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—We investigate slow-light via stimulated Brillouin scattering in a room temperature optical fiber that is pumped by a spectrally broadened laser. Broadening 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 \(\Omega_B\) so that the anti-Stokes absorbing resonance cancels out substantially 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 \(\Delta \omega_p \gg \Omega_B\). Using this general approach, we increase the Brillouin slow-light bandwidth to over 12 GHz from its nominal linewidth of \(\sim 30\) 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—Slow Light, Stimulated Brillouin Scattering, Optical Fiber, Pulse Propagation, Q penalty.

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], [3]. It is usually achieved using coherent optical methods [1]. Slow-light techniques have many applications in optical communication systems, including optical buffering, data synchronization, and signal processing [2], [3].

In this regard, fiber-based SBS slow light is limited to data rates less than a few tens of Mbps due to the narrow Brillouin resonance width (\(\sim 30\) 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 a 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, a first step toward understanding performance penalties incurred by this slow-light method. Section IV concludes the paper.

II. SBS SLOW LIGHT

In a SBS slow-light system, a continuous-wave (CW) laser beam (angular frequency \(\omega_p\)) 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 \(\Omega_B\) is the Brillouin frequency shift, and absorption in the vicinity of the anti-Stokes frequency \(\omega_{as} = \omega_p + \Omega_B\).

A pulse (denoted interchangeably by the “probe” or “data” pulse) launched along the +z-direction experiences slow (fast) light propagation when its carrier frequency \(\omega\) 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 \(g_0(\omega)\) and the pump spectrum of the pump field \(I_p(\omega_p)\) as shown by

\[
g(\omega) = g_0(\omega) \otimes I_p(\omega_p) = \int_{-\infty}^{\infty} \frac{g_0 I_p(\omega_p)}{1 - i(\omega + \Omega_B - \omega_p)/(\Gamma_B/2)} d\omega_p,
\]

where \(g_0\) is the linecenter SBS gain coefficient for a monochromatic pump field, and \(\Gamma_B\) is the intrinsic SBS linewidth (FWHM in radians/s). 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 \(T_{del} = G_0/\Gamma_B\) 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 11 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 in our experiment. 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 \( \Omega_B \), which is the condition of the experiment of Ref. [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 our experiment.

In our analysis, we take the pump power spectrum as

\[
I_p(\omega_p) = \frac{I_0}{\sqrt{\pi \Delta\omega_p}} \exp\left[-\left(\frac{\omega_p - \omega_0}{\Delta\omega_p}\right)^2\right].
\]  

(2)

Inserting this expression into Eq. 11 and evaluating the integral results in a complex SBS gain function given by

\[
g(\omega) = g_0 I_0 \sqrt{\pi \eta} w(\xi + i\eta),
\]

where \( w(\xi + i\eta) \) is the complex error function \([15]\), \( \xi = (\omega + \Omega_B - \omega_0)/\Delta\omega_p \), and \( \eta = \Gamma_B/(2\Delta\omega_p) \).

When \( \eta \ll 1 \) (the condition of our experiment), the gain function is given approximately by

\[
g(\omega) = g_0 I_0 \sqrt{\pi \eta} \exp(-\xi^2) \text{erfc}(-i\xi),
\]

where \( \text{erfc} \) is the complementary error function. The width (FWHM, rad/s) of the gain profile is given by \( \Gamma = 2\sqrt{\ln 2} \Delta\omega_p \), which should be compared to the unbroadened resonance width \( \Gamma_B \). 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

\[
T_{\text{del}} = \frac{d\text{Im}[g(\omega)L/2]}{d\omega}\bigg|_{\omega=\omega_c} = \frac{2\sqrt{\ln 2} G}{\sqrt{\pi \eta}} \approx 0.94 \frac{G}{\Gamma}.
\]

(5)

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

\[
T_{\text{out}}^2 = T_0^2 + \frac{G}{\Delta\omega_p^2}.
\]

(6)

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

\[
\frac{T_{\text{del}}}{T_0} = \frac{3}{\sqrt{\pi \eta} T_0 \Delta\omega_p}.
\]

(7)

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

![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: \( \Delta\omega_p/\Omega_B = 2.5 \).](image)

![Fig. 2. Relative SBS delay as a function of the SBS resonance linewidth.](image)

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

\[
g(\omega) = \frac{G}{L} \left(e^{-\xi^2} \text{erfc}(-i\xi) - e^{-\xi^2} \text{erfc}(-i\xi_-)\right),
\]

where \( \xi_- = (\omega \pm \Omega_B - \omega_0)/\Delta\omega_p \). As shown in Fig. 1, the anti-Stokes absorption shifts the effective peak of the SBS gain to lower frequencies when \( \Delta\omega_p \) is large, 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. Figure 2 shows the relative delay as a
function of the resonance bandwidth, where it is seen 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 demonstrates that it is possible to obtain practical slow-light bandwidths that can somewhat exceed a few times $\Omega_B$.

**III. Experiments and Results**

As discussed above, the SBS slow-light pulse delay $T_{det}$ is proportional to $G/\Gamma$. 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 our experiment, 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 (Tektronix, 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 Ohms. 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 $\Omega_B/2\pi \approx 9.6$ GHz. CW light from another tunable laser is amplitude-modulated to form data pulses that counter-propagate 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.

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. Figure 4(a) shows an example of the spectra. It is seen that the features overlap and that Eq. 4 does an excellent job in predicting our observations, where we adjusted $\Gamma$ 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 non-ideality could be avoided by using a laser with a greater tuning sensitivity.

![Fig. 3. Experiment setup. EDFA: Erbium-doped fiber amplifier, MZM: Mach-Zehnder modulator, FPC: fiber polarization controller, HNLF: highly nonlinear fiber.](image)

![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. Pulse delay (b) and pulse width (c) 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 Eq. 5. In (c), the dashed curve is obtained with Eq. 6. (d) Pulse waveforms at 0-dB and 14-dB SBS gain. The input data pulsewidth is $\sim 75$ ps.](image)

Based on the measured SBS bandwidth, we chose a pulsewidth (FWHM) of $\sim 75$ ps ($T_0 \sim 45$ ps) produced by a 14 GB/s electrical pulse generator. Figures 4(b)-(d) show the experimental results for such input pulses. Figure 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 $\sim 580$ mW that is coupled into the HNLF, which gives a gain of about 14 dB. It is seen 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 Eq. 5, which tends to underestimate the time delay that is enhanced by the contribution from the anti-Stokes line (see Fig. 2). Figure 4(c) shows the width of the delayed pulse as a function of gain. The data pulse is seen 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 Eq. 6. Figure 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. These thermally-induced delays are not included in Fig. 4(b).

To investigate how the pulse broadening seen in Fig. 4(c) might impact a communication system, we examine the pattern dependence of the pulse distortion. For example, in 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.

Figures 5(a)-(c) show 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 Q-factor (signal quality factor) of input and output pulses, which is defined as \( Q = 10 \log_{10} \left( \frac{m_1 - m_0}{\sigma_1 + \sigma_0} \right) \), where \( m_1 \), \( m_0 \), \( \sigma_1 \), \( \sigma_0 \) 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. Figure 5(d) shows the Q-penalty as a function of time delay for 10 Gb/s 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 seen 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 (BER < \( 10^{-9} \)) is found at a normalized delay of 0.25 or less. 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.

ACKNOWLEDGMENT

We gratefully acknowledge the loan of the fast pulse generator and sampling oscilloscope by Martin Brooke of the Duke Electrical and Computer Engineering Department.

REFERENCES

[1] R. W. Boyd and D. J. Gauthier, in Progress in Optics, E. Wolf, Ed. (Elsevier, Amsterdam, 2002), Vol. 43, Ch. 6, pp. 497–530.
[2] D. Gauthier, “Slow light brings faster communication,” Phys. World, vol. 18, no. 12, pp. 30–32, Dec. 2005.
[3] D. J. Gauthier, A. L. Gaeta, and R. W. Boyd, “Slow Light: From basics to future prospects,” Photonics Spectra, vol. 40, no. 3, pp. 44–50, Mar. 2006.
[4] R. W. Boyd, D. J. Gauthier, and A. L. Gaeta, “Applications of slow-light in telecommunications,” Optics & Photonics News, vol. 17, no. 4, pp. 19–23, Apr. 2006.
[5] Y. Okawachi, M. S. Bigelow, J. E. Sharping, Z. Zhu, A. Schweinsberg, D. J. Gauthier, R. W. Boyd, and A. L. Gaeta, “Tunable all-optical delays via Brillouin slow light in an optical fiber,” Phys. Rev. Lett., vol. 94, pp. 153902–153902-4, Apr. 2005.
[6] K. Y. Song, M. G. Herr´ ez, and L. Th´ evenaz, “Observation of pulse delaying and advancement in optical fibers using stimulated Brillouin scattering,” Opt. Express, vol. 13, no. 1, pp. 82–88, Jan. 2005.
[7] K. Y. Song, M. G. Herr´ ez, and L. Th´ evenaz, “Long optically controlled delays in optical fibers,” Opt. Lett., vol. 30, no. 14, pp. 1782–1784, Jul. 2005.
[8] M. G. Herr´ ez, K. Y. Song, and L. Th´ evenaz, “Optically controlled slow and fast light in optical fibers using stimulated Brillouin scattering,” Appl. Phys. Lett., vol. 87, pp. 081113-1–081113-3, Aug. 2005.
[9] Z. Zhu, D. J. Gauthier, Y. Okawachi, J. E. Sharping, A. L. Gaeta, R. W. Boyd, and A. E. Willner, “Numerical study of all-optical slow-light delays via stimulated Brillouin scattering in an optical fiber,” J. Opt. Soc. Am. B, vol. 22, no. 11, pp. 2378–2384, Nov. 2005.
[10] J. E. Sharping, Y. Okawachi, and A. L. Gaeta, “Wideband slow light using a Raman fiber amplifier,” Opt. Express, vol. 13, no. 16, pp. 6092–6098, Aug. 2005.
[11] D. Dahan and G. Eisenstein, “Tunable all optical delay via slow and fast light propagation in a Raman assisted fiber optical parametric amplifier: a route to all optical buffering,” Opt. Express, vol. 13, no. 16, pp. 6234–6249, Aug. 2005.
[12] M. D. Stenner and M. A. Neifeld, Z. Zhu, A. M. C. Dawes, and D. J. Gauthier, “Distortion management in slow-light pulse delay,” Opt. Express, vol. 13, no. 25, pp. 9995–10002, Dec. 2005.
[13] M. G. Herr´ ez, K. Y. Song, and L. Th´ evenaz, “Arbitrary-bandwidth Brillouin slow light in optical fibers,” Opt. Express, vol. 14, no. 4, pp. 1395–1400, Feb. 2006.
[14] Z. Zhu, A. M. C. Dawes, D. J. Gauthier, L. Zhang, and A. E. Willner, “12-GHz-bandwidth SBS slow light in optical fibers,” presented at the Optical Fiber Communications Conf., Anaheim, CA, 2006, Paper PDP1.
[15] M. Abramowitz and I. A. Stegun, eds., Handbook of Mathematical functions (Dover, New York, 1974), Ch. 7.
[16] R. W. Boyd, D. J. Gauthier, A. L. Gaeta, and A. E. Willner, “Maximum time delay achievable on propagation through a slow-light medium,” Phys. Rev. A, vol. 71, no. 023801–023801-4, 2005.
[17] L. Zhang, T. Luo, W. Zhang, C. Yu, Y. Wang, and A. E. Willner, “Optimizing operations to reduce data pattern dependence induced by slow light elements,” presented at the Optical Fiber Communications Conf., Anaheim, CA, 2006, Paper OFP7.

Zhaoming Zhu received a Bachelor degree in Electronic Engineering and an M.S. degree in Applied Physics from Tsinghua University, Beijing, China, in 1995 and 1998, respectively, and a Ph.D. degree in Optics from the University of Rochester 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 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, and the M.A. degree in physics from Duke University, Durham, NC in 2002 and 2005 respectively. He is currently pursuing the Ph.D. degree in the Duke University Department of Physics. 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 (OSA) and the American Physical Society (APS) and currently 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 CW two-photon optical laser as a Post-Doctoral 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 in 1992 and the National Science Foundation in 1993. He is currently the Anne T. and Robert M. Bass Professor of Physics and Biomedical Engineering at Duke. 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 was born in Anshan, Liaoning, China, in 1978. He received the B.S. and M.S. degree from Tsinghua University, Beijing, China, in 2001 and 2004, respectively. His thesis was on birefringence and polarization dependent coupling in photonic crystal fibers. Now he is pursuing the Ph.D. degree in the Department of Electrical Engineering, the University of Southern California, Los Angeles. His current research interests include fiber-based slow light, photonic crystal fibers, nonlinear optics, and fiber optical communication systems.

Lin Zhang is a student member of the Optical Society-America (OSA) and IEEE Lasers and Electro-Optics Society (LEOS). He was awarded as one of top-ten outstanding graduate students of 2003 year at Tsinghua University.

Andrew M. C. Dawes received the B.A. degree with honors in physics from Whitman College, Walla Walla, WA, and the M.A. degree in physics from Duke University, Durham, NC in 2002 and 2005 respectively. He is currently pursuing the Ph.D. degree in the Duke University Department of Physics. 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 (OSA) and the American Physical Society (APS) and currently 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 CW two-photon optical laser as a Post-Doctoral 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 in 1992 and the National Science Foundation in 1993. He is currently the Anne T. and Robert M. Bass Professor of Physics and Biomedical Engineering at Duke. 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 (’87-M’88-SM’93-F’04) received the Ph.D. degree from Columbia University, New York. He has worked at AT&T Bell Laboratories and Bellcore. He is currently Professor of Electrical Engineering at 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 has received 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 & 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, Co-Chair of the OSA Science and Engineering Council, General Co-Chair of the Conference on Lasers and Electro-Optics (CLEO), 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).