# SBS based Slow-Light Performance Comparison of 10-Gb/s NRZ, PSBT and DPSK Signals

Lilin Yi <sup>a,b</sup>, Yves Jaouën<sup>a</sup>, Weisheng Hu<sup>b</sup>, Yikai Su<sup>b</sup>, Philippe Gallion<sup>a</sup> <sup>a</sup>GET/Telecom Paris, CNRS UMR5141, 46 rue Barrault, 75634 Paris, France. Email: lilin.yi@enst.fr <sup>b</sup>SKL of AOCSN, Shanghai Jiao Tong University, 800 Dongchuan Rd, Shanghai 200240, China

## 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). By directly modulating the pump laser diode (LD) using current noise source, the SBS gain bandwidth and profile can be simply controlled by the peak-to-peak value and power density distribution of the current noise. Super-Gaussian noise modulation of the Brillouin pump LD allows a flat-top and sharp-edge SBS gain spectrum, which can reduce slow-light induced distortion in case of 10-Gb/s NRZ and PSBT signals. For the 10-Gb/s NRZ signal, the error-free slow-light operation has been achieved for the fist time and 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 owing to its high spectral efficiency and strong dispersion tolerance. The maximal delay of 51 ps with error-free operation has been achieved. Furthermore, 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.

**Keywords:** Slow light, stimulated Brillouin scattering (SBS), modulation format, non-return-to-zero (NRZ), phase-shaped binary transmission (PSBT), differential phase-shifted-keying (DPSK), demodulation

## **1. INTRODUCTION**

Slow light, referring to slowing down the group velocity of light by manipulating dispersion of media, has attracted extensive interest owing to its potential applications from quantum computing to optical communications, which could enable the implementation of the optical memory or buffer [1]. In principle, any signal falling into an optical resonance in media will experiences strong dispersion so as to induce slow light. Therefore the key point for slow light is to find a narrowband gain or absorption peak in optical media. Among all proposed techniques, slow-light mechanism based on Stimulated Brillouin Scattering (SBS) in optical fiber has achieved much attention [2-11]. 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 [6-7]; (iii) minimizing the signal distortions to improve the signal quality after delay [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  $\sim 10$  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 evaluate the delay and system performances of 10-Gb/s signals in SBS based slow-light delay line in terms of non-return-to-zero (NRZ), phase-shaped-binary-transmission (PSBT) and DPSK modulation formats. 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

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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<sup>-9</sup>) slow-light operation for 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 dispersiontolerance [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. SBS GAIN-SHAPED SCHEMES



Fig. 1 The output power and wavelength of the laser diode vary with the injection current.

For controlling the delay of 10-Gb/s signals, it is necessary to enhance the SBS gain bandwidth up to ~10 GHz. We broaden the SBS gain bandwidth by direct modulating the Brillouin pump LD using a noise source as Ref. 4 and 5. Under the direct modulation condition, the output of a LD has large chirp, which means the output wavelength variation with the injection current. Figure 1 shows the output power and wavelength of the LD variation with the injection current exceeds the threshold of the LD, the output power quickly increases with the current and gets to saturation when the injection current is very strong. However, the output wavelength always linearly increases with the injection current because of the refractive index variation of the LD. Therefore the peak-to-peak value and the power density distribution of the driven current can determine the spectral bandwidth and profile of the output laser. Based on the characteristics of the LD, if we use a Gaussian nose source to directly modulate the LD, the corresponding output spectrum is also with Gaussian-distribution and the spectral bandwidth can be tuned by varying the peak-to-peak voltage of the Gaussian noise source.

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 becomes narrower, 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, so the SBS gain is higher for the same pump power compared with the Gaussian-shaped case.

Regarding that the super-Gaussian SBS gain shape can reduce the SBS filtering effect, we further explain it as follows. Fig. 2(a) shows the pump spectra of Gaussian and super-Gaussian cases at the same 3-dB bandwidth of 10-GHz and same total power of 19dBm. The peak power of super-Gaussian case is a little higher than that in the Gaussian case. The corresponding SBS gain spectra at different pump power levels are shown in Fig. 2 (b) and (c). When the pump spectrum is Gaussian-shaped, the corresponding SBS gain is also Gaussian-shaped, and the 3-dB gain bandwidth is decreased from 5.8 GHz to 4.1 GHz when the pump power increases from 19 dBm to 21dBm. The narrow SBS gain bandwidth filters most of the frequency components of the signal so as to induce data pattern-dependent distortion. However, for the super-Gaussian pump case, owing to the flat-top of the pump spectrum, the SBS gain bandwidth slowly decreases with the increase of the pump power. The corresponding 3-dB gain bandwidths are 8.2 GHz and 7.5 GHz for the pump power of 19 dBm and 21 dBm, respectively. Therefore the SBS gain filtering effect can be strongly reduced compared with the Gaussian pump case. What's more, in the super-Gaussian pump case, because the pump power is mostly distributed at the centre of the pump spectrum, the corresponding SBS gain is also higher than that in the Gaussian pump case, as shown in Fig. 2 (b) and (c).



Fig. 2 (a) The simulated Gaussian and super-Gaussian pump spectra with the same bandwidth and total power. (b) The corresponding SBS gain spectra at 19-dBm pump power. (c) The corresponding SBS gain spectra at 21-dBm pump power.



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

To realize the super-Gaussian pump spectrum, we use 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 Fig. 3 (a) and (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. When the Gaussian noise is amplified to saturation regime, the Gaussian noise becomes a super-Gaussian one after the saturated amplification. We can choose the working

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. 4 (a) The output optical spectra of the LD with Gaussian and Super-Gaussian noise modulation. (b) The SBS gain spectra for Gaussian and Super-Gaussian noise pump modulation at a 23-dBm pump power.

Figure 4 (a) shows the pump spectra in case of Gaussian and super-Gaussian noise modulation measured by coherent heterodyne technique. 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 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 use 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, the Gaussian-shaped filter is preferable for direct DPSK demodulation [13, 14] because its spectral function is very similar with that of the 1-bit-delay Mach-Zehnder interferometer in low frequencies. We propose to use the Gaussian-shaped pump to generate a Gaussian-shaped SBS gain so as to simultaneously demodulate and delay the DPSK signal [15]. In this case, the pump spectral width is set at 8 GHz and the corresponding SBS gain bandwidth is about 6.5 GHz for 18-dBm pump power.

# **3. EXPERIMENT**

Figure 5 depicts the experimental set-up. The signal 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<sup>th</sup> order Bessel filter with a ~2.7-GHz cut-off frequency [16], subsequently amplifying the voltage of the data to  $2V_{\pi}$  and adjusting the MZM bias voltage at transmission nulling point. In this experiment, a 2<sup>7</sup>-1 word length sequence is used for BER measurements because the bandwidth (~3GHz) of our used PSBT electrical filter is non-optimal and the driver voltage does not get  $2V_{\pi}$  [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. 5 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 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 at 5 dBm, thus the Rayleigh backscattered power of the broadband pump is  $\sim$ 20dB lower than the output signal power, as

shown in Fig. 6 (a). Here the spectra of the 10-Gb/s DPSK signal are plotted as an example, but similar results have been obtained for the 10-Gb/s NRZ and PSBT signals. In this experiment, we used a ~0.1-nm bandwidth flat-top fiber Bragg grating (FBG) to minimize the coherent crosstalk. The filtered optical spectra are shown in Fig. 6(b). Note that the PSBT signal has bad noise-tolerance due to the poor eye-opening, so it is necessary to use an optical narrow band filter for suppressing the noise so as to achieve good signal quality.



Fig. 6 The optical spectra of 10-Gb/s DPSK signals amplified by SBS before FBG (a) and after FBG (b).

Finally the signal is sent into a photoreceiver, which 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  $10^{-9}$ .

## 4. RESULTS AND DISCUSSION

Firstly, we demonstrate error-free slow-light operation of the 10-Gb/s NRZ signal. Figure 7 shows the eye diagram with corresponding delay time, BER and pulse pattern evolutions of the 10-Gb/s NRZ signal for different pump power levels. When the pump power is off, the signal is mainly distorted by the narrow band FBG. Compared to the BtB case, the power penalty is about 1.5dB. After turning on the pump power, the stimulated SBS gain induces time delay. The larger the pump power is, the higher the gain value and the delay-time are. The single "1" pulse and consecutive "1" pulses experience different signal gain [3], corresponding to different time delays; therefore it is difficult to define the delay by comparing the temporal positions of the pulses. In the following measurements, we define the delay-time by comparing the maximal eye-opening point at different pump power levels. When the input signals are PRBS data, the measured time delay using this technique is more reliable. The obtained delay-times are 17, 35 and 50 ps for 19, 21 and 22-dBm pump powers, respectively. The gain bandwidth is reduced when the pump power enhances, 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. But the super-Gaussian shaped SBS gain slows down the bandwidth reducing 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 for 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. 7 Delay-time, eye diagram, BER and pulse pattern evolution with pump power for 10-Gb/s NRZ signal.

It has been introduced that PSBT modulation format allows high spectral efficiency and strong dispersion-tolerance. We propose to use the PSBT format to increase the tolerance to the SBS filtering effect and the dispersion-distortion so as to further improve the signal quality. Figure 8 shows the delay, eye diagram, BER and pulse pattern evolutions of the 10-Gb/s PSBT signal for different pump power levels. Without pump power, 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. Note that we did not optimize the signal polarization state after changing the transmitter, which results in the lower SBS pump efficiency than that in NRZ case, which means more pump power is required for a same signal gain. 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 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 can be solved by using an enhanced-PSBT modulation format [19] to achieve better delay performance.



Fig. 8 Delay-time, eye diagram, BER and pulse pattern evolutions with pump power for the 10-Gb/s PSBT signal.



Fig. 9 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-Zehnder 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 9 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 in Fig. 10. In all the cases, the delay linearly increases with the on-off gain. For all the cases, the delay linearly increases with the on-off gain. 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]. 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. 10 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.

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