Improved slow-light performance of 10 Gb/s NRZ, PSBT and DPSK signals in fiber broadband SBS

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Abstract: We have demonstrated error-free operations of slow-light via stimulated Brillouin scattering (SBS) in optical fiber for 10-Gb/s signals with different modulation formats, including non-return-to-zero (NRZ), phase-shaped binary transmission (PSBT) and differential phase-shift-keying (DPSK). The SBS gain bandwidth is broadened by using current noise modulation of the pump laser diode. The gain shape is simply controlled by the noise density function. Super-Gaussian noise modulation of the Brillouin pump allows a flat-top and sharp-edge SBS gain spectrum, which can reduce slow-light induced distortion in case of 10-Gb/s NRZ signal. The corresponding maximal delay-time with error-free operation is 35 ps. Then we propose the PSBT format to minimize distortions resulting from SBS filtering effect and dispersion accompanied with slow light because of its high spectral efficiency and strong dispersion tolerance. The sensitivity of the 10-Gb/s PSBT signal is 5.2 dB better than the NRZ case with a same 35-ps delay. The maximal delay of 51 ps with error-free operation has been achieved. Futhermore, the DPSK format is directly demodulated through a Gaussian-shaped SBS gain, which is achieved using Gaussian-noise modulation of the Brillouin pump. The maximal error-free time delay after demodulation of a 10-Gb/s DPSK signal is as high as 81.5 ps, which is the best demonstrated result for 10-Gb/s slow-light.

OCIS codes: (060.4370) Nonlinear optics, fiber; (060.0060) Fiber optics and optical communications; (060.4080) Modulation; (290.5900) Scattering, stimulated Brillouin.

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1. Introduction

Recently, slow light based on the group velocity control of signal propagation, has attracted much interest due to potential applications in future optical communication networks, such as optical buffering and data synchronization. Among all proposed techniques, slow-light mechanism based on stimulated Brillouin scattering (SBS) in optical fibers has attracted extensive attention [1-10]. The time delay is proportional to the peak gain and inversely proportional to the gain bandwidth [11]. The relevant research topics mainly focus on three aspects: (i) broadening the SBS gain bandwidth to support high-speed data delay by modulating the Brillouin pump [3-5]; (ii) improving the fractional delay to increase the storage capability by cascading SBS based delay-lines [6] or combining the Brillouin gain and loss spectra of two different SBS pumps [7]; (iii) minimizing the signal distortions to improve the signal quality after delay by using multi-line Brillouin pump [8]. For practical applications, the signal quality after delay is of important consideration. However, there are few publications particularly focusing on improving the quality of the delayed signals at high bit-rates. Until now, the system performance in terms of bit error rate (BER) and sensitivity for 10-Gb/s signals transmitted in SBS based slow-light have been investigated only in case of differential phase-shifted-keying (DPSK) modulation format [9], where the sensitivity was degraded by ~10 dB for a maximum 42-ps delay. The distortions in SBS based slow-light process mainly come from two aspects: filtering effect of the SBS gain and dispersion accompanied with the slow-light.

In this paper we especially focus on minimizing the signal distortions and improving the system performances of 10-Gb/s signals in SBS based slow light for different modulation formats: non-return-to-zero (NRZ), phase-shaped binary transmission (PSBT) and DPSK. Firstly, in the case of 10-Gb/s signals, the coherent crosstalk between Rayleigh backscattering noise of the broadband Brillouin pump and the signal must be taken into account. Therefore the input signal power should be maximized to improve the signal to Rayleigh-noise ratio. Then a narrow-band fiber Bragg grating (FBG) is inserted to filter the Rayleigh backscattering noise so as to minimize the crosstalk. Secondly, we use a super-Gaussian noise source to directly modulate the Brillouin pump LD for achieving a super-Gaussian SBS gain with a flat-top and sharp-edges, which can reduce the impact of the SBS filtering effect. Based on these techniques, for the first time, we have obtained error-free (BER<10^{-9}) slow-light operation for

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a 10-Gb/s NRZ signal, and the maximal delay-time with error-free operation is 35 ps. Furthermore, it is well-known that the PSBT format allows high spectral efficiency and strong dispersion-tolerance [12]. Hence, we propose to utilize the PSBT format to further minimize the distortions resulting from the gain filtering effect and the dispersion in SBS based slow-light. For a 10-Gb/s PSBT signal, a negative power penalty, i.e. ~-2 dB for a 25-ps delay-time, has been obtained. When the delay-time is increased to 35 ps, the sensitivity of the PSBT signal is 5.2 dB better than that in the NRZ case. Maximum of 51-ps delay with error-free operation can be obtained, and the corresponding power penalty is only 4 dB. A DSPK signal is usually demodulated using a 1-bit delay Mach-Zehnder interferometer. The corresponding transfer function is Cosine shape which is approximate with Gaussian shape for low frequencies. So a DPSK signal can also be demodulated using a Gaussian-shaped filter [13, 14]. We have simultaneously demodulated and delayed the DPSK signal using Gaussian-shaped SBS gain filtering effect [15]. Owing to the DPSK characteristics and the direct-demodulation using the SBS gain, the maximal error-free time delay of a 10-Gb/s DPSK signal is as high as 81.5 ps, which is up to date the best result for 10-Gb/s slow-light demonstrations.

2. Experimental setup

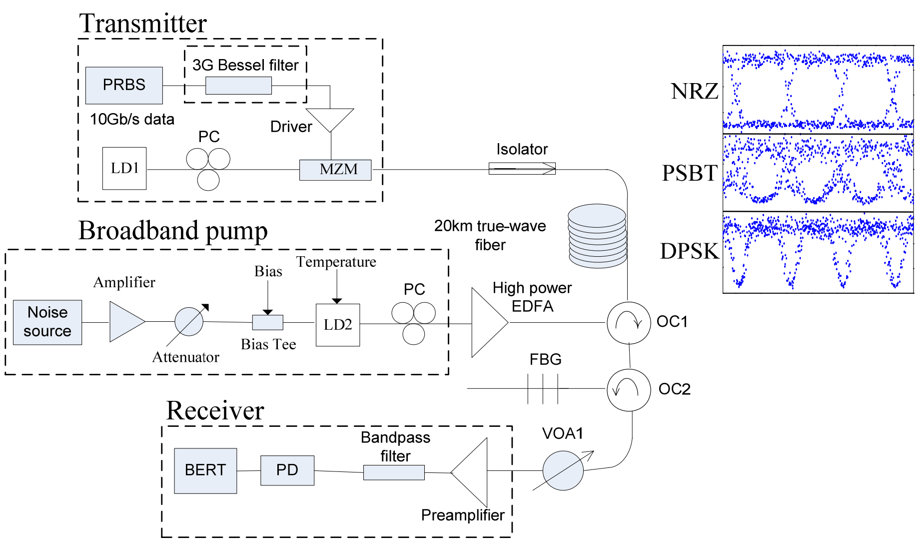

Fig. 1. Experimental set-up. (LD) laser diode, (MZM) Mach-Zehnder modulator, (EDFA) Erbium-doped fiber amplifier, (PC) polarization controller, (OC) optical circulator, (FBG) fiber Bragg grating, (VOA) variable optical attenuator, (PD) photodiode, (BERT) bit-error-rate tester.

Figure 1 depicts the experimental set-up. The transmitter consists of a laser diode (LD1) operating at 1548.26nm, and a Mach-Zehnder modulator (MZM) driven by a 10-Gb/s pseudo-random bit sequence (PRBS). Based on a 10-Gb/s NRZ transmitter, a 10-Gb/s PBST modulation format can be achieved by filtering the electrical NRZ signal using a 5^{th} order Bessel filter with a ~2.7-GHz cut-off frequency [16], which is subsequently amplified to $2V_\pi$ while the MZM bias is controlled at its transmission nulling point. In this experiment, a 2^7-1 word-length sequence is used for BER measurements because the bandwidth (~3 GHz) of the used PSBT electrical filter is non-optimal and the driver voltage does not reach exactly $2V_\pi$ [17]. The 10-Gb/s DPSK modulation format is simply obtained by removing the Bessel filter from the 10-Gb/s PSBT transmitter. The insets of Fig.1 correspond to the eye diagrams of the 10-Gb/s NRZ, PSBT and DPSK signals, respectively. The signal is launched into a 20-km True-wave (TW) fiber with a ~10.75-GHz Brillouin frequency shift. The SBS pump source is a directly modulated laser diode (LD2), whose central wavelength can be precisely

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controlled by temperature and bias current. The pump LD is modulated by a Gaussian noise source (Tektronix AFG3252), which is followed by a high power electrical amplifier and an attenuator for controlling the peak-to-peak voltage, corresponding to the pump spectral bandwidth. Subsequently the broadened Brillouin pump is boosted by a high power erbium-doped fiber amplifier (EDFA).

The coherent crosstalk between the signal and the Rayleigh backscattering of the broadband pump is a major contribution to performance degradation in the 10-Gb/s SBS based slow-light. Firstly we set the input signal power to 5 dBm, thus the Rayleigh backscattered power of the broadband pump is ~20 dB lower than the output signal power, as shown in Fig. 2(a). Here the spectra of the 10-Gb/s PSBT signal are plotted as an example, similar results have been obtained for 10-Gb/s NRZ and DPSK signals. The pump wavelength is closed to the zero-dispersion wavelength of the Truewave fiber, so parametric amplified spontaneous emission (ASE) located at both sides of the pump wavelength is observed. In this experiment we used a ~0.1-nm bandwidth flat-top fiber Bragg grating (FBG) to suppress the parametric ASE power and minimize the coherent crosstalk. The filtered optical spectra are shown in Fig. 2(b).

The photoreceiver consists of an optical preamplifier, a tunable optical filter, a 10-Gb/s PIN-FET photodetector (PD) and a bit-error-rate tester (BERT). Before the receiver, a variable optical attenuator (VOA) is used in order to tune the optical power for the BER measurements. In the following measurements, all the results in term of sensitivity and power penalty have been defined at a BER of 10^{-9}.

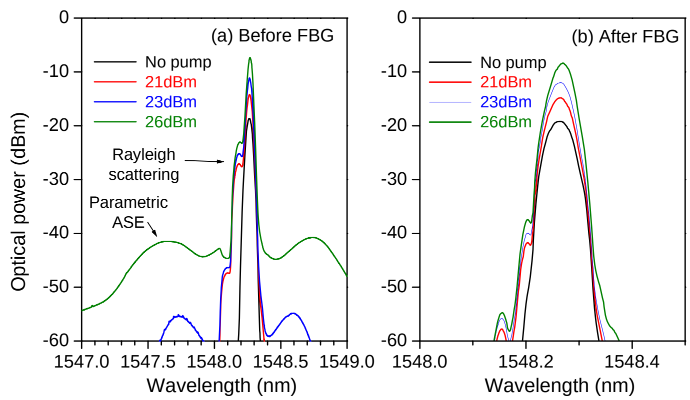

Fig. 2. The optical spectra of 10-Gb/s PSBT signals amplified by SBS. (a) Measured before FBG, and (b) after FBG.

3. Improved pump broadening

For controlling the delay of the 10-Gb/s signals, it is necessary to enhance the SBS gain bandwidth up to ~10 GHz. Direct modulation of the pump LD has been proposed as an effective method to obtain broadband SBS gain. Most of the previous works utilized the Gaussian noise modulation to achieve a Gaussian-shaped broadband SBS gain [4-5]. However, because the SBS gain exponentially increases with the pump power, the SBS gain bandwidth rapidly narrows down, which induces strong signal filtering effect. Consequently, the sensitivity of the delayed signal is strongly degraded with increasing the pump power [9]. If the pump spectrum is super-Gaussian shaped, it would bring to three benefits: firstly, the corresponding SBS gain is like a flat-top filter, which can reduce the SBS filtering distortion [18]; secondly, the SBS gain profile has sharp edges, which can increase the phase shift and correspondingly the time delay [10]; finally the pump power is mostly distributed at the centre of the pump spectrum, thus the SBS gain is higher for the same pump power compared with the Gaussian-shaped case.

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To realize the super-Gaussian noise modulation, we used a high power electrical amplifier to boost the electrical Gaussian noise. The temporal traces of the electrical power distribution of the Gaussian and super-Gaussian noises are shown in Figs. 3(a) and 3(b), respectively, which are observed using an oscilloscope in color mode. When the Gaussian noise is linearly amplified, the noise power density is still Gaussian shaped. While when the Gaussian noise is amplified to saturation regime, the Gaussian noise becomes a super-Gaussian one after the saturated amplification. One can choose the operation regimes of the electrical amplifier by varying its driven voltages. This control method is much simpler than that in [10], where the pump spectra are shaped by using synthesized pump chirp.

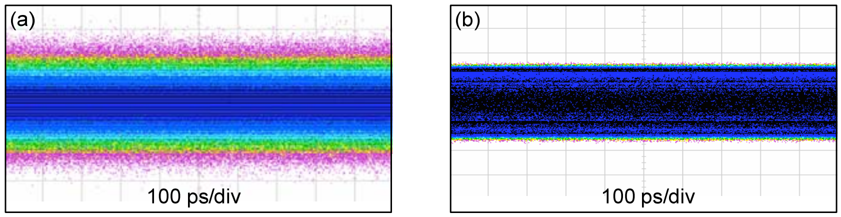

Fig. 3. The power spectra of Gaussian noise (a) and super-Gaussian noise (b) observed by an oscilloscope in color mode.

Figure 4(a) shows the pump spectra in case of Gaussian and super-Gaussian noise modulations measured by coherent heterodyne technique. The pump bandwidth is controlled by the peak-to-peak voltage of the noise source. The 3-dB bandwidths of both the pump spectra are ~12 GHz. The corresponding SBS gain spectra in small signal (-20dBm) input condition are shown in Fig. 4(b). At a 22-dBm pump power, the 3-dB bandwidths of the Gaussian and super-Gaussian shaped SBS gain spectra are 8 and 7 GHz, respectively. In the super-Gaussian case, the peak gain is ~6 dB higher and the edges of the gain profile are sharper compared with the Gaussian noise case. Therefore, for a same delay-time, the signal quality in the super-Gaussian case would be better than that in the Gaussian noise one. In the following experiments, we used the super-Gaussian noise modulation of the Brillouin pump to achieve improved signal quality of 10-Gb/s NRZ and PSBT signals in SBS based slow light. However, Gaussian-shaped filtering is suitable for direct DPSK demodulation [13, 14]. We have proposed Gaussian-shaped SBS filtering effect to directly demodulate DPSK signals [15]. In this case, the pump spectral width is set to 8 GHz and the corresponding SBS gain bandwidth is about 6.5 GHz for 18-dBm pump power.

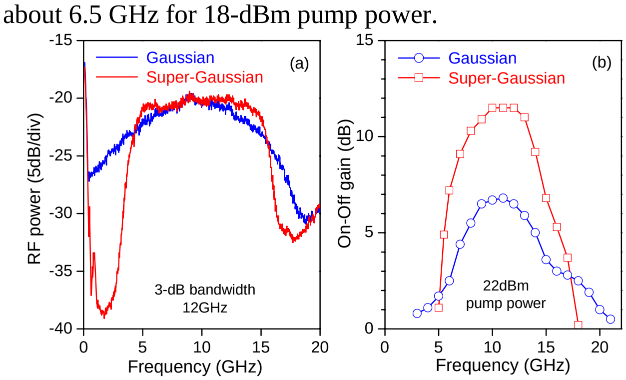

Fig. 4. The SBS pump spectra (a) and the corresponding gain spectra (b) in case of Gaussian-noise and super-Gaussian noise modulation of the Brillouin pump LD.

4. Experimental results and discussion

Firstly, we demonstrate error-free slow-light operation of the 10-Gb/s NRZ signal. Figure 5 shows the eye diagram with corresponding delay time, BER and pulse pattern evolutions of

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the 10-Gb/s NRZ signal for different pump power levels. The larger the pump power is, the higher the gain value and the delay-time are. The single “1” pulses and consecutive “1” pulses experience different signal gain [3], corresponding to different time delays. The induced amplitude variation and time jitter result in data pattern-dependent delay and distortion. Therefore we define the delay-time by comparing the maximal eye-opening point at different pump power levels. The obtained delay-times are 17, 35 and 51 ps with 19, 21 and 22-dBm pump powers, respectively. The gain bandwidth is reduced when the pump power increases, and the narrow gain bandwidth induces strong filtering effect, which is the main cause of the signal distortion in all the previous SBS based slow-light demonstrations. However the super-Gaussian shaped SBS gain mitigates the bandwidth-reduction process. When the pump power is increased to 22 dBm, corresponding to a 10.8-dB On-Off gain, error-free operation cannot be obtained even we have detuned the carrier from the gain peak to minimize the filtering effect [3, 9]. From the temporal positions of the pulses, it is clear that the pulses experience strong distortion at a 23-dBm pump power. The maximal delay-time with error-free operation (BER<10^{-9}) is 35 ps. This is the first slow-light demonstration of 10-Gb/s NRZ signals with error-free operation, which is attributed to suppressing the Rayleigh backscattering and utilizing the super-Gaussian SBS gain.

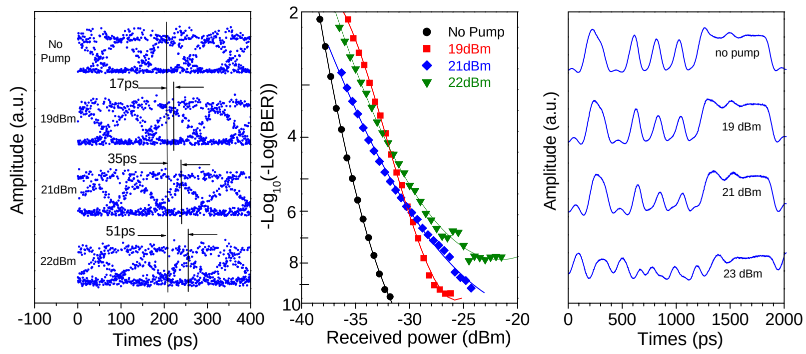

Fig. 5. Delay-time, eye diagram, BER and pulse pattern evolutions with pump power for the 10-Gb/s NRZ signal.

It is well-known that PSBT modulation format allows high spectral efficiency and strong dispersion-tolerance. We propose to use the PSBT format to increase tolerance to the SBS filtering effect and the dispersion-distortion so as to further improve the signal quality. Figure 6 shows the delay, the eye diagram, the BER and pulse pattern evolutions of the 10-Gb/s PSBT signal at different pump power levels. Without the pump, the receiver sensitivity is -28.2 dBm, which has taken into account the FBG filtering effect. There are some small ripples on the “0” bits of the PSBT signal, which can be seen from both the eye diagram and the temporal pulse curve. The high-frequency ripples mainly consist of 10-GHz sinusoidal components [16], which are not totally suppressed by the Bessel electrical filter. The SBS mechanism acts as a narrow-band optical filter, which suppresses the small ripples and increases the eye opening of the “0” bits, so the signal quality is improved after the SBS amplification and delay. When the pump power is set to 22 dBm, corresponding to a 7-GHz gain bandwidth and a 5.6-dB On-Off gain, the delay-time is 25 ps, and the eye opening is improved and the sensitivity achieves an optimum of -30.2 dBm. In addition to the filtering effect, the improved sensitivity is also attributed to the dispersion-tolerance of the PSBT format, which can reduce the dispersion-distortion induced by the slow-light effect. Further increasing the pump power will filter the high frequency components of the PSBT signals and induce additional distortions. When the pump power is increased to 26 dBm, corresponding to an 11.2-dB On-Off gain, the delay-time is increased to 55 ps but error-free operation cannot be achieved. Compared with the NRZ signal, the SBS filtering effect is not the main distortion

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factor since the PSBT signal has narrower spectral width. From the temporal pulse curves, we can see that there is no strong pattern-dependent distortion even though the pump power is increased to 27 dBm. It is the increased noise that results in the sensitivity degradation because the PSBT has a poor eye opening and thus a poor tolerance to the noise [14]. The maximal delay-time with error-free operation is 51 ps at a 25-dBm pump power. Note that the noise problem could be reduced by using an enhanced-PSBT modulation format [19] to achieve better delay performance.

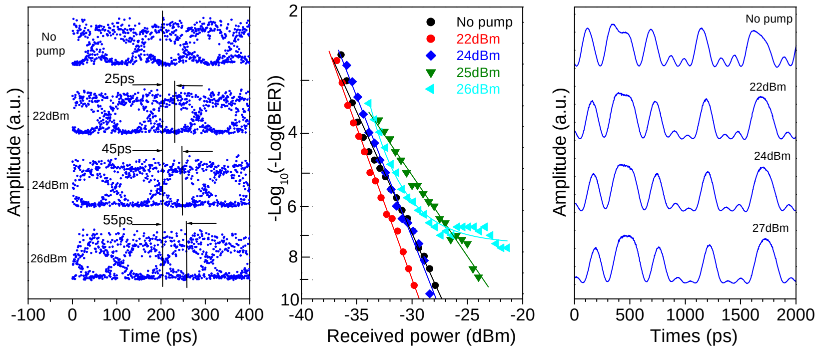

Fig. 6. Delay-time, eye diagram, BER and pulse pattern evolutions with pump power for the 10-Gb/s PSBT signal.

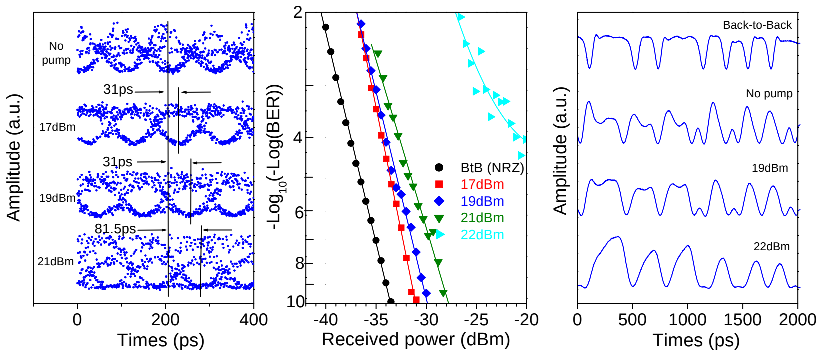

Fig. 7. Delay-time, eye diagram, BER and pulse pattern evolutions with pump power for the 10-Gb/s DPSK signal.

Different techniques have been proposed to demodulate a DSPK signal, such as a 1-bit delay Mach-Zenhder interferometer or a Gaussian-shaped FBG [13]. We have proposed to use the Gaussian-shaped SBS gain to simultaneously demodulate and delay the DPSK signals [15]. Figure 7 shows the delay, eye diagram, BER and pulse pattern evolutions of the 10-Gb/s DPSK signal for different pump power levels. The DPSK signal is mainly distorted by the 0.1-nm bandwidth FBG when SBS pump is off. When the pump power is increased to 17 dBm, resulting in a 7-GHz SBS gain bandwidth, the DPSK signal is demodulated to a duobinary signal, and the corresponding delay-time is 31 ps. With the further increase of the pump power, the gain value is enhanced but the gain bandwidth is reduced, which increases the delay-time and the signal distortion. When the pump power is 21 dBm, the delay is up to 81.5 ps, which is the maximal error-free time delay for 10-Gb/s signals up to date. Different from the PSBT case, the noise is not the main source of the sensitivity degradation any more. A strong distortion is induced when the narrow SBS gain bandwidth is not optimized for DPSK demodulation. We can see obvious pattern-dependent distortion of the demodulated DPSK signal from the temporal pulse curve at 23-dBm pump power.

Finally, we measured the time delay variation with the SBS On-Off gain and the sensitivity variation with the delay for the 10-Gb/s NRZ, PSBT and DPSK signals, as shown

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in Fig. 8. In all the cases, the delay linearly increases with the on-off gain. For the NRZ and PSBT cases, note that we did not optimize the signal polarization state, resulting in a same On-Off gain with different pump power levels. However, the delay time evolutions with the On-Off gain are exactly the same due to the same SBS gain shape. The DPSK signal presents larger delay at the same gain owing to the narrower gain bandwidth. For the NRZ case, the sensitivity is degraded with the delay due to the SBS gain filtering effect. While for both PSBT and DPSK signals the gain bandwidths have an optimum to achieve the best sensitivities, corresponding to 7 and 6.5 GHz, respectively. For the same amount of 35-ps delay, the sensitivity of the PSBT is 5 dB better than the NRZ case. The power penalty of the PSBT signal is only 4 dB for the maximum delay of 51 ps, which is better than the results (10 dB for 42 ps) reported in [9]. Moreover, the delay performance of the PSBT format could be improved using an optimized electrical PSBT filter [20]. For the 10-Gb/s DPSK signal, the optimal sensitivity after direct-demodulation using SBS gain is about -32 dBm, which is similar to the back-to-back sensitivity of the 10-Gb/s NRZ signal, and the corresponding time delay is about 45 ps. The maximal delay-times with error-free operation are 35 ps, 51 ps and 81.5 ps for 10-Gb/s NRZ, PSBT and DPSK signals, respectively. The best delay performance of the DPSK signal is attributed to the format characteristics and the SBS based direct-demodulation technique.

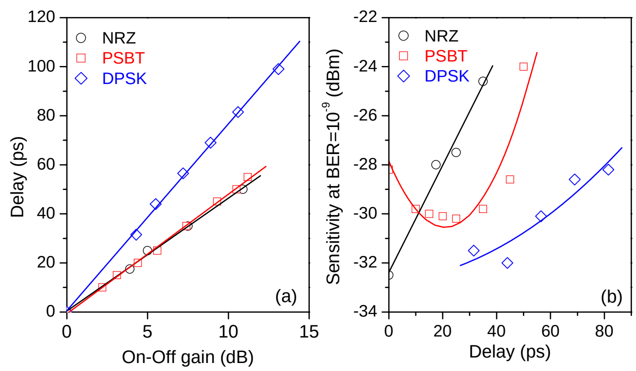

Fig. 8. (a) Delay versus the signal gain and (b) sensitivity versus the delay for 10-Gb/s NRZ, PSBT and DPSK signals.

5. Conclusion

In this paper, we have analyzed the signal distortions of the SBS-based slow light, and presented solutions to minimize them for improving the signal quality after delay. Then we have investigated the delay performances of 10-Gb/s signals with different modulation formats, i.e. NRZ, PSBT and DPSK. By suppressing the Rayleigh backscattering noise and using a super-Gaussian noise modulation of the Brillouin pump, the error-free slow-light operation of a 10-Gb/s NRZ signal has been obtained for the first time. The maximal achieved delay-time is 35 ps. Furthermore, by using PSBT modulation format which allows high spectral efficiency and strong dispersion-tolerance, the system performance of a SBS based slow-light delay line is improved compared with the NRZ case. A negative power penalty at BER = 10^{-9} versus the time delay has been obtained (i.e. -2 dB for 25 ps delay-time), which is the first demonstration of slow-light delay with negative power penalty. Error-free operation can be achieved for a delay-time up to 51 ps, and the corresponding power penalty is only 4 dB. Finally, we used a Gaussian-shaped SBS gain to simultaneously demodulate and delay a 10-Gb/s DPSK signal. The maximal error-free time delay is as high as 81.5 ps, which is attributed to the direct-demodulation technique and the advantages of the DPSK format, i.e. high spectral efficiency, strong dispersion- and noise-tolerance. The results obtained in this paper provide possible solutions to practical system applications such as packet synchronization by using the SBS-based slow light.