Comparison of delay enhancement mechanisms for SBS-based slow light systems

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Abstract: We compare two simple mechanisms for the enhancement of the time delay in slow light systems. Both are based on the superposition of the Brillouin gain with additional loss. As we will show in theory and experiment if two losses are placed at the wings of a SBS gain, contrary to other methods, the loss power increases the time delay. This leads to higher delay times at lower optical powers and to an increase of the zero gain delay of more than 50%. With this method we achieved a time delay of more than 120ns for pulses with a temporal width of 30ns. To the best of our knowledge, this is the highest time delay in just one fiber spool. Beside the enhancement of the time delay the method could have the potential to decrease the pulse distortions for high bit rate signals.

OCIS codes: (999.9999) Slow light; (290.5900) Scattering, stimulated Brillouin; (060.4370) Nonlinear optics, fibers

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1. Introduction

The alteration of the propagation velocity of light pulses by light has attracted much recent interest since – beside a fundamental physical point of view – it offers the possibility to develop practical devices. Optical delay lines, optical buffers and optical equalizers, are very important in the field of telecommunications, for instance. But, slow and fast light can enable several other applications including optical signal processing, radio frequency photonic, nonlinear optics, and time resolved spectroscopy [1]. Many different mechanisms and material systems can be used for the control of the pulse velocity. Among these are ultracold [2] and hot [3] atomic gases, Rubidium vapor [4], semiconductor nanostructures [1], quantum well [5] and quantum dot [6] systems and photonic crystal waveguides [7]. However, since optical fibers can be integrated seamlessly into existing systems, especially nonlinear effects in optical fibers are of special interest in the telecommunications area. Among these the exploitation of the group velocity alteration due to the nonlinear effect of stimulated Brillouin scattering (SBS) is very important [8]. This has several reasons; a) off the shelf telecom equipment can be used, b) SBS works in the fibers entire transparency range and in all types of fibers, c) a relatively large pulse delay requires only small pump powers.

However, the SBS has three severe disadvantages; a) for a pump wavelength of 1550nm the natural Brillouin gain has a bandwidth of only 30MHz in standard single mode fibers (SSMF), b) the maximum delay time is restricted by the accompanied amplification of the pulse, c) since the delay mechanism is a dispersion, the pulses experience a distortion. A modulation of the pump laser can increase the bandwidth to around two times the Brillouin shift [9], an incorporation of an additional pump laser can enhance the bandwidth further [10]. On the other hand, the modulation leads to smaller delay times. The maximum pulse delay is restricted by the pump depletion due to the inherent amplification process. In recent experiments the pulse delay was decoupled from the amplification [11, 12] which can lead to very high pulse delays of around 100ns [13] in just one fiber loop. But this technique requires very high pump powers. Here we will compare this method with a new one which alters the slope of the gain by a superposition of two loss lines at its wings. With this method we achieved higher delay times at lower optical powers and the zero gain delay will be increased to more than 50%. Pulses with a temporal width of 30ns were delayed to more than 120ns which is – to the best of our knowledge – the highest time delay in just one fiber spool. Beside the enhancement of the time delay we have found hints that the method can decrease the pulse distortions.

2. Theory

In a SBS based slow light system a strong pump wave with a frequency ω_{P1} generates a gain bandwidth at a center frequency $\omega_0 = \omega_{P1} - \omega_B$ for a counter propagating wave via Brillouin scattering in the fiber (Stokes amplification), see Fig. 1(a) top. The frequency shift between the generated gain and the pump wave is the so called Brillouin shift ω_B which is around 2π x 11GHz in SSMF. The gain has a Lorentzian shape and its FWHM bandwidth 2γ depends on environmental conditions like temperature and strain and on the fiber type [14]. In SSMF it is around 2π x 30MHz but it can easily be enhanced by a modulation of the pump wave.

For a Lorentzian gain line the complex transfer function can be found from the wavenumber $k(\omega)$ and can be written as [15]

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$$H(\omega)=\exp(ik(\omega)z)=\exp\left(izn_0\frac{\omega}{c}+\frac{ig_0\gamma}{(\omega-\omega_0)+i\gamma}\right) \tag{1}$$

where n_0 is the linear refractive index and z the length of the medium, c is the velocity of light in a vacuum and g_0/z is the line center Brillouin gain coefficient. The amount of Eq. (1)

$$\left|H(\omega)\right|=\exp\left(\frac{g_0\gamma^2}{(\omega-\omega_0)^2+\gamma^2}\right) \tag{2}$$

is responsible for the amplification of the pulse (Fig. 1(a), middle), whereas the derivation of the phase of Eq. (1) leads to the group index change (Fig. 1(a), bottom) and the pulse delay.

$$\Delta t_D=\frac{z}{c}(n_0-1)+g_0\gamma\frac{\gamma^2-(\omega-\omega_0)^2}{\left[(\omega-\omega_0)^2+\gamma^2\right]^2} \tag{3}$$

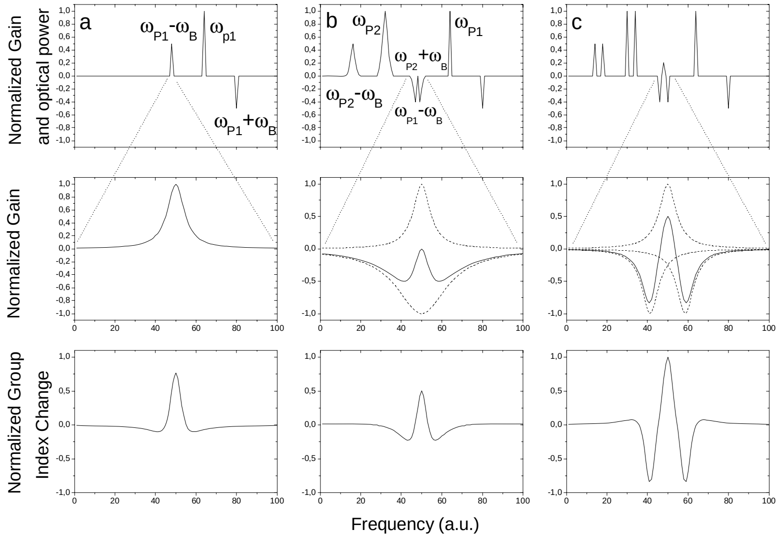

Fig. 1. Normalized gain and power for the pump waves (top), normalized gain at ω_0 (middle) and group index change (bottom) for a gain produced by just one pump laser (a), for a gain superimposed with a broad loss produced by an additional direct modulated pump laser (b) and for a gain superimposed with two losses at its wings (c).

In the line center ($\omega = \omega_0$) the Gain is $G = g_0$ and the pulse delay due to SBS is $\Delta t_{\mathrm{DSBS}} = g_0/\gamma$. Therefore, the time delay is always accompanied by a pulse amplification and the maximum time delay is restricted by the saturation of the amplification process. For zero amplification ($g_0 = 0$) the time delay is $\Delta t_{\mathrm{DZA}} = 0$. The maximum time delay is $\Delta t_{\mathrm{Max}} = g_{\mathrm{th}}/\gamma$ with g_{th} as the maximum gain coefficient. This maximum gain coefficient is defined by the pump depletion which depends on many different parameters like the Brillouin bandwidth and on the optical power of the input pulse. But, even for very low input pulse powers the

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maximum gain coefficient is restricted by the threshold of Brillouin scattering. This threshold defines the maximum pump power that can be coupled into the fiber. All additional optical power is scattered back by Brillouin scattering [14].

If a wave with a frequency shift $\omega_{P1} + \omega_B$ propagates in the fiber in an opposite direction to ω_{P1} it acts like a pump wave for the counter propagating wave with the frequency ω_{P1}, i.e. optical power is scattered from this wave to the pump. Therefore, at a frequency around $\omega_{P1} + \omega_B$ the SBS process generates a loss in the fiber (anti-Stokes absorption). If a second pump wave with the frequency $\omega_{P2} = \omega_{P1} - 2\omega_B$ propagates in the fiber the gain from ω_{P1} at $\omega_{P1} - \omega_B$ is superimposed with the loss generated at $\omega_{P2} + \omega_B$, see Fig. 1(b). In principle it is the same behavior like electromagnetically induced transparency [12]. For this configuration the complex transfer function can be written as

$$H(\omega) = \exp\left(k_L + \frac{ig_1\gamma_1}{(\omega-\omega_0)+i\gamma_1} - \frac{ig_2\gamma_2}{(\omega-\omega_0)+i\gamma_2}\right) \tag{4}$$

with $k_L = izn_0\omega/c$, g_1 and g_2 as the coefficients of gain and loss and γ_1 and γ_2 as its half bandwidths. In the line center the over all gain is $G = g_1 - g_2$ and the time delay due to SBS can be written as $\Delta t_{DSBS} = g_1/\gamma_1 - g_2/\gamma_2$. Hence, amplification and delay can be decoupled from each other. The loss compensates the gain but, the time delay will be reduced as well. For zero amplification ($g_1 = g_2 = g$) and $\gamma_2 = n\gamma_1$ the time delay is $\Delta t_{DZA} = \frac{n-1}{n}\frac{g}{\gamma_1}$. Therefore, only if the loss is much broader than the gain the time delay is almost the same as without an additional loss. Equation (4) only holds if the gain and loss spectrum have a Lorentzian distribution. Experimentally the loss is broadened by a direct modulation of the laser diode which results in a Gaussian distribution of the loss spectrum. To simplify the discussion this is neglected here.

However, due to the fact that delay and amplification are decoupled from each other much higher gains g_1 (and therefore time delays) are possible. For the natural Brillouin gain we achieved very high time delays with this method [13]. However, since the loss laser produces not only a loss but at $\omega_{P2} - \omega_B$ a gain, the maximum loss is restricted by the threshold of Brillouin scattering. Furthermore, since the loss is spread over a large spectrum it requires very high optical powers.

If at the wing of a Stokes gain an anti-Stokes loss is introduced the slow light delay arising from the wing of the anti-Stokes resonance enhances the delay at the center of the Stokes resonance [16]. If a gain is superimposed with two losses at its wings the delay can be further enhanced [see Fig. 1(c)]. In this case the complex transfer function is.

$$H(\omega) = \exp\left(k_L + \frac{ig_1\gamma_1}{(\omega-\omega_0)+i\gamma_1} - \frac{ig_2\gamma_2}{\omega-(\omega_0-\delta)+i\gamma_2} - \frac{ig_2\gamma_2}{\omega-(\omega_0+\delta)+i\gamma_2}\right) \tag{5}$$

with 2δ as the frequency separation between the two loss spectra. These two losses can be generated very easy by an amplitude modulation of ω_{P2} with suppressed carrier. The normalized group index change as a function of the frequency separation between the loss spectra can be seen in Fig. 2. If $\delta/\gamma < 1$ the loss reduces the gain drastically and hence, the time delay is smaller as without additional losses. For $\delta/\gamma = 1$ the time delay is the same in both cases. But, if the frequency separation is higher the loss spectra will increase the time delay. This is due to the fact that the time delay is a function of the Brillouin gains slope and

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the additional loss spectra increase its gradient. The maximum time delay can be found at $\delta = \sqrt{3}\gamma$. The enhancement of the time delay depends on the loss power, if it is increased higher time delays can be achieved.

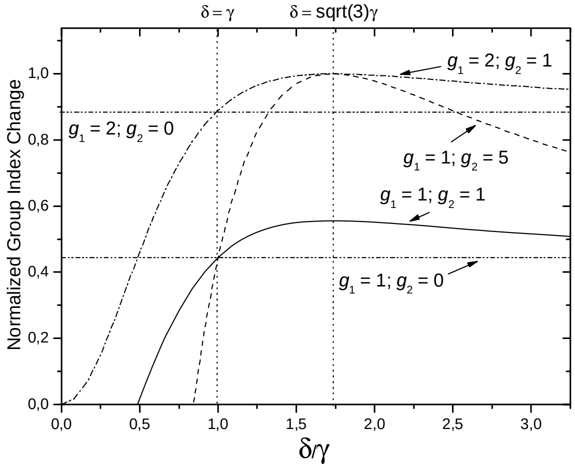

Fig. 2. Normalized group index change as a function of the normalized frequency separation between the loss spectra for different relations between gain (g_1) and loss (g_2), both have the same bandwidth ($\gamma_1 = \gamma_2$).

If all lines have the same Brillouin bandwidth $\gamma_1 = \gamma_2 = \gamma$ and $\delta = \sqrt{3}\gamma$ it follows from Eq. (5) that the over all gain in the line center can be written as $G = g_1 - g_2/2$. In this case the time delay due to SBS is $\Delta t_{DSBS} = (g_1 + 0.25\, g_2)/\gamma$. Hence, delay and amplification are decoupled as well but – contrary to the aforementioned technique – the loss power increases the time delay. For zero amplification ($g_2 = 2g_1$) the time delay is $\Delta t_{DZA} = 1.5g_1/\gamma$. Which corresponds to a more than 50% improvement of the time delay in comparison to the direct superposition of gain and loss. If the separation between the two loss lines is chosen smaller ($\delta = \gamma$) the over all gain is $G = g_1 - g_2$. For zero amplification ($g_2 = g_1$) the time delay is $\Delta t_{DZA} = g_1/\gamma$, which is still an improvement in comparison to the aforementioned method.

The maximum time delay is restricted by the gain at $\omega_{P2} - \omega_B$. Therefore, a further increase of the maximum time delay is possible if an additional, broadened laser line at a frequency $\omega_{P3} = \omega_{P1} - 4\omega_B = \omega_{P2} - 2\omega_B$ is introduced.

For applications like optical buffers in the telecommunications area the natural Brillouin bandwidth is much too low but it can be easily enhanced by a direct or external modulation of the pump laser. In this case the gain has a Gaussian distribution. For broad gain spectra the gain function is given approximately by [16].

$$g(\omega) = g_G \exp\left(-\frac{\omega - \omega_0}{\gamma_G}\right)^2 erfc\left[-i\left(\frac{\omega - \omega_0}{\gamma_G}\right)\right] \tag{6}$$

with g_G as the line center gain and γ_G as the 1/e-bandwidth of the Gaussian distribution, erfc describes the complementary error function. If Eq. (6) is introduced into Eq. (5) the gain and group index change for a superposition of a Gaussian gain with two Lorentzain losses at its wings can be calculated.

As can be seen from Fig. 3, as expected, the losses at the wings increase the group index change drastically and decrease the over all gain. But at the same time, with this method the bandwidth of the group index can be made broad and flat. The broader bandwidth leads to higher delay able data rates and the flat distribution can reduce the distortions since higher order terms of the wavenumber are minimized [15]. The *x*-axis of the group index change in Fig. 3 is normalized to the 1/e-bandwidth of the Gaussian distribution γ_{G}. Hence, with the proposed method a Gaussian distribution of any bandwidth can lead to broader and flatter group index changes. Since the bandwidth of the Gaussian distribution can be made very broad with a direct modulation of the pump laser [9] or the incorporation of additional pumps [10], very high data rates are possible.

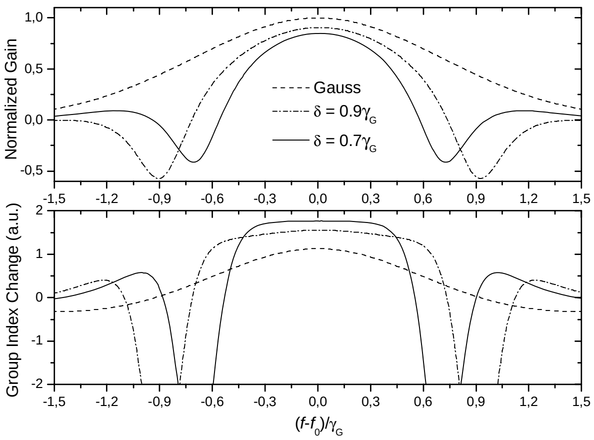

Fig. 3. Normalized gain and group index change for a pure Gaussian Brillouin spectrum (dashed line) and a Gaussian spectrum superimposed with two Brillouin losses at its wings.

3. Experiment

The schematic experimental set up is shown in Fig. 4. Gain and loss are produced by two independent distributed feedback laser diodes (Pump1 = gain; Pump2 = loss) at a wavelength of around 1550nm. Both are shifted in frequency to each other (22GHz) by temperature controlling. The frequency separation corresponds to twice the Brillouin shift in our SSMF. By a direct modulation of the laser current of Pump1 with a noise signal the gain spectrum can be broadened. The same can be done with the loss spectrum generated by Pump2. For the generation of two loss lines Pump2 can be externally modulated by a sinusoidal signal with a Mach-Zehnder modulator which is driven in a suppressed carrier regime. Two times the frequency of the sinusiodal signal defines the separation between the loss lines (2δ). Gain and loss are superimposed via a 3dB coupler and can independently be amplified with two EDFA`s. The pump waves are coupled into a 50km SSMF via a circulator. We used such a very long fiber in order to minimize the required pump powers. From the other side the very narrow wave (<1kHz) of a fiber laser (Signal) was coupled into the same fiber via a modulator. The modulator was driven by a waveform generator in order to produce pulses with a temporal duration of around 30ns. The delayed pulses were detected by a photodiode (PD) and interpreted by an oscilloscope (Osci).

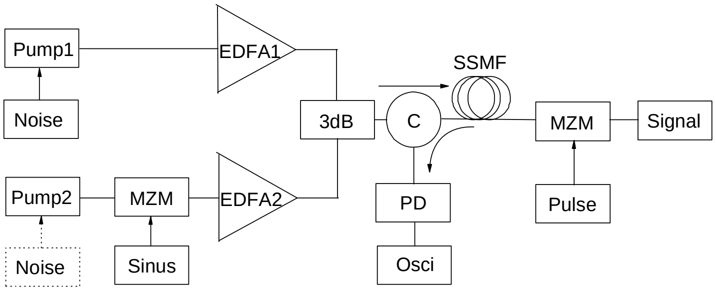

Fig. 4. Schematic experimental set up (polarizers, attenuators and bias controls are not shown). MZM; Mach-Zehnder modulator, PD; photodiode; SSMF; standard single mode fiber, C; circulator, EDFA erbium doped fiber amplifier.

The measured results for the discussed cases can be seen in Fig. 5. As shown on the left side, without an additional loss the linear increase of the time delay with increasing pump power goes up to around 30ns (squares). After that the time delay can be increased further but, due to the pump depletion, the enhancement is rather low. If a broad loss is introduced the linear time delay can be almost doubled to around 60ns. If two loss spectra are superimposed at the wings of the gain the linear time delay goes up to around 90ns. If the pump power is increased further, a time delay of more than 120ns can be achieved, which is – to the best of our knowledge – the highest time delay in just one fiber spool. If we compare the delay with the pulse width of the reference (30ns) the storage capacity is 4Bit. However, the pulse width of the output pulse was 85ns which corresponds to a storage capacity of 1.4Bit.

In comparison to the case *b* (gain superimposed with a broad loss) the distortion seems to be increased. In [13] the pulse width was almost doubled for a pulse delay of around 100ns. Here this is already the case for a pulse delay of around 80ns. However, we address these higher distortions to the imperfectness of our experimental set up. If the gain and group index bandwidths in Fig. 1 are compared it can be seen that these bandwidths remain almost the same for the three cases. Hence, the pulse distortions should be almost the same as well. In the present set up gain and loss lines are produced from different DFB laser sources. Each DFB laser shows a jitter in it's output spectrum which is in the MHz-range. Since the sources are independent from each other the difference frequency between both shows a jitter as well. For case *b* this is no problem since the loss is very broad. But, for case *c* the bandwidth of the loss and gain lines corresponds to the natural Brillouin width of around 30MHz. Hence, a jitter of several MHz results in a permanent change of the Brillouin bandwidths and the delay time. If gain and loss lines are produced from just one laser source the jitter plays no role and the pulse distortions should be reduced. Due to the fact that our loss amplifier was restricted to 14dBm, the presented time delays are not the achievable maxima.

If the gain is broadened by an additional modulation the time delays are reduced but, the advantage is, that the pulse distortions are reduced as well (right side in Fig. 5). For a pump power of 14mW we achieved a time delay of around 21ns if only the gain is present. The 30ns input pulse was broadened to 33.8ns. If the two loss spectra are introduced at the wings the time delay is increased to 31.4ns for the same pump power. Although we have a 50% higher pulse delay the pulse width of the output was only 33.6ns. Hence, as expected from the theory, it seems like the method reduces in fact the distortions. However, for some other measured data this is not so clear. We assume that the insufficiencies of our experimental equipment are responsible for that. So, a further investigation of this behavior is required. In order to eliminate the drift between the pump laser diodes we plan to generate gain and loss lines from just one laser source.

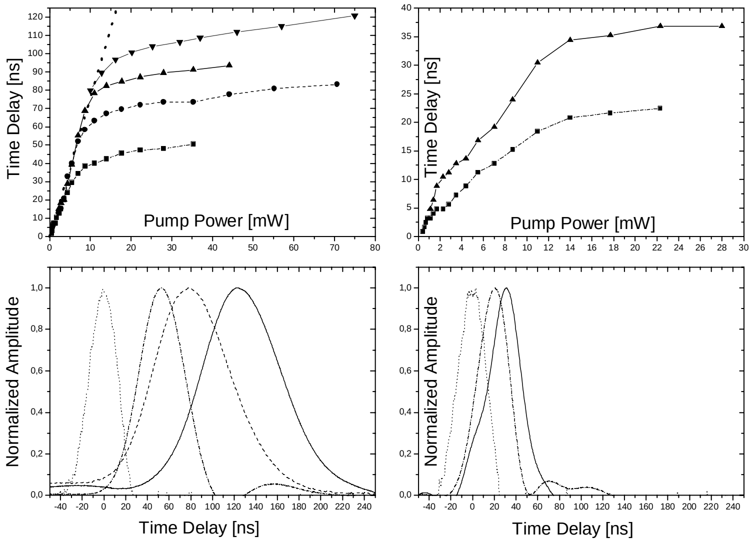

Fig. 5. Experimental results for the time delay as a function of the pump power (top) and selected pulse shapes for different time delays (bottom). On the left side the results for a natural Brillouin gain of around 30MHz are shown, on the right side the gain bandwidth was broadened to 60MHz (both FWHM). The dotted lines show the reference pulses, with the dashed-dotted lines (squares) the case without an additional loss is shown. The solid lines show the case if two loss spectra are placed at the wings of the gain (left side, triangles down P_{Loss} = 14dBm, triangles up P_{Loss} = 11dBm, $\delta/\gamma = 1$). The loss power for the right side was 9dBm and the frequency separation between the loss spectra 56MHz). The dashed line on the left side (circles) shows the result for the direct superposition of a gain with a broad loss (the loss power was 10.1dBm and its bandwidth 180MHz).

4. Conclusion

In conclusion we have compared two methods for the enhancement of the time delay in SBS based slow light delay systems. The superposition of two loss lines at the wings of the gain has several advantages over the direct superposition of a gain with a broad loss. We achieved higher delay times at lower optical powers, the zero gain delay was enhanced to more than 50% and the maximum time delay was 120ns. Beside the enhancement of the time delay the method could have the potential to decrease the pulse distortions for high bit rate signals.

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