Broadband SBS Slow Light in an Optical Fiber

Zhaoming Zhu, *Member, OSA*, Andrew M. C. Dawes, *Student Member, OSA*, Daniel J. Gauthier, *Fellow, OSA*, Lin Zhang, *Student Member, IEEE, Student Member, OSA*, and Alan E. Willner, *Fellow, IEEE, Fellow, OSA*

***Abstract*—In this paper, we investigate slow light via stimulated Brillouin scattering (SBS) in a room temperature optical fiber that is pumped by a spectrally broadened laser. Broadening the spectrum of the pump field increases the linewidth $\Delta\omega_p$ of the Stokes amplifying resonance, thereby increasing the slow-light bandwidth. One physical bandwidth limitation occurs when the linewidth becomes several times larger than the Brillouin frequency shift Ω_B so that the anti-Stokes absorbing resonance substantially cancels out the Stokes amplifying resonance and, hence, the slow-light effect. We find that partial overlap of the Stokes and anti-Stokes resonances can actually lead to an enhancement of the slow-light delay-bandwidth product when $\Delta\omega_p \simeq 1.3\,\Omega_B$. Using this general approach, we increase the Brillouin slow-light bandwidth to over 12 GHz from its nominal linewidth of ∼30 MHz obtained for monochromatic pumping. We controllably delay 75-ps-long pulses by up to 47 ps and study the data-pattern dependence of the broadband SBS slow-light system.**

***Index Terms*—Optical fiber, pulse propagation, Q-penalty, slow light, stimulated Brillouin scattering (SBS).**

I. Introduction

THERE HAS been great interest in slowing the propagation speed of optical pulses (so-called slow light) using coherent optical methods [1]. Slow-light techniques have many applications for future optical-communication systems, including optical buffering, data synchronization, optical memories, and signal processing [2]–[4]. It is usually achieved with resonant effects that cause large normal dispersion in a narrow spectral region (approximately equal to the resonance width), which increases the group index and, thus, reduces the group velocity of optical pulses. Optical resonances associated with stimulated Brillouin scattering (SBS) [5]–[9], stimulated Raman scattering [10], and parametric amplification [11] in optical fibers have been used recently to achieve slow light.

The width of the resonance enabling the slow-light effect limits the minimum duration of the optical pulse that can be effectively delayed without much distortion and, therefore, limits the maximum data rate of the optical system [12]. In this regard, fiber-based SBS slow light is limited to data rates of less than a few tens of megabits per second due to the narrow Brillouin resonance width (∼30 MHz in standard single-mode optical fibers). Recently, Herráez *et al.* [13] increased the SBS slow-light bandwidth to about 325 MHz by broadening the spectrum of the SBS pump field. Here, we investigate the fundamental limitations of this method and extend their work to achieve an SBS slow-light bandwidth as large as 12.6 GHz, thereby supporting data rates of over 10 Gb/s [14]. With our setup, we delay 75-ps pulses by up to 47 ps and study the data-pulse-quality degradation in the broadband slow-light system.

This paper is organized as follows. The next section describes the broadband-pump method for increasing the SBS slow-light bandwidth and discusses its limitations. Section III presents the experimental results of broadband SBS slow light, where we investigate the delay of single and multiple pulses passing through the system. From the multiple-pulse data, we estimate the degradation of the eye diagram as a function of delay, which is a first step toward understanding performance penalties incurred by this slow-light method. Section IV concludes this paper.

II. SBS Slow Light

In an SBS slow-light system, a continuous-wave (CW) laser beam (angular frequency ω_p) propagates through an optical fiber, which we take as the $-z$-direction, giving rise to amplifying and absorbing resonances due to the process of electrostriction. A counterpropagating beam (along the $+z$-direction) experiences amplification in the vicinity of the Stokes frequency $\omega_s = \omega_p - \Omega_B$, where Ω_B is the Brillouin frequency shift, and absorption in the vicinity of the anti-Stokes frequency $\omega_{\rm as} = \omega_p + \Omega_B$.

A pulse (denoted interchangeably by the "probe" or "data" pulse) launched along the $+z$-direction experiences slow (fast)-light propagation when its carrier frequency ω is set to the amplifying (absorbing) resonance [5]–[9]. In the small-signal regime, the output-pulse spectrum is related to the input spectrum through the relation $E(z = L, \omega) = E(z = 0, \omega)\exp[g(\omega)L/2]$, where L is the fiber length, and $g(\omega)$ is the complex SBS gain function. The complex gain function is the convolution of the intrinsic SBS gain spectrum $\tilde{g}_0(\omega)$ and the power spectrum of the pump field $I_p(\omega_p)$ and is given by

$$g(\omega) = \tilde{g}_0(\omega) \otimes I_p(\omega_p) = \int_{-\infty}^{\infty} \frac{g_0 I_p(\omega_p)}{1 - i(\omega + \Omega_B - \omega_p)/(\Gamma_B/2)} d\omega_p \qquad (1)$$

where g_0 is line-center SBS gain coefficient for a monochromatic pump field, and Γ_B is the intrinsic SBS resonance

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Z. Zhu, A. M. C. Dawes, and D. J. Gauthier are with the Department of Physics and the Fitzpatrick Center for Photonics and Communications Systems, Duke University, Durham, NC 27708 USA (e-mail: zzhu@phy.duke.edu; dawes@phy.duke.edu; gauthier@phy.duke.edu).

L. Zhang and A. E. Willner are with the Department of Electrical and Computer Engineering, University of Southern California, Los Angeles, CA 90089 USA (e-mail: linzhang@usc.edu; willner@usc.edu).

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linewidth (full-width at half-maximum (FWHM) in radians per second). The real (imaginary) part of $g(\omega)$ is related to the gain (refractive index) profile arising from the SBS resonance.

In the case of a monochromatic pump field, $I_p(\omega_p) = I_0\delta(\omega_p - \omega_{p0})$, and hence, $g(\omega) = g_0 I_0/[1 - i(\omega + \Omega_B - \omega_{p0})/(\Gamma_B/2)]$; the gain profile is Lorentzian. For a data pulse whose duration is much longer than the Brillouin lifetime $1/\Gamma_B$ tuned to the Stokes resonance ($\omega = \omega_s$), the SBS slow-light delay is given by $T_{\text{del}} = G_0/\Gamma_B$, where $G_0 = g_0 I_0 L$ is the gain parameter, and $\exp(G_0)$ is the small-signal gain [5]–[9]. The SBS slow-light bandwidth is given approximately by $\Gamma_B/2\pi$ (FWHM in cycles/s).

Equation (1) shows that the width of the SBS amplifying resonance can be increased by using a broadband pump. Regardless of the shape of the pump-power spectrum, the resultant SBS spectrum is approximately equal to the pump spectrum when the pump bandwidth is much larger than the intrinsic SBS linewidth. This increased bandwidth comes at some expense: The SBS gain coefficient scales inversely with the bandwidth, which must be compensated using a higher pump intensity or using a fiber with larger g_0.

To develop a quantitative model of the broadband SBS slow light, we consider a pump source with a Gaussian power spectrum, as realized in this paper. To simplify the analysis, we first consider the case when the width of the pump-spectrum broadened Stokes and anti-Stokes resonances is small in comparison to Ω_B, which is the condition of the experiment of [13]. Later, we will relax this assumption and consider the case when $\Delta\omega_p \sim \Omega_B$, where the two resonances begin to overlap, which is the case of this paper.

In our analysis, we take the pump-power spectrum as

$$I_p(\omega_p) = \frac{I_0}{\sqrt{\pi}\Delta\omega_p} \exp\left[-\left(\frac{\omega_p - \omega_{p0}}{\Delta\omega_p}\right)^2\right]. \tag{2}$$

Inserting this expression into (1) and evaluating the integral results in a complex SBS gain function given by

$$g(\omega) = g_0 I_0 \sqrt{\pi}\eta \mathrm{w}(\xi + i\eta) \tag{3}$$

where $\mathrm{w}(\xi + i\eta)$ is the complex error function [15], $\xi = (\omega + \Omega_B - \omega_{p0})/\Delta\omega_p$, and $\eta = \Gamma_B/(2\Delta\omega_p)$.

When $\eta \ll 1$ (the condition of this paper), the gain function is given approximately by

$$g(\omega) = g_0 I_0 \sqrt{\pi}\eta \exp(-\xi^2)\mathrm{erfc}(-i\xi) \tag{4}$$

where erfc is the complementary error function. The width (FWHM, in radians per second) of the gain profile is given by $\Gamma = 2\sqrt{\ln 2}\Delta\omega_p$, which should be compared to the unbroadened resonance width Γ_B. The line-center gain of the broadened resonance is given by $G = \sqrt{\pi}\eta G_0$.

The SBS slow-light delay at line center for the broadened resonance is given by

$$T_{\text{del}} = \left.\frac{d\mathrm{Im}\,[g(\omega)L/2]}{d\omega}\right|_{\omega=\omega_s} = \frac{2\sqrt{\ln 2}}{\sqrt{\pi}}\frac{G}{\Gamma} \approx 0.94\frac{G}{\Gamma}. \tag{5}$$

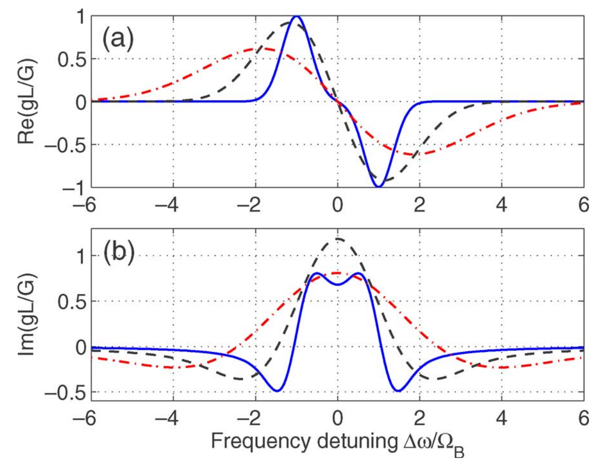

Fig. 1. SBS gain profiles at different pump-power spectrum bandwidth $\Delta\omega_p$. (a) Real part and (b) imaginary part of $g(\omega)$ as a function of frequency detuning from the pump frequency. Solid curves: $\Delta\omega_p/\Omega_B = 0.5$. Dashed curves: $\Delta\omega_p/\Omega_B = 1.3$. Dashed-dotted curves: $\Delta\omega_p/\Omega_B = 2.5$.

A Gaussian pulse of initial pulsewidth T_0 ($1/e$ intensity half-width) exits the medium with a broader pulsewidth T_{out} determined through the relation [9]

$$T_{\text{out}}^2 = T_0^2 + \frac{G}{\Delta\omega_p^2}. \tag{6}$$

Assuming that a slow-light application can tolerate no more than a factor of two increase in the input pulsewidth ($T_{\text{out}} = 2T_0$), the maximum attainable delay is given by

$$\left(\frac{T_{\text{del}}^{\max}}{T_o}\right) = \frac{3}{\sqrt{\pi}} T_0 \Delta\omega_p \tag{7}$$

which is somewhat greater than that found for a Lorentzian line [16]. From (7), it is shown that large absolute delays for fixed $\Delta\omega_p$ can be obtained by taking T_0 as large.

We now turn to the case when the pump spectral bandwidth $\Delta\omega_p$ is comparable with the Brillouin shift Ω_B. In this situation, the gain feature at the Stokes frequency $\omega_{p0} - \Omega_B$ overlaps with the absorption feature at the anti-Stokes frequency $\omega_{p0} + \Omega_B$. The combination of both features results in a complex gain function given by

$$g(\omega) = \frac{G}{L}\left(e^{-\xi_+^2}\mathrm{erfc}(-i\xi_+) - e^{-\xi_-^2}\mathrm{erfc}(-i\xi_-)\right) \tag{8}$$

where $\xi_\pm = (\omega \pm \Omega_B - \omega_{p0})/\Delta\omega_p$. As shown in Fig. 1, when $\Delta\omega_p$ is large, the cancellation of the Stokes gain by anti-Stokes absorption shifts the effective SBS gain peak to lower frequencies and reduces the slope of the linear phase-shift region and, hence, the slow-light delay. For intermediate values of $\Delta\omega_p$, slow-light delay arising from the wings of the anti-Stokes resonances enhances the delay at the center of the Stokes resonance. Therefore, there is an optimum value of the resonance linewidth that maximizes the delay. Fig. 2 shows the relative delay (slow-light delay in terms of the input pulsewidth) as a function of the resonance bandwidth, where it is shown that the optimum value occurs at $\Delta\omega_p \sim 1.3\,\Omega_B$ and that the delay falls off only slowly for large resonance bandwidths. This result

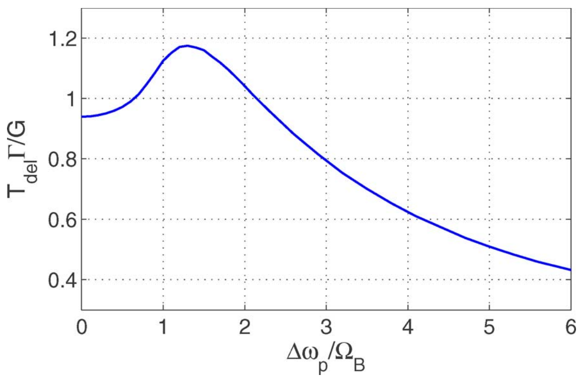

Fig. 2. Relative SBS delay as a function of the SBS resonance linewidth.

demonstrates that it is possible to obtain practical slow-light bandwidths that can somewhat exceed a few times Ω_B.

III. Experiments and Results

As discussed above, the SBS slow-light pulse delay $T_{\rm del}$ is proportional to G/Γ. The decrease in G that accompanies the increase in $\Delta\omega_p$ needs to be compensated by increasing the fiber length, pump power, and/or using highly nonlinear optical fibers (HNLF). In this paper, we use a 2-km-long HNLF (OFS, Denmark) that has a smaller effective modal area and, therefore, a larger SBS gain coefficient g_0 when compared with a standard single-mode optical fiber. We also use a high-power Erbium-doped fiber amplifier (EDFA, IPG Model EAD-1K-C) to provide enough pump power to achieve appreciable gain.

To achieve a broadband pump source, we directly modulate the injection current of a distributed feedback (DFB) single-mode semiconductor laser. The change in injection current changes the refractive index of the laser gain medium and, thus, the laser frequency, which is proportional to the current-modulation amplitude. We use an arbitrary waveform generator (TEK, AWG2040) to create a Gaussian noise source at a 400-MHz clock frequency, which is amplified and summed with the dc injection current of a 1550-nm DFB laser diode (Sumitomo Electric, STL4416) via a bias-T with an input impedance of 50 Ω. The resultant laser power spectrum is approximately Gaussian. The pump-power spectral bandwidth is adjusted by changing the peak–peak voltage of the noise source.

The experiment setup is shown schematically in Fig. 3. Broadband laser light from the noise-current-modulated DFB laser diode is amplified by the EDFA and enters the HNLF via a circulator. The Brillouin frequency shift of the HNLF is measured to be $\Omega_B/2\pi = 9.6$ GHz. CW light from another tunable laser is amplitude modulated to form data pulses that counterpropagate in the HNLF with respect to the pump wave. Two fiber-polarization controllers (FPC) are used to maximize the transmission through the intensity modulator and the SBS gain in the slow-light medium. The amplified and delayed data pulses are routed out of the system via a circulator and detected by a fast photoreceiver (12-GHz bandwidth, New Focus Model 1544B) and displayed on a 50-GHz-bandwidth sampling oscilloscope (Agilent 86100A). The pulse delay is determined from the waveform traces displayed on the oscilloscope.

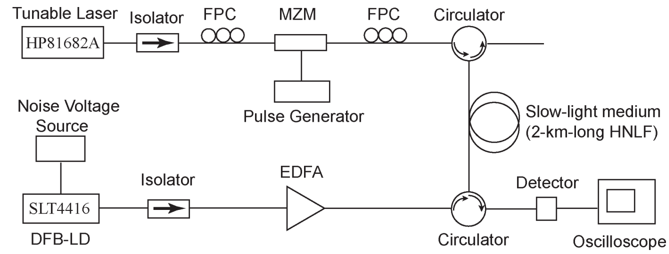

Fig. 3. Experiment setup. EDFA: Erbium-doped fiber amplifier. MZM: Mach–Zehnder modulator. FPC: Fiber-polarization controller. HNLF: Highly nonlinear fiber.

To quantify the effect of the bandwidth-broadened pump laser on the SBS process, we measured the broadened SBS gain spectra by scanning the wavelength of a CW laser beam and measuring the resultant transmission. Fig. 4(a) shows an example of the spectra. It is shown that the features overlap and that (4) does an excellent job in predicting our observations, where we adjusted Γ to obtain the best fit. We find $\Gamma/2\pi =$ 12.6 GHz $(\Delta\omega_p/\Omega_B \sim 0.8)$, which is somewhat smaller than the optimum value. We did not attempt to investigate higher bandwidths to avoid overdriving the laser with the broadband signal. This nonideality could be avoided by using a laser with a greater tuning sensitivity.

Based on the measured SBS bandwidth, we chose a pulsewidth (FWHM) of ∼75 ps $(T_0 \sim 45$ ps) produced by a 14-Gb/s electrical-pulse generator. Fig. 4(b)–(d) shows the experimental results for such input pulses. Fig. 4(b) shows the pulse delay as a function of the gain experienced by the pulse, which is determined by measuring the change in the pulse height. A 47-ps SBS slow-light delay is achieved at a pump power of ∼580 mW that is coupled into the HNLF, which gives a gain of about 14 dB. It is shown that the pulse delay scales linearly with the gain, demonstrating the ability to control all optically the slow-light delay. The dashed line in Fig. 4(b) is obtained with (5), which tends to underestimate the time delay that is enhanced by the contribution from the anti-Stokes line (see Fig. 2). Fig. 4(c) shows the width of the delayed pulse as a function of gain. The data pulse is shown to be broadened as it is delayed, where it is broadened by about 40% at a delay of about 47 ps. The dashed curve in Fig. 4(c) is obtained with (6). Fig. 4(d) shows the waveforms of the undelayed and delayed pulses at a gain of 14 dB. We observe pulse delays that are due to fiber lengthening under strong pump conditions due to fiber heating (∼20 ps at a pump power of ∼580 mW). These thermally induced delays are not included in Fig. 4(b).

To investigate how the pulse broadening shown in Fig. 4(c) might impact a communication system, we examine the pattern dependence of the pulse distortion. For example, in nonreturn-to-zero (NRZ) data format, a single "1" pulse has a different gain than consecutive "1" pulses [17]. The pattern-dependent gain could induce a different "1" level in the whole data stream, while pattern-dependent delay can lead to a large timing jitter.

Fig. 5(a)–(c) shows the delayed-pulse waveforms of three simple NRZ data patterns with a bit-rate of 14 Gb/s. It is clear that the pulses overlap when they are closer to each other, which degrades the system performance. To quantify the signal-quality degradation, we use the signal-quality factor

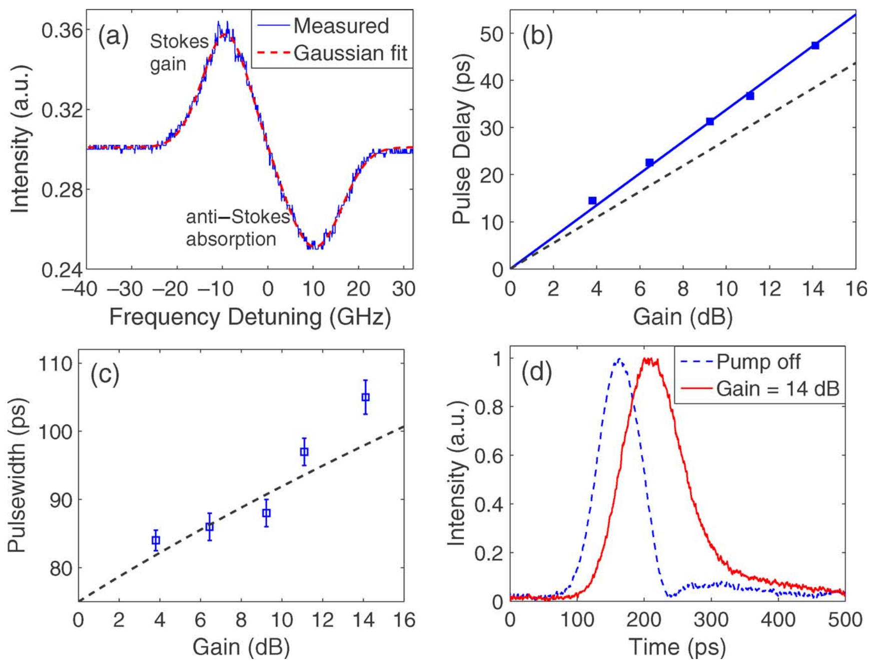

Fig. 4. Observation of broadband slow-light delay. (a) Measured SBS gain spectrum with a dual Gaussian fit. The SBS gain bandwidth (FWHM) is found to be 12.6 GHz. (b) Pulse delay and (c) pulsewidth as a function of SBS gain. In (b), the solid line is the linear fit of the measured data (solid squares), and the dashed line is obtained with (5). In (c), the dashed curve is obtained with (6). (d) Pulse waveforms at 0- and 14-dB SBS gain. The input-data pulsewidth is ∼75 ps.

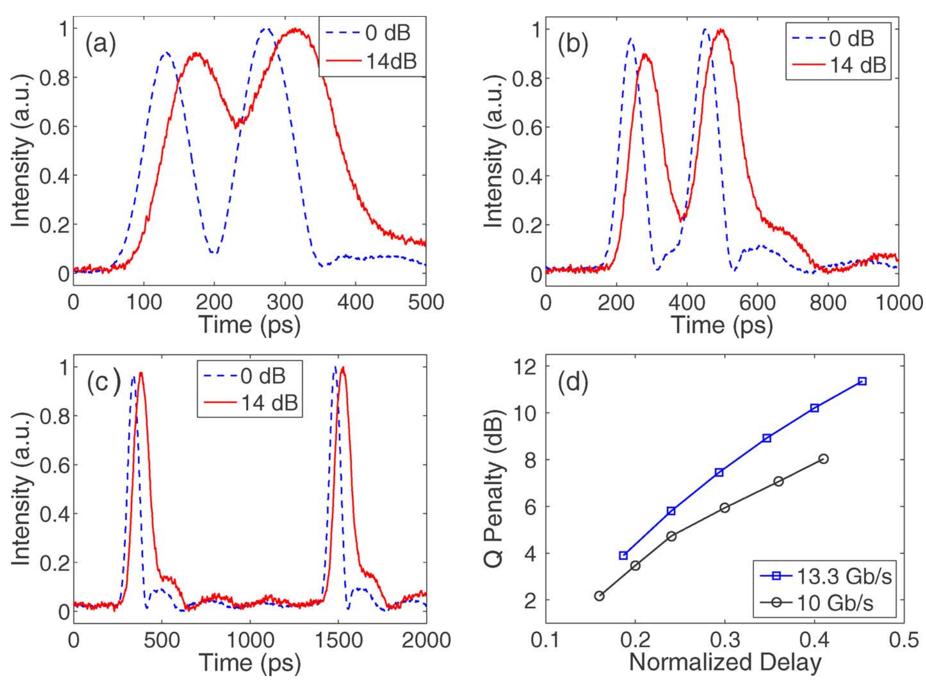

Fig. 5. Pattern dependence of SBS slow-light delay. (a) Data pulses of pattern “101.” (b) Data pulses of pattern “1001.” Note the change in the horizontal scale. (c) Data pulse of pattern “10000000000000001.” In (a)–(c), the data bit-rate is 14 Gb/s, and the input single pulsewidth is ∼75 ps. (d) Calculated Q-penalty versus normalized time delay for 13.3- and 10-Gb/s bit-rate data.

(Q-factor) of input and output pulses, which is defined as $(m_1 - m_0)/(\sigma_1 + \sigma_0)$, where m_1, m_0, σ_1, and σ_0 are the mean and standard deviation of the signal samples when a “1” or “0” is received. We examine the Q-penalty (decrease in Q-factor) produced by the broadband SBS slow-light system by numerical simulations. The fitted gain spectrum shown in Fig. 4(a) is used in the simulations. Fig. 5(d) shows the Q-penalty as a function of time delay for 10- and 13.3-Gb/s bit-rate data streams, respectively. In the simulations, the “1” pulse is assumed to be Gaussian shaped with a pulsewidth (FWHM) of the bit time (100 ps for 10 Gb/s, 75 ps for 13.3 Gb/s). The slow-light delay is normalized by the bit time so that Q-penalties in different bit-rate systems can be compared. It is shown that the Q-penalty increases approximately linearly with the normalized delay and that the 13.3-Gb/s data rate incurs a higher penalty than the 10-Gb/s data rate. The penalty is higher at the higher data rate, because the higher speed signal is more vulnerable to the pattern dependence, especially when the slow-light bandwidth is comparable to the signal bandwidth. Error-free transmission ($\mathrm{BER} < 10^{-9}$) is found at a normalized delay of 0.25 or less for the 10-Gb/s rate. In an optimized system, it is expected that the pattern dependence can be decreased using a spectrum-efficient signal-modulation format or the signal-carrier frequency-detuning technique [17], for example.

IV. Conclusion

In summary, we have increased the bandwidth of SBS slow light in an optical fiber to over 12 GHz by spectrally broadening the pump laser, thus demonstrating that it can be integrated into existing data systems operating over 10 Gb/s. We observed a pattern dependence whose power penalty increases with increasing slow-light delay; research is underway to decrease this dependence and improve the performance of the high-bandwidth SBS slow-light system.

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Zhaoming Zhu received the Bachelor’s degree in electronic engineering and the M.S. degree in applied physics from Tsinghua University, Beijing, China, in 1995 and 1998, respectively, and the Ph.D. degree in optics from the University of Rochester, Rochester, NY, in 2004. His Ph.D. research on “Photonic crystal fibers: characterization and supercontinuum generation” was supervised by Prof. T. G. Brown.

Currently, he is a Postdoctoral Research Associate under the mentorship of Prof. D. J. Gauthier at Duke University, Durham, NC, studying optical-fiber-based slow-light effects and applications. His research interests include nonlinear optics, guided-wave and fiber optics, and photonic crystals.

Dr. Zhu is a member of the Optical Society of America and the American Physical Society.

Andrew M. C. Dawes received the B.A. degree (with honors) in physics from Whitman College, Walla Walla, WA, in 2002 and the M.A. degree in physics from Duke University, Durham, NC, in 2005, where he is currently working toward the Ph.D. degree at the Department of Physics.

He is currently with the Department of Physics and the Fitzpatrick Center for Photonics and Communications Systems, Duke University. His research interests include slow light in optical fiber, pattern formation in nonlinear optics, and all-optical switching and processing systems.

Mr. Dawes is a Student Member of the Optical Society of America and the American Physical Society and, currently is a Walter Gordy Graduate Fellow of the Duke University Department of Physics and a John T. Chambers Fellow of the Fitzpatrick Center for Photonics and Communications Systems.

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.

Lin Zhang (S'04) was born in Anshan, Liaoning, China, in 1978. He received the B.S. and M.S. degrees from Tsinghua University, Beijing, China, in 2001 and 2004, respectively. His thesis was on birefringence and polarization-dependent coupling in photonic-crystal fibers. He is currently working toward the Ph.D. degree with the Department of Electrical Engineering, the University of Southern California, Los Angeles (USC).

He is currently with the Department of Electrical and Computer Engineering, USC. His current research interests include fiber-based slow light, photonic-crystal fibers, nonlinear optics, and fiber-optical-communication systems.

Mr. Zhang is a Student Member of the Optical Society America and the IEEE Lasers and Electro-Optics Society. He is the recipient of the award as one of the top-ten outstanding graduate students of 2003 at Tsinghua University.

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

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 525 publications, including one book.

Prof. Willner is a Fellow of the Optical Society of America (OSA) and was a Fellow of the Semiconductor Research Corporation. He is the recipient of the 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 Lasers and Electro-Optics Society (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. His professional activities have included President of IEEE 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, Cochair of the OSA Science and Engineering Council, General Cochair of the Conference on Lasers and Electro-Optics, General Chair of the LEOS Annual Meeting Program, Program Cochair of the OSA Annual Meeting, and Steering and Program Committee member of the Conference on Optical Fiber Communications.