Simultaneous demodulation and slow light of differential phase-shift keying signals using stimulated-Brillouin-scattering-based optical filtering in fiber

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For the first time to our knowledge, we demonstrate simultaneous demodulation and slow-light delay of differential phase-shift keying (DPSK) signals at flexible bit rates using the stimulated-Brillouin-scattering-based optical filtering effect in optical fiber. Both 10 and 2.5 Gbit/s DPSK signals have been demodulated and delayed with excellent performances. In the case of the10 Gbit/s DPSK signal, after demodulation the tunable delay range with error-free operation is about 50 ps, which we believe is the best result obtained for 10 Gbit/s slow-light demonstrations. For the 2.5 Gbit/s DPSK signal, the optimal sensitivity after demodulation is −36.5 dBm, which is comparable with the back-to-back sensitivity of a 2.5 Gbit/s nonreturn-to-zero signal. © 2007 Optical Society of America

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Differential phase-shift keying (DPSK) modulation format is very attractive in optical communication systems owing to its high tolerance to fiber, nonlinear impairments, and amplified spontaneous emission (ASE) noise [1]. Versatile techniques have been proposed to demodulate optical DPSK signals, such as 1 bit delay Mach–Zehnder interferometer (MZI) [2], birefringent fiber loop [3], and Gaussian-shaped fiber Bragg grating (FBG) [4]. Among them, the FBG-based demodulation is the simplest and the most reliable solution. However, once the FBG has been fabricated, it can be used only at a fixed bit rate and wavelength. Furthermore, it is very difficult to demodulate low-speed DPSK signals (e.g., 2.5 Gbit/s or less) based on the present FBG technology. Stimulated Brillouin scattering (SBS) in optical fiber has been proposed as an active optical filter with flexible tunability [5]: the central wavelength, bandwidth, and gain profile can be adjusted by changing the wavelength, spectral width, and shape of the Brillouin pump. On the other hand, SBS in optical fiber has recently been extensively studied to slow down light group velocity for potential packet synchronization and data buffering [6–8]. Generally, slow light results from enhancement of the group index induced by an optical resonance in the optical medium. In this Letter, for the first time to our knowledge, we propose to use the SBS effect to simultaneously demodulate and delay DPSK signals at flexible bit rates (for example at 10 and 2.5 Gbits/s).

Figure 1 shows the experimental setup. The DPSK transmitter consists of a laser diode (LD1) operating at 1548.26 nm, a polarization controller (PC), and a Mach–Zehnder modulator (MZM) driven by a 2^{23}-1 pseudorandom bit sequence (PRBS) data. The MZM is biased at the transmission null point for DPSK generation [1]. The DPSK signal is then launched into a 20 km TrueWave (TW) fiber with a 10.75 GHz Brillouin frequency shift. The SBS gain acts as both an optical-induced demodulator and a delay line. The SBS pump source is a directly modulated laser diode (LD2), whose central wavelength can be precisely adjusted by tuning the temperature and bias current. The pump laser diode is modulated by a Gaussian noise source (Tektronix AFG3252), and subsequently boosted by a high-power (+30 dBm) erbium-doped fiber amplifier (EDFA). The pump spectral bandwidth can be flexibly tuned by varying the peak-to-peak voltage of the Gaussian noise source. In the 10 Gbit/s SBS-based slow-light experiment, coherent crosstalk between the signal and the Rayleigh backscattering of the broadband pump is the dominant noise contribution. Consequently, we set the input signal power at 5 dBm to improve the signal–Rayleigh noise ratio (more than 20 dB). Furthermore, we used a ~0.1 nm bandwidth flattop FBG to minimize the coherent crosstalk induced by

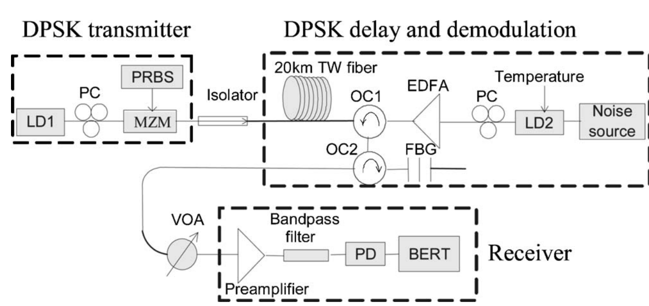

Fig. 1. Experimental setup for DPSK demodulation and slow light based on SBS in optical fiber. OC1, OC2, optical circulators. Other abbreviations defined in text.

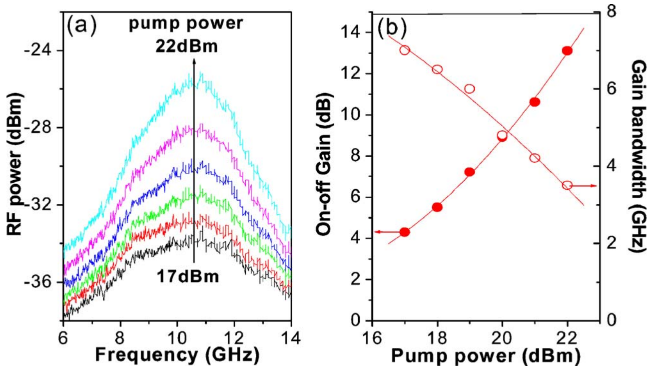

Fig. 2. (Color online) (a) SBS gain spectra measurement for different pump-power levels. (b) SBS gain and bandwidth evolution with pump power for 10 Gbit/s DPSK signal.

the Rayleigh backscattering. Therefore the SBS amplification is the main noise factor for the demodulation and delay process. Finally the signal is sent into a photoreceiver, which consists of an optical preamplifier, a tunable optical filter, a PIN photodiode (PD), and a bit-error-rate tester (BERT). A variable optical attenuator (VOA) is inserted after the SBS stage for the bit-error-rate (BER) measurement so as to evaluate the signal quality after demodulation and delay.

When a signal, denoted as $E_{\text{in}}(\omega)$, is transmitted through a fiber with broadband SBS gain, the output field $E_{\text{out}}(\omega)$ can be expressed as that in [6]

$$E_{out}(\omega) = \exp(g(\omega)L_{eff}/2)E_{in}(\omega), \tag{1}$$

where L_{eff} is the effective length of the fiber and $g(\omega)$ is the complex SBS gain function resulting from the convolution of the broadband pump spectrum and the natural Brillouin gain bandwidth of the fiber [6]:

$$g(\omega) = \int \frac{g_B}{1 - i(\omega + \Omega_B - \omega_p) \Big/ \dfrac{\Gamma_B}{2}} I_p(\omega_p)\mathrm{d}\omega_p, \tag{2}$$

where $I_p(\omega_p)$ is the pump-power spectrum with a Gaussian distribution due to the Gaussian profile of the modulation current noise. In the above equations, g_B is the Brillouin peak gain coefficient, Ω_B is the Brillouin frequency shift, and Γ_B is the photon decay rate. The real part of $g(\omega)$ is related to the SBS gain profile, and the imaginary part represents the phase shift, which results in DPSK demodulation and time delay.

The shape and bandwidth of the optical filtering function induced by the SBS effect in fiber are the most important parameters for DPSK demodulation. Compared with the standard 1 bit delay MZI with a cosine-shaped transmission curve, the Gaussian-shaped filter has a very similar shape with that of the MZI in low-frequency region; therefore it can also be used for DPSK demodulation. For optimal DPSK demodulation, the SBS-induced optical filter should be Gaussian shaped and its bandwidth should be around 60% of the bit rate [4]. Figure 2(a) shows the SBS gain spectra at different pump-power levels measured by the coherent heterodyne technique for an 8 GHz pump spectral bandwidth. The Gaussian profile of the SBS gain can be explained by the Gaussian nature of the pump modulation noise. The SBS gain increases exponentially with the pump power; therefore in the broadband pump case, the gain in the center frequency of the SBS gain spectrum increases more rapidly than that at the edges with the increase of the pump power, resulting in a narrower SBS gain bandwidth. The peak gain and the gain bandwidth variations versus the pump power are shown in Fig. 2(b). The bandwidth decreases from 7 to 3.5 GHz when the pump power increases from 17 to 22 dBm, which is particularly convenient for finely optimizing the DPSK demodulation. Figure 3 shows the demodulated eye diagrams of the 10 Gbit/s DPSK signal at different pump-power levels, obtained both in numerical simulations and experimental measurements. In the numerical simulations, we take into account the combined FBG and SBS filtering effects for consistency with the experiment, and neglect SBS noise factor, which leads to slight differences when compared with the measurement results. When the pump is off, the DPSK signal is mainly distorted by the FBG, whose shape and bandwidth are not optimized for DPSK demodulation. When the pump power is 17 dBm, corresponding to a 7 GHz gain bandwidth, the DPSK signal is successfully demodulated and a duobinary signal is obtained at the SBS-based filter output. For a 20 dBm pump power, the SBS gain bandwidth is decreased to 4.5 GHz. Such a narrow bandwidth induces pattern-dependent distortions of the DPSK signal.

We first present the demodulation and delay performances of a 10 Gbit/s DPSK signal. Figure 4(a) shows the BER versus the received power of the demodulated 10 Gbit/s DPSK signal for various pump-power levels. With an 18 dBm pump power that results in 6.5 GHz gain bandwidth, we obtain the best demodulation performance. The sensitivity after the demodulation is −32.1 dBm, which is ~2 dB worse than the back-to-back (BtB) sensitivity of a 10 Gbit/s nonreturn-to-zero (NRZ) signal. The degradation is mainly resulted from the noise and dispersion contributions. Furthermore, increasing the pump power reduces the SBS gain bandwidth, thus distorting the signal and degrading the sensitivity ($\text{BER} = 10^{-9}$).

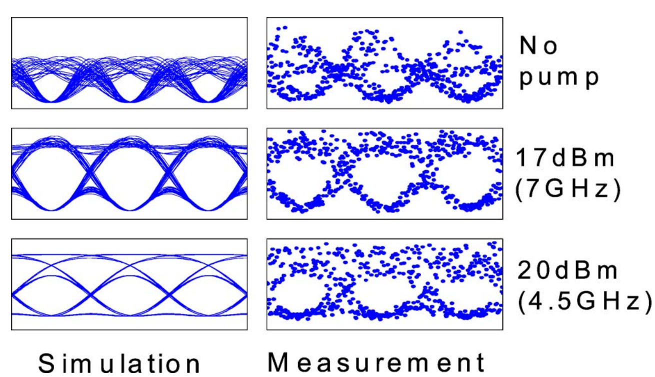

Fig. 3. (Color online) Simulated and measured eye diagrams of 10 Gbit/s DPSK signal after SBS-based demodulation.

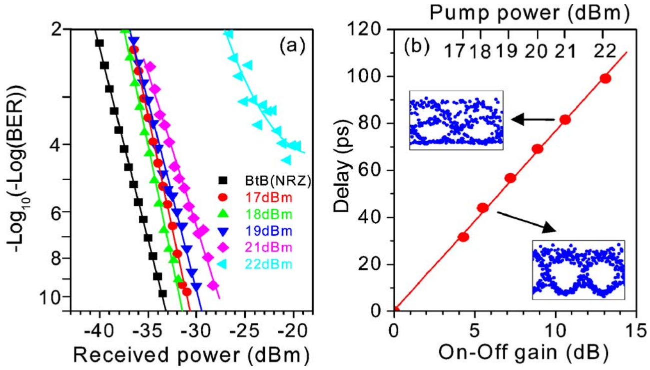

Fig. 4. (Color online) (a) BER and (b) delay-time evolution with pump power for 10 Gbit/s DPSK signal. The insets in (b) are eye diagrams.

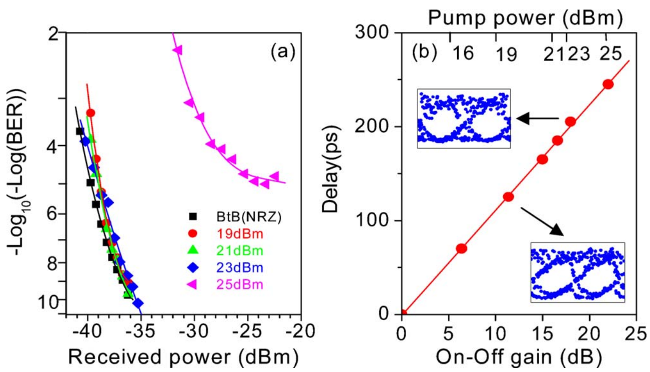

Fig. 5. (Color online) (a) BER and (b) delay-time evolution with pump power for 2.5 Gbit/s DPSK signal. The insets in (b) are eye diagrams.

When the pump power is increased up to 22 dBm, resulting in a 3.5 GHz gain bandwidth, the demodulated DPSK signal is strongly distorted, and error-free operation cannot be obtained. On the other hand, the SBS gain also induces DPSK signal delay, which increases when the pump power is enhanced, as shown in Fig. 4(b). The insets of Fig. 5 show the demodulated eye diagrams of the DPSK signal at 18 and 21 dBm pump power, respectively. The delay time linearly increases with the on–off peak gain, and the maximal delay time with error-free operation is 81.5 ps. However, considering that the DPSK signal cannot be demodulated without SBS gain, there is a minimum delay for the DPSK demodulation. In our case, the value is about 31 ps at the 17 dBm pump power. Thus the practical tunable delay range is about 50 ps with the pump power varied from 17 to 21 dBm, and the corresponding maximal sensitivity degradation is ~4 dB.

Finally, we measure the demodulation and delay performances of a 2.5 Gbit/s DPSK signal, as shown in Fig. 5. The pump spectral bandwidth is set at 3.5 GHz. By changing the pump power, the SBS gain bandwidth can be precisely tuned to demodulate the DPSK signal. When the pump power is tuned to 21 dBm, corresponding to a 1.7 GHz gain bandwidth, the sensitivity reaches the optimum value of −36.6 dBm, which is similar to the BtB sensitivity of a 2.5 Gbit/s NRZ signal. Like the 10 Gbit/s DPSK demodulation case, the narrower the SBS bandwidth is, the stronger the distortions of the DPSK signal are. The tunable delay range is about 135 ps for the 2.5 Gbit/s DPSK signal, considering the minimum delay of about 70 ps for the DPSK demodulation. Note that narrower SBS gain spectrum induces strong dispersion; however, low-speed signals can better tolerate dispersion than high-speed signals. Thus lower-speed DPSK signals (for example at 622 Mb/s or less) can also be demodulated by SBS, which cannot be realized by Gaussian-shaped FBGs.

In summary, we demonstrate the simultaneous demodulation and delay of DPSK signals using SBS-based optical filtering effect in fiber. By tuning the SBS gain bandwidth, the SBS-based demodulator and delay line can work at flexible bit rates. This work reports the simultaneous demodulation and tunable delay of both 10 and 2.5 Gbit/s DPSK signals. A maximal tunable delay range of 50 ps with error-free operation ($BER < 10^{-9}$) for the demodulated 10 Gbit/s DPSK signal has been achieved, which is to our knowledge the best result for 10 Gbit/s signals. For the 2.5 Gbit/s DPSK signal, the obtained optimal sensitivity after demodulation is similar to the BtB case of a NRZ signal. The results imply that the SBS-based optical filtering effect would be attractive for optical communications communities.

References

1. A. H. Gnauck and P. J. Winzer, J. Lightwave Technol. **23**, 115 (2005).
2. E. Swanson, J. Livas, and R. Bondurant, IEEE Photon. Technol. Lett. **6**, 263 (1994).
3. C. W. Chow and H. K. Tsang, IEEE Photon. Technol. Lett. **17**, 1313 (2005).
4. D. Penninckx, H. Bissessur, P. Brindel, E. Gohin, and F. Bakhti, in *Proceedings of 27th European Conference on Optical Communication, ECOC '01* (IEEE, 2001), Vol. 3, pp. 456–457.
5. T. Tanemura, Y. Takushima, and K. Kikuchi, Opt. Lett. **27**, 1552 (2002).
6. Z. Zhu, A. M. C. Dawes, D. J. Gauthier, L. Zhang, and A. E. Willner, J. Lightwave Technol. **25**, 201 (2007).
7. L. Yi, L. Zhan, W. Hu, and Y. Xia, IEEE Photon. Technol. Lett. **19**, 619 (2007).
8. B. Zhang, L. Yan, I. Fazal, L. Zhang, A. E. Willner, Z. Zhu, and D. J. Gauthier, Opt. Express **15**, 1878 (2007).