Observation of large 10-Gb/s SBS slow light delay with low distortion using an optimized gain profile

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Abstract: An optimum SBS gain profile is designed to achieve better slow-light performance. It consists of a nearly flat-top profile with sharp edges. Tunable delays up to 3 pulse widths for 100-ps-long input pulses, corresponding to 10 Gb/s data rates, are found while keeping an output-input pulse-width ratio below 1.8. Bit-error-rate (BER) measurements performed for a non-return-to-zero modulation format demonstrates 28 ps of delay under error-free operation.

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References and links

1. Introduction

Stimulated Brillouin scattering (SBS) in standard optical telecommunication fibers has proven effective in realizing slow light at room temperature and thus has become a very interesting candidate for all-optical processing in telecommunications networks [1]-[5]. In SBS slow light, the delay experienced by the pulses depends on the SBS gain, which is proportional to the pump power and hence can be adjusted in real time.

The main drawback of SBS slow light for use in modern communication systems is the inherently small bandwidth of the gain for a monochromatic pump beam, which is \( \sim 40 \text{ MHz} \) in standard optical fibers. This narrow bandwidth translates into large distortion of the delayed pulses for data rates above \( \sim 40 \text{ Mb/s} \). Thus, broadening the bandwidth to allow transmission of pulses at typical telecommunication data rates of 10 Gb/s without distortion is required.

Stenner et al. [6] showed that the frequency-dependent gain (the so-called filtering effect) is the dominant cause for distortion. Furthermore, they showed that distortion can be reduced using two gain lines, which flatten the gain over a finite bandwidth. Different studies have followed this approach to minimize distortion while maximizing the achievable fractional delay. Schneider et al. [7] showed a \( \sim 30\% \) reduction of the pulse broadening using three different Brillouin gain lines in a two-stage-delay-line. Shi et al. [8] showed an increase by a factor of two in the fractional delay at three times larger modulation bandwidth for an optimized triple-gain-line medium as compared with a simple-gain-line. More recently Sakamoto et al. [9] used 20 discrete line pump spectra to suppress the broadening factor (defined as the output-to-input pulse-width ratio) to 1.19 for 5.44-ns-long pulses in a two-stage-delay-line. However, all of these approaches are based on the use of a multiple pump spectral lines by means of an external phase or intensity modulator, which limits the maximum bandwidth achievable to a hundred of MHz with present-day commercially-available modulators. The maximum value obtained up to now using this approach is \( \sim 330 \text{ MHz} \) [10].

Larger bandwidths have been obtained by directly modulating the injection current of the pump laser. Herr´ aez et al. [4] were the first to demonstrate this effect, broadening a 35 MHz SBS gain line to 325 MHz. Zhu et al. [3] created a 12.6-GHz-wide Gaussian-shaped SBS gain profile by modulating the pump laser current with a Gaussian noise source. They obtained a delay of 47 ps for 75-ps-long input pulses. However, frequency-dependent gain is still present for the Gaussian profile, which causes pulse distortion for large delays. Recently, direct modulation of the pump laser current by a super-Gaussian noise source has been performed by Yi et al. [11]. They showed that the filtering effect is reduced with this scheme because the edges of the gain profile are sharpened. Their experiments showed a maximum time delay of 35 ps for a 10 Gb/s NRZ signal with error-free operation.

Optimization of a broadband gain profile has been conducted theoretically by Pant et al. [12]
to determine the SBS gain profile that minimizes distortion under the constraint of a maximum available pump power. They found that the optimum profile is essentially a flat-top gain spectrum with sharp edges, surrounded by narrow absorption features for bandwidths below 7 GHz. Above 7 GHz, the absorption features are no longer needed. Their calculations reveal an increase in delay by a factor of 1.3 in comparison to a Gaussian-shaped gain profile for a fixed pump power and allowed pulse distortion. More recently, Schneider [13] obtained essentially the same results, showing an enhancement of the time delay when two narrow losses are superimposed at the wings of the gain. Moreover, Tanemura et al. [14] and Zadok et al. [15] also designed flat-top SBS gain profiles to obtain low-distortion narrow-band filters for microwave photonic applications with 3-dB bandwidths up to 2.5 GHz.

Here, we develop a systematic procedure to minimize distortion while maximizing pulse delay for data rates of 10 Gb/s, which has not been addressed by other studies to the best of our knowledge. We approach this task by generating an optimum broadband SBS gain profile, which, according to the discussion above, consists of a nearly rectangular spectral profile. The procedure described in this work can be easily generalized to any DFB laser used as the pump in SBS slow-light experiments.

In order to fulfill this goal, we directly modulate the laser injection current with an optimized waveform. To obtain the optimum profile, we start with a waveform that accounts for the transient behavior of the instantaneous pump laser frequency, following the work of Shalom et al. [16]. This approach has also been used by Zadok et al. [17] to design a pump spectrum with sharp edges. They showed an increase in the delay by a factor of 30% for 270-ps-long pulses, compared with random modulation of the pump laser injection current. However, the gain profiles they obtained deviate substantially from a flat-top profile. In our approach, we measure the transient behavior of the pump laser frequency for a step change in the injection current and use this information as the input to an iterative scheme that allows us to obtain an optimum spectral profile.

The paper is organized as follows. Section I describes the procedure to obtain the flat-top SBS gain profile, and accounts for the results. Section II describes the delay performance for 100-ps-long pulses and quantifies the pulse distortion by the output-to-input pulse-width ratio. Section III shows the BER measurements for a 10 Gb/s non-return-to-zero (NRZ) data format and the maximum delay achieved with error-free operation. Finally, Section IV summarizes our main conclusions.

2. Experimental design of the optimal SBS gain profile

It is well known that modulating the injection current of DFB lasers causes the frequency of the output light to change, which has been used extensively to broaden the pump spectrum [18]. The resultant SBS gain spectrum is then given by the convolution of the pump spectrum with the complex gain of the medium [19], which has a Lorentzian profile. To design an optimum broadband SBS gain profile, we must generate a suitable pump spectrum and hence tailor the injection current waveform.

The frequency chirp of the laser beam under current modulation has two main contributions, as described in Ref. [16]. The first is called adiabatic chirp, which is associated with the effect of the injection current on the index of refraction of the laser cavity. It follows almost instantaneously the current variation and increases the laser frequency for an increasing current. The second contribution is a thermal chirp. A sudden increase of the injection current is followed by a slower temperature increase, which modifies the index of refraction and hence the frequency. This frequency variation has an exponential time dependence under a step change of current and is opposite to the adiabatic chirp. The time constants that describe this frequency change
depend on the thermal constants of the different layers of the laser, and can be as fast as a few nanoseconds [16]. Therefore, even for fast modulation of the injection current, an analysis of these time constants and the adiabatic chirp is necessary to obtain a precise design of the laser spectrum.

To obtain an optimized waveform for modulating the pump laser current, we generalize the semi-empirical model introduced in Ref. [16]. In particular, we assume that the change of the instantaneous frequency under a current variation is given by

\[ \nu(t) - \nu_0 = \alpha [i(t) - i_0]^2 + \beta [i(t) - i_0] - h_T \otimes [i(t) - i_0] . \]  

(1)

Here, the first two terms on the right-hand-side of Eq. 1 account for the adiabatic chirp, where we have included a nonlinear contribution with coefficient \( \alpha \). We will show below that this contribution must be taken into account to design an optimum slow-light channel at bandwidths exceeding a few GHz. The coefficient \( \beta \) measures the usual linear adiabatic chirp, as described in Ref. [16]. Both \( \alpha \) and \( \beta \) are parameters describing a particular DFB laser, while \( \nu_0 \) is the reference frequency value for a background injection current \( i_0 \). The modulation waveform of the current is given by \( i(t) \).

We measure the frequency chirp by beating the modulated pump laser beam with a second unmodulated beam generated by an auxiliary laser. If \( i(t) \) takes the form of a step function, the adiabatic chirp gives the stationary value \( \Delta \nu_{st} \) of the frequency shift. Figure 1 shows \( \Delta \nu_{st} \) as a function of the step amplitude \( i - i_0 \) for a pump laser used in one part of our experiments (Sumitomo Electric, model STL4416), where a substantial quadratic dependence is visible. By fitting the adiabatic-chirp part of Eq. 1 to the data, we find \( \alpha = 0.0013 \, \text{GHz/mA}^2 \) and \( \beta = 0.36 \, \text{GHz/mA} \).

The thermal chirp is described in Eq. 1 by the convolution between the injection current with the impulse response of the thermal chirp \( h_T \), which is given by

\[ h_T = \sum a_n e^{-t/\tau_n} . \]  

(2)

To obtain the values of the parameters \( a_n \) and \( \tau_n \) we measure the total chirp produced by a step change in \( i(t) \) and fit the temporal evolution of the beat frequency to a sum of exponentials. We find that the dominant contributions to the thermal chirp can be captured using three time
constants, whose values are given in Table 1. Note that the dominant term has a rather fast time constant of only 7.5 ns.

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<tr>
<td></td>
<td>$\tau_j$ (ns)</td>
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<td>46</td>
<td>190</td>
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Table 1. Time constants and coefficients of the impulse response of the thermal chirp.

To optimize the SBS gain spectrum, we modulate initially the injection current with a triangular function with amplitude $\Delta i_{\text{max}} = 50$ mA (see Fig. 2(a)), generated by an arbitrary waveform generator (Tektronix, AFG3251). There is a great latitude in choosing the modulation period $T$. It must be much shorter than the transit time of light through the optical fiber that serves as the slow light medium (10 $\mu$s in our case). On the other hand, longer $T$ produces a broader spectrum for a given injection current. We choose $T = 2.5$ $\mu$s.

Figure 2(b) shows the measured SBS gain profile using the triangular modulation waveform with $i_0 = 100$ mA. It is seen clearly that the resultant gain profile is asymmetric. To explain this behavior, we calculate the time derivative of the adiabatic frequency chirp, which indicates, in first approximation, the time spent at each frequency in one period. A nearly constant value of this derivative is required to achieve a flat spectrum profile. For the sake of simplicity, we focus on the semi-period $[T/4, 3T/4]$ as the frequency goes through the whole range of possible values. The value of the derivative is $d\Delta v(t)/dt = -(4/T)\Delta i_{\text{max}}[2\alpha\Delta i_{\text{max}}(2-4t/T)+\beta]$. This expression clearly shows a linear dependence on time due to the presence of the nonlinear adiabatic chirp, which causes the asymmetry shown in the gain profile. The maximum variation
of this term is $16\alpha\Delta\nu_{\text{max}}^2/T$, which is almost 50% of the maximum value of $d\Delta\nu(t)/dt$ for these laser parameters. This result shows that the nonlinear term of the adiabatic chirp is affecting substantially the slow light performance at large bandwidths where high current modulation amplitudes are used.

Correcting this asymmetry can be accomplished by adding a small quadratic term to the triangular waveform, which results in the SBS gain lineshape shown in Fig. 2(d). The modulation function is then given by

$$i(t) = \Delta i_{\text{max}} \begin{cases} at^2 + (4/T - aT/4)t & \text{if } t \leq T/4 \\ at^2 - (4/T + a3T/4)t + 2 + 2aT^2/4^2 & \text{if } T/4 < t \leq 3T/4 \\ at^2 + (4/T - a9T/4)t + 5aT^2/4 - 4 & \text{if } 3T/4 < t \leq T. \end{cases} \tag{3}$$

The optimum value of the quadratic coefficient $a$ can be obtained by applying an iterative scheme. First, we estimate a value of $a$ based on the knowledge of the adiabatic chirp coefficient. With the modulation waveform given by Eq. 3, the time derivative of the adiabatic frequency chirp can be approximated by a parabolic dependence on time

$$\frac{d\Delta\nu(t)}{dt} \simeq -\frac{12\alpha a\Delta\nu_{\text{max}}^2}{T^2} t^2 + \Delta\nu_{\text{max}} \left( \frac{16\alpha\Delta\nu_{\text{max}}}{T^2} + a\beta + 10a\Delta\nu_{\text{max}}\alpha \right) t$$

$$- \Delta\nu_{\text{max}} \left[ \beta \left( \frac{4}{T} + \frac{3aT}{4} \right) + 16\alpha\Delta\nu_{\text{max}} \left( \frac{1}{T} + \frac{aT}{4} \right) \right], \tag{4}$$

where quadratic terms in $a$ have been neglected. To minimize the variation of this derivative, the center of the parabola is chosen to be at the center of the time interval, i.e. $t = T/2$. This condition allows us to obtain the estimated $a \simeq -(16/T^2)\alpha\Delta\nu_{\text{max}}/(\beta - 2\alpha\Delta\nu_{\text{max}})$, which gives $a \simeq -3.4 \times 10^{-7}$ ns$^{-2}$. Starting from this value, we make small changes in $a$ while the resultant gain profile is measured for each value. We then compare this profile to an optimum flat-top laser parameters. This result shows that the nonlinear term of the adiabatic chirp is affecting substantially the slow light performance at large bandwidths where high current modulation amplitudes are used.

Previous work on obtaining a low-distortion SBS gain profile has been done by Yi et al. [11] at large bandwidth. Super-Gaussian noise modulation was used in their work to obtain a super-Gaussian gain spectrum with sharper edges. They showed that the maximum delay under free-error operation is increased with this scheme. However, this approach gives a gain spectrum that is closer to a Gaussian than a super-Gaussian profile for our Sumitomo laser. We find that
this is due to the relatively slow time constants of the thermal chirp. Simulations carried out using Eq. 1 with faster thermal time constants that for the Sumitomo laser predict a spectrum that is closer to a super-Gaussian function. Therefore, knowledge of the time constants of the frequency chirp is necessary even when a noise distribution is used to modulate the injection current. Besides that, as mentioned above, slow modulation with the optimum waveform shows a larger frequency excursion for a given $\Delta i_{\text{max}}$ than fast modulation with noise.

3. Slow light performance

The experimental setup is depicted in Fig. 3. We use a 2-km-long Highly Nonlinear Fiber (OFS) that has a smaller effective modal area and thus a higher SBS gain for a given input power in comparison to a standard single-mode fiber. A high-power Erbium-doped fiber amplifier (IPG, EAD-1K-C) provides enough pump power to obtain appreciable gain. Two identical DFB lasers (Sumitomo Electric, STL4416) are used as the pump and the probe lasers and the necessary frequency tuning is achieved by controlling the temperature of each laser. The pump spectrum is broadened by injecting the optimized waveform previously described into the pump-laser drive current using a 50 $\Omega$-impedance bias-T. The signal pulses are created by amplitude modulating the output of the probe laser with a Mach-Zehnder modulator, which is driven by a pattern generator. The data pulses are measured with a 50-GHz bandwidth digital sampling oscilloscope.

The delay performance is improved with respect to the Gaussian gain profile, as predicted in Ref. [12]. Figure 4(a) shows the experimental fractional delay, defined as the ratio between the time delay and the full width at half maximum (FWHM) of the input pulses. A maximum value of 3 is achieved for a single pulse with an input pulse width of 100 ps and a pump power of $\sim$440 mW. Figure 4(b) shows the output-to-input pulse-width ratio, which remains below 1.8 for the range of input pump powers used. The simulated results, obtained using the undepleted pump approximation [12], can be seen in the same graphs for the simulated optimal profile, showing a good agreement with the experimental results. For the sake of comparison, we also show the simulated results with a Gaussian gain profile of the same FWHM and total pump power as
the simulated optimum gain profile. The experimental results for the fractional delay shows an improvement of 1.3 times the simulated results for a Gaussian gain profile. The distortion for the optimum gain profile is also reduced by a factor of 1.2 at high gains with respect to the Gaussian profile.

Lower broadening factors may be needed for application in telecommunication transmission at 10 Gb/s. This could be achieved by increasing the pump spectrum bandwidth up to 10 GHz. Unfortunately, the laser described in the previous section does not reach this bandwidth for the available injection current $\Delta i_{\text{max}}$. In order to fulfill this goal, we use another DFB laser as the pump laser (Fitel, FOL15DCWC-A82-19340-B). The previous procedure is repeated to obtain the optimum modulation waveform for this laser. In this case, the adiabatic chirp coefficients are $\alpha = 0.0012 \text{ GHz/mA}^2$ and $\beta = 0.35 \text{ GHz/mA}$, which are similar to the Sumitomo laser parameters. The coefficients and time constants of the thermal chirp are shown in Table 2. We choose the same period $T = 2.5 \mu s$ for the modulation waveform, and the new parameters for the optimum waveform are $a = 1.5 \cdot 10^{-7} \text{ ns}^{-2}$, $d_2 = 0.12$, $d_3 = 0.09$, and $i_0 = 200 \text{ mA}$. Figure 5(a) shows the flat-top gain profile obtained with this pump laser with a bandwidth of 9.2 GHz.

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<td>$a_j$ (GHz/mA)</td>
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<td>0.5</td>
<td>0.3</td>
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<tr>
<td>$\tau_j$ (ns)</td>
<td>16</td>
<td>52</td>
<td>200</td>
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Table 2. Time constants and coefficients of the impulse response of the thermal chirp for the Fitel laser.

Using this broader-bandwidth flat-top gain profile, the distortion can be reduced. However, the delay is also reduced because the SBS gain is lower at this broader bandwidth at a given laser power. Figure 5(a) shows the delay as a function of the pump power, while Fig. 5(b) shows the measured output-to-input width ratio. A delay of 2.1 pulses with a broadening factor of 1.3 has been achieved.
4. BER measurements

To assess the behavior of an optimum slow-light profile communication applications, we propagate a high data-rate stream of pulses through our system. We measure the bit-error-rate (BER) performance for a $2^7-1$ 10-Gb/s NRZ pseudo-random bit sequence (PRBS) and measure the maximum delay achieved with error-free operation ($BER < 10^{-9}$). The MZM (EOspace, 12 Gb/s) is driven by a PRBS generated by a Pattern Generator (HP 70004A) to create the optical input sequence. An optical modulator driver (JDS, H301-1110) is used to increase the amplitude of the modulation. We use the 9.2-GHz gain profile shown in Fig. 5(a). The power reaching the photodetector (NewFocus, 1544B, 1 mW maximum input power) is kept constant in all the measurements using a variable attenuator placed before the receiver. An Error Performance Analyser (Agilent, 70843B, 0.1-12 Gb/s) is used to measure the BER. With this device, we were not able to directly measure the slow-light delay of the data stream. Therefore, we use a 8-GHz oscilloscope (Agilent, DSO80804B) to measure the delay. Although the limited bandwidth of the oscilloscope distorts the pseudo-random bit sequence, we find that the temporal position of the maximum eye opening, and thus the delay, can be determined accurately as verified by numerical simulations of our system.

BER performance is mainly degraded by the noise introduced by the Raleigh backscattering and by the filtering effect of the limited gain bandwidth. We use an input signal power of up to 12 dBm to reduce the former cause of degradation while the flat top SBS gain profile reduces the latter while improving the delay, as discussed in Sec. 2. Figure 6 shows the eye diagram for the output and input sequences for an input pump power of 160 mW, which corresponds to a maximum SBS gain of 13 dB. The maximum delay under free-error operation is 28 ps which was achieved for this input pump power. This result is below the 35 ps delay time achieved with
error-free operation by Yi et al. in [11].

In our experiment, we believe that the optical input sequence is already somewhat distorted (just below a BER of $10^{-12}$, the limit of the BER analyzer. Thus, relatively low distortion by the slow-light channel raises the error above the error-free threshold. In addition, Raleigh back-scattering of the pump light may contribute to the noise seen in Fig. 6, which degrades the BER. This scattered light could be partially removed using a spectral filter before the photodetector. Finally, we note that other modulation formats, such as PSBT or DPSK, have been shown to provide better performance due to higher dispersion tolerance and spectral efficiency [11, 20].

5. Conclusions

We have obtained an optimized SBS gain profile to achieve large delay of 10 Gb/s signals while minimizing the pulse distortion. To obtain the profile, measurements of the instantaneous frequency evolution of the pump laser are performed. These measurements are used to design an optimal waveform to modulate the injection current of the pump laser to obtain a flat top gain profile. Delay and distortion performance are measured showing delays up to 3 times the input pulse width while keeping the output-to-input pulse-width ratio below 1.8, or reaching fractional delays up to 2.1 with of 1.3 when a broader gain profile of 9.2 GHz is used. Bit-error-rate measurements of an amplitude-modulated NRZ signal show error-free operation up to a delay time of 28 ps.

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