98,102]. Future work would need to address the challenge of employing SBS slow light and related techniques in engineering applications.

In his review paper of 2008 [7], Thévenaz raised several open questions. One notable issue was the potential enhancement of light–matter interaction subject to slow light conditions. Such enhancement was observed in photonic crystals [103] and atomic gas [104] slow light media. Recently, evidence to the contrary has been reported with respect to SBS, as Beer–Lambert absorption of gas molecules within a PCF was unaffected by slow light conditions [105]. Further study is required to clarify and determine the prospects of SBS in interaction enhancement. Slow light phenomena were also suggested as a means for improving the sensitivity of interferometers [106–108]. Shi *et al.* demonstrated an enhanced interferometric sensitivity using a rubidium vapor slow light medium [106], and Shi and Boyd analyzed the potential for performance improvement using various slow light configurations [107]. To the best of our knowledge, however, SBS slow light elements have not yet been used for the increase of sensitivity in interferometers. The open issues of three years ago, for the most part, still call for further research.

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