Time delay limits of stimulated-Brillouin-scattering-based slow light systems

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We discuss the maximum achievable time delay of stimulated-Brillouin-scattering-based systems that rely on the superposition of gain and loss spectra. As we will show, the time delay can be enhanced up to 8.5 times if the gain is superimposed with a broad loss and 9.5 times if two narrow losses are superimposed at the wings of the gain. Furthermore, we show that the parametric interaction between the different pump waves is negligibly small. Our theoretical analysis does not include pulse distortions that are accompanied by the delay. © 2008 Optical Society of America

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The alteration of the group velocity of optical pulses (slow and fast light) offers a way to many very interesting applications. Among these are time resolved spectroscopy, nonlinear optics, radio frequency photonics, and optical signal processing. The effect of stimulated Brillouin scattering (SBS) has especially attracted much recent interest since it offers many advantages over other slow light methods. Recently, it was shown that photonic crystal and nonsilica-based fibers with a large Brillouin gain coefficient can slow down and accelerate light in a few meters of fiber length [1,2].

On the other hand, the natural Brillouin gain in an optical fiber has several serious disadvantages: (i) the pulse delay is accompanied by a distortion of its shape, (ii) only very small data rates can be delayed since the gain bandwidth is very narrow, and (iii) the time delay is coupled with an amplification of the pulses. By a modulation of the pump wave [3] or a superposition of several gains [4] and losses [5,6], which will be produced simultaneously by different pumps, most of the disadvantages can be circumvented [7]. However, since the studies that investigate the limits of SBS-based delay lines are restricted to the classical setup where the pulse will be delayed within a gain spectrum [8–10], the limits of these new approaches are not clear. Here we will enhance these studies to the new setups where a gain is superimposed with one [5,6] or two losses [7] with respect to the maximum achievable time delay.

A pump wave generates a gain for counterpropagating pulses if they are downshifted in frequency by the Brillouin shift. For upshifted counterpropagating pulses the same pump wave generates a loss. Gain and loss both have a Lorentzian shape (see inset a in Fig. 1 for the gain). In the line center the gain is $g = g_P P_P L_{\mathrm{eff}}/A_{\mathrm{eff}}$, where g_P is the peak value of the SBS-gain coefficient, P_P is the input pump power, and L_{eff} and A_{eff} are the effective length and area of the fiber. Owing to the high dispersion and the accompanying group index change, in the center of the gain bandwidth the pulses will be delayed by $\Delta t = g/\gamma$, with γ as the half 3 dB bandwidth of the Brillouin gain. But, since a gain is involved, the delay is accompanied by an amplification of the pulses. Here the gain responsible for the time delay will be called time-delay gain g_{TD}, whereas the gain responsible for the amplification is the amplification gain g_A. For one pump wave both are the same and the delay line can be represented by a SBS-based amplifier.

If no counterpropagating pulses are present the amplification gain amplifies the noise in the fiber. If this gain is above a certain threshold a backscattered Stokes wave will be generated and amplified. The amplification reduces the pump power and therefore the gain. Hence, the maximum available amplification gain is restricted by the threshold of Brillouin scattering. For a low loss uniform fiber the threshold gain is [11] $g_{ATh} = 19$. For a modulated pump wave the SBS peak gain g_P is reduced. However, for a reduced g_P the pump power P_P can be increased by the same amount. So, we assume that—if enough pump power is available—the maximum amplification gain in the line center stays the same with and without the broadening. As in every amplifier, the amplification

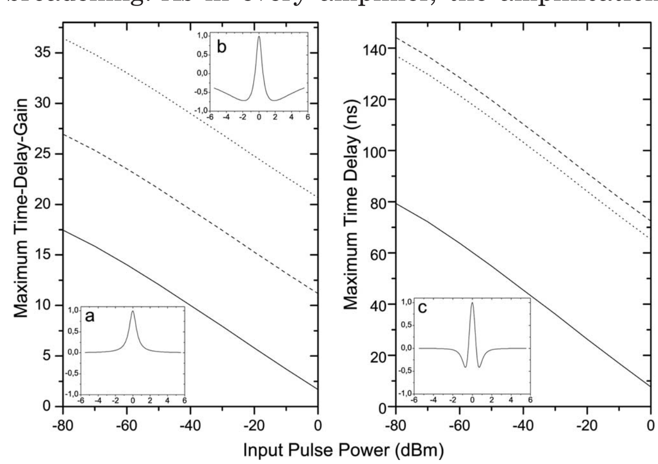

Fig. 1. Maximum time-delay gain and time delay for a Lorentzian gain (solid curve and inset a), a gain superimposed with a three times broader loss (dotted curve and inset b), and a gain superimposed with two losses at its wings (dashed curve and inset c). Please note that only for the first case does the time-delay gain equal the amplification gain. The insets show the normalized gain as a function of the normalized frequency $(\omega - \omega_B)/\gamma$ with ω_B as the frequency of the Brillouin shift and γ as the Brillouin gain linewidth.

reduces the pump power and the gain. Therefore, the amplification becomes saturated. If pump depletion and the attenuation in the fiber are ignored, the maximum amplification gain can be written as [10]

$$g_{A\max} = \ln\left(\frac{\exp([1-\xi]g_{ATh}) - \xi}{1-\xi}\right), \quad (1)$$

with $\xi = P(L)/P_P$. For very low output pulse powers $P(L) \to 0$, the maximum amplification gain equals the threshold gain $g_{A\max} \approx g_{ATh} = 19$. In Fig. 1 (left) the maximum amplification gain is shown with the solid curve for a standard single-mode fiber with an attenuation of $\alpha = 0.209$ dB/km, $g_P = 2 \times 10^{-11}$ m/W, $A_{\mathrm{eff}} = 86\ \mu\mathrm{m}^2$, and a length of $L = 50.45$ km. Since only one pump wave is present the amplification gain equals the time-delay gain. Owing to the amplifier saturation the maximum induced gain depends on the power of the input pulse. Since a broadening of the gain reduces the time delay, the maximum delay can be achieved for the natural SBS bandwidth $\gamma/(2\pi) \approx 35$ MHz. The highest achievable time delay is shown in Fig. 1 (right).

If the gain is superimposed with a broad loss (see inset b in Fig. 1), the delay can be decoupled from the amplification [5]. The loss can be produced by a second laser with a center frequency that is downshifted in frequency by twice the Brillouin shift and broadened by a direct modulation with a noise signal. The loss directly reduces the amplification gain; it is $g_A = g_1 - g_2$. But the time delay is a function of the phase change. The corresponding time delay is [7] $\Delta t = g_1/\gamma_1 - g_2/\gamma_2$ with $g_{1,2}$ and $\gamma_{1,2}$ as the SBS-gain coefficient and the linewidth of the gain and loss, respectively. So if the loss is much broader than the gain $\gamma_2 \gg \gamma_1$, the time delay is only slightly reduced.

The second laser produces a loss that is upshifted in frequency by the Brillouin shift. But at the same time, for a downshifted counterpropagating signal, it produces a gain. Therefore, the maximum loss that can be produced by the laser is limited by the Brillouin threshold. However, since the loss generated by the second laser compensates the gain generated by the first, the gain g_1 can be made higher. In the maximum, the gain g_1 can be increased by $g_{2Th} = 19$. With this method we achieved very high time delays up to around 100 ns [6]. The dotted curves in Fig. 1 show the maximum gain induced by the higher frequency pump and the corresponding time delay for a loss that is three times broader than the gain spectrum.

Since the loss has to be much broader than the gain, this method requires very high pump powers, especially for broad gains. If the gain is superimposed with two narrow losses at its wings (see inset c in Fig. 1) the delay will be decoupled from the amplification as well. The two losses can be very simply produced by a second laser that is externally modulated in a suppressed carrier regime [7]. If we assume that the gain and losses have the same bandwidth and both losses are equal, the amplification gain is $g_A = g_1 - g_2/2$ for a frequency separation between the losses of $2 \times \delta = 2 \times \sqrt{3}\gamma$. Since two gains are produced simultaneously by the loss laser, the maximum loss is again restricted by the SBS threshold. Therefore, in the maximum g_1 can be increased by $g_{2Th}/2 = 9.5$. Hence, the highest gain induced by the higher frequency pump is smaller as shown by the dashed curve in Fig. 1 (left). However, contrary to the aforementioned method, the time delay will not be decreased but increased by the losses. The time delay in the line center is [7] $\Delta t = (g_1 + 0.25 g_2)/\gamma$. Therefore, this method requires less pump power but can result in higher time delays. In our experiments we achieved time delays of more than 120 ns [7].

If the gain is superimposed with one or two losses, two or three strong pump waves propagate into the same direction. This can result in a parametric interaction between the waves via the third-order nonlinear susceptibility $\chi^{(3)}$. In consequence, the pump waves generate new mixing products. Since the mixing products counterpropagate to the pulses, the signal-to-noise ratio will not be decreased by this process. But the new generated waves could reduce the maximum pump power and therefore the gain and time delay. If a loss is superimposed with a broad gain, two strong pump waves interact. In this case, only two new waves are generated via four-wave mixing (FWM). In Fig. 2 (inset a) the two pump waves (1 and 2) separated in frequency by two times the Brillouin shift $2\omega_B$ and the mixing products are shown. According to the condition for the conservation of energy $\omega_{i,j,k} = \omega_i + \omega_j - \omega_k$, $k \neq i,j$ and $i,j = 1,2$, the new waves 112 and 221 are upshifted and downshifted from pump waves 1 and 2 by twice the Brillouin shift. Assuming that the pump waves are not depleted, the output peak power of the new generated waves is [12]

$$P_{i,j,k} = \left(\frac{D}{3}\gamma L_{\mathrm{eff}}\right)^2 P_i P_j P_k e^{-\alpha L}\eta, \quad (2)$$

with $D = 3$ if two pump waves ($i = j \neq k$) and 6 if three pump waves ($i \neq j \neq k$) are involved; γ is the nonlinear

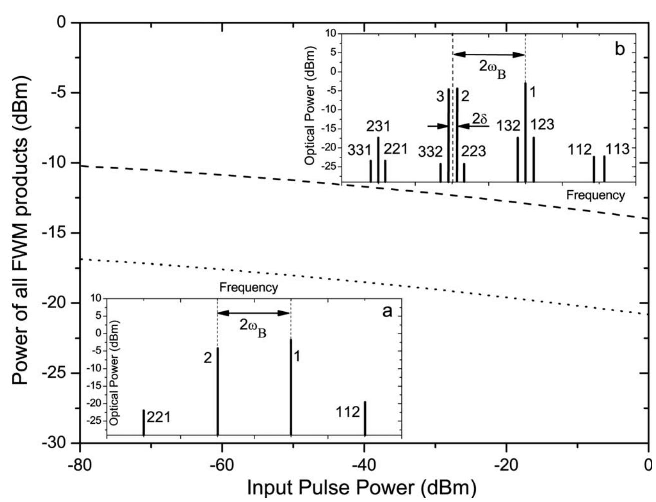

Fig. 2. Summarized power of all generated FWM products for a two- (dotted curve) and three-wave interaction (dashed curve). The insets show the optical output powers of the generated waves and the pump waves for the two- (inset a) and three-wave interactions (inset b) and a pulse input power of −60 dBm.

coefficient; P_i, P_j, and P_k are the input peak powers of the pump waves; and η is the efficiency of the mixing process that depends on the phase matching between the involved waves. Here we assume the worst case, which means that all waves are perfectly matched ($\eta = 1$) and copolarized. The dotted curve in Fig. 2 shows the summarized power of the two mixing products for the parameters given above and $\gamma = 1.2\ \mathrm{W}^{-1}\,\mathrm{km}^{-1}$. Since the maximum pump power of P_1 can increase with a decreasing input pulse power, the power of the mixing products increases as well. But the pump power reduction by this process is negligibly small.

If the gain is superimposed with two losses, we have a three wave interaction. This results in nine mixing products, which are shown in inset b of Fig. 2. Furthermore, three of the mixing products (231, 132, and 123) are stronger than the others since they are generated with $D = 6$. However, according to the discussion above, for the two loss case the maximum pump power P_1 can only be half as high as for the one loss case. Owing to this the summarized power of all generated mixing products is not very much increased, as shown by the dashed curve in Fig. 2. Therefore the parametric interaction can be neglected for both cases.

In conclusion, we have shown that the maximum time delay of a SBS-based slow light system depends on the input pulse power and on the gain induced by the higher frequency pump wave. The time delay can be enhanced if the gain is superimposed with a broad loss. If the loss is three times broader than the gain, the time-delay enhancement is between 8.55—for a 1 mW pulse—and 1.9 if the input pump power is −60 dBm. However, the method requires very high optical powers for the loss. This problem can be circumvented if the gain is superimposed with two narrowband losses at its wings. Contrary to the broad loss case, the losses at the wings enhance the time delay in the center. Since the losses have a narrow bandwidth, which does not have to be broadened for broad gains, the method requires much lower optical power. For the given parameters we have a time-delay enhancement of 9.5 and 2 times for a 1 mW and a −60 dBm pulse. Since the Brillouin process is much more effective than the parametric interaction between the pump waves, the pump power reduction owing to FWM can be neglected. Therefore, a further enhancement of the time delay can be achieved if additional pump sources are included. Of course, the different pump waves can be generated by an appropriate modulation of one laser source. If a third pump wave is downshifted to the first by 4 times the Brillouin shift, its generated loss can compensate the gain produced by the second pump. If the third pump laser is modulated like the second, it can compensate the gains of the one and the two loss case. Hence, if we neglect the wavelength dependence of the SBS gain, the maximum loss generated by the second laser can be doubled. For the given parameters this would result in a maximum time delay for the −60 dBm pulse of 180 ns for the one loss case and 193 ns for the two loss system. The delay is always accompanied by pulse distortions. The maximum time delay for a given application is restricted by the tolerable amount of these distortions. The distortions can be reduced by a broadening of the gain and a reduction of the higher-order terms of the complex wave number. But even if enough pump power is available, this reduces the achievable time delay. At the same time, broad and high gains lead to a high amount of amplified spontaneous emission (ASE), which will be added to the signal. If the gain is superimposed with two narrowband losses, the time delay is enhanced by these losses. Therefore, higher time delays at broad and rather low gains are possible with this approach. At the same time, the bandwidth of the group index can be made flat [7], which reduces the higher-order wavenumber terms. Hence, the last method has the potential to delay high data rates with low distortions.

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