Time delay enhancement in stimulated-Brillouin-scattering-based slow-light systems

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We show a simple method of time delay enhancement in slow-light systems based on the effect of stimulated Brillouin scattering. The method is based on the reduction of the absolute Brillouin gain by a loss produced by an additional pump laser. With this method we achieved pulse delays of nearly 100 ns in a standard single-mode fiber. In the presented approach the delay or acceleration of optical signals is decoupled from their amplification or attenuation, which allows the adaptation of the pulse amplitudes to the given application. © 2007 Optical Society of America

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The concept of slow and fast light based on stimulated Brillouin scattering (SBS) has attracted much recent interest since it offers the possibility of developing practical devices such as optical delay lines, optical buffers, and optical equalizers for telecommunications systems.[1] The exploitation of SBS in optical fibers has several advantages over other slow-light methods: (i) the SBS requires—at least in long fibers—only a small pump power for high delays, (ii) Brillouin scattering works in all fiber types and over the entire transparency range of the fiber, and (iii) off-the-shelf telecom equipment can be used for slow-light delay lines. With SBS delay lines the group velocity can be controlled over a very large range. For instance, in a short optical fiber the group velocity was changed from 71,000 km/s to more than the speed of light in vacuum.[2]

Most of the SBS delay lines presented so far can be seen as Brillouin amplifiers. Therefore, all delayed pulses will be amplified, whereas all accelerated pulses will be attenuated. Brillouin amplifiers have three important disadvantages: (1) the amplified spontaneous emmission noise can be about 20 dB higher than that of an ideal amplifier,[3] (2) the natural bandwidth of Brillouin scattering is only about 30 MHz, and (3) the maximum pulse delay is limited by the pump depletion. The first and second disadvantages can be circumvented since, under particular circumstances, the amplified spontaneous emission can be reduced significantly[4] and the Brillouin bandwidth can be enhanced drastically.[5] But the maximum pulse delay is in most experiments only around 30 ns for the natural Brillouin bandwidth in a standard single-mode fiber of a length of a few kilometers.[1,6] If four delay lines are cascaded, this maximum delay can be enhanced to 152 ns.[7] On the other hand, this approach is rather complicated, since it requires additional equipment and the Brillouin properties of all fiber segments must be identical.

In Ref. 8 a SBS-based slow-light system that is not a Brillouin amplifier was presented. In this approach two widely separated absorption resonances were generated by SBS, which led to a delay for pulses whose frequency lies in between the two lines. With this approach they achieved a pulse delay of around 3 ns.

Here we present for the first time, to the best of our knowledge, a pulse delay of around 100 ns in just one fiber spool. The amplitudes of the delayed or accelerated pulses do not depend on the delay or acceleration time and can be adapted to the given application.

Our concept is based on the fact that the amplification of the pulse and therefore the pump depletion depends on the absolute height of the Brillouin gain in its line center, whereas the pulse delay is a function of its shape in the frequency domain. So, if the shape remains the same and only the height is reduced, the amplitude of the delayed signal will be reduced, but its delay time will be unchanged. Because the pump depletion can be reduced as well, higher maximum delay times will be possible with this concept.

In the insets of Fig. 1 two different Brillouin gains can be seen; their shapes are identical in the center region only. The right-hand inset shows the Lorentzian shape of the natural Brillouin gain. It starts from zero and is very high in the center, which would re-

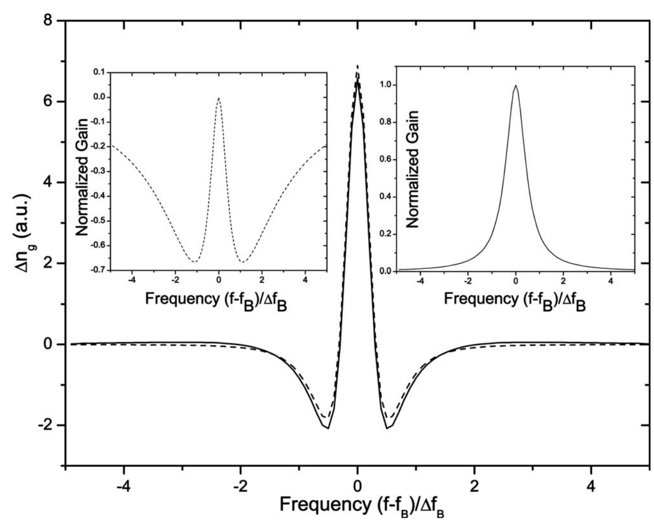

Fig. 1. Alteration of the group velocity index for two different shapes of the Brillouin gain, shown in the insets (f_B is the Brillouin frequency shift and Δf_B is the bandwidth of the Brillouin gain).

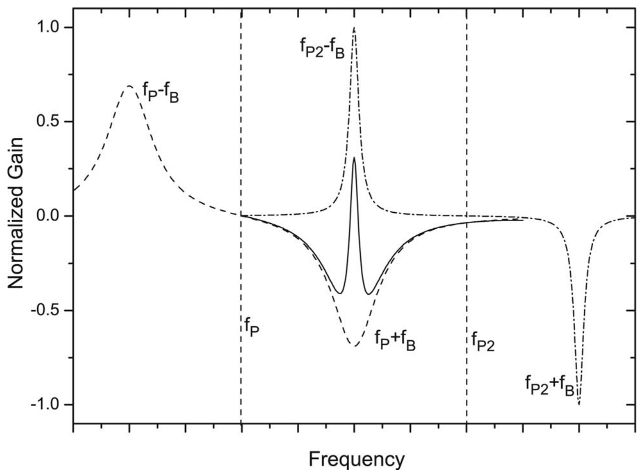

Fig. 2. Brillouin gain and loss spectra generated by two laser diodes at optical frequencies of f_p and $f_{p2}=f_{p1}+2f_B$.

sult in a high amplification of the pulses. The gain in the left-hand inset is a loss, in fact; only in the center region does it have an absolute value of zero, i.e., the amplitude of the delayed pulse will not be altered during the delay process. Nevertheless, the change of the group velocity index Δn_g and therefore the expected pulse delay is nearly equal for both Brillouin gains.

A Brillouin gain shape like that in the left-hand inset of Fig. 1 can be generated with two pump lasers as shown in Fig. 2. One pump laser at an optical frequency of f_P generates a gain (Stokes) at a frequency region f_P-f_B and a loss (anti Stokes) at a frequency region f_P+f_B (dashed curve in Fig. 2), with f_B as the Brillouin shift in the fiber. In standard single-mode fibers this Brillouin shift is around 11 GHz. The gain produced by the pump is broadened by a modulation of the pump laser. A second pump laser has a frequency of $f_{P2}=f_P+2f_B$ and a narrower spectrum. Again, it generates a loss at $f_{P2}+f_B$ and a gain at $f_{P2}-f_B$ (dashed–dotted curve in Fig. 2). The center of the loss from f_P coincides with the gain center from f_{P2}, since $f_{P2}-f_B=f_P+f_B$. The superposition between both spectra shows the expected shape (solid curve in Fig. 2).

To test the properties of this idea we used the experimental setup shown in Fig. 3. A noise source with a bandwidth of 24 MHz modulates the control current of two laser diodes directly. The bandwidth of the laser diodes—and the bandwidth of the generated Brillouin gain—is determined by the modulation degree of the current. This can be adjusted for each laser diode independently by a potentiometer. The relation between the optical powers of the two pump lasers can be controlled with a tunable coupler. The amplified pump waves are coupled into a 50 km standard single-mode fiber (SSMF) via the $1\rightarrow 2$ port of a circulator. We used such a long fiber to reduce the pump power requirements. From the other side the very narrow wave (<1 MHz) of a fiber laser was coupled into the same fiber via a Mach–Zehnder modulator (MZM). The MZM was driven by a waveform generator, and the signal was coupled out by circulator port $2\rightarrow 3$, detected by a photodiode, and interpreted by an oscilloscope.

First we measured the spectra of the generated Brillouin gains in the fiber. To do this we drove the MZM in a suppressed carrier regime with a sinusoidal signal generated by the waveform generator. Due to the suppressed carrier amplitude modulation, two sidebands will be generated in the output of the MZM. By changing the frequency of the sinus we were able to scan one of the sidebands through the Brillouin gain spectrum. In the spectrum the sideband was amplified depending on the Brillouin gain generated by the counterpropagating pump waves. The output power of the sideband as a function of the frequency is a measure for the unknowm spectrum. For convenience we used an optical powermeter instead of the photodiode and the oscilloscope in Fig. 3. The results can be seen in Fig. 4.

The shape of the superimposed spectra depends on the relations between the optical powers and the bandwidths of the pump lasers. Therefore, it can be controlled by the tunable coupler and the potentiometer in the setup. On the left-hand side of Fig. 4, a small gain was generated in a broad loss spectrum, which is useful for the delay of optical signals, whereas on the right-hand side a small loss was generated in a broad gain, which is useful for their acceleration.

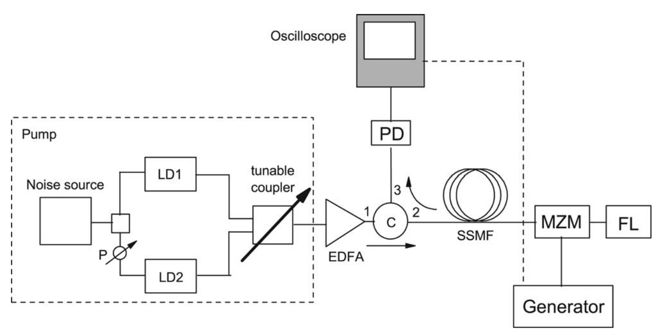

Fig. 3. Principal setup (required isolators are not shown). SSMF, standard single-mode fiber; PD, photodiode; FL, fiber laser; LD1, LD2, laser diodes; EDFA, erbium-doped fiber amplifier; C, circulator; P, potentiometer.

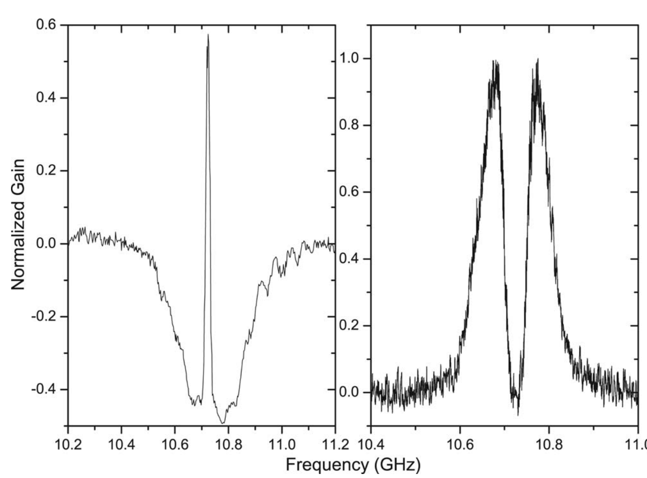

Fig. 4. Measured Brillouin gain spectra for two different optical powers and bandwidths of the pump lasers.

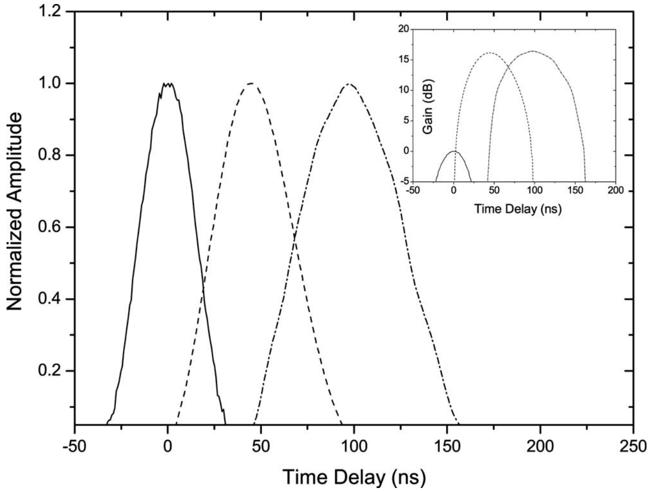

Fig. 5. Normalized amplitudes of optical pulses delayed with a conventional Brillouin gain spectrum (dashed curve) and with a gain spectrum similar to that shown in the left-hand side of Fig. 4 (dashed–dotted curve). The solid curve shows the reference signal, and in the inset the pulse amplitudes are shown on a logarithmic scale.

With a Brillouin spectrum similar to that of the left-hand side of Fig. 4, we delayed optical pulses that were generated by the waveform generator. The pulses had a temporal width of around 34 ns. For detection of the pulse delay we used the setup shown in Fig. 3. The result is presented in Fig. 5.

First we delayed the pulses in a conventional manner without an additional loss spectrum. For this measurement the power of the gain laser at the erbium-doped fiber amplifier output was 12.4 dBm. The pulse delay was around 45 ns (dashed curve in Fig. 5). The amplification gain $[10 \log(A_D/A_R)]$, with A_D as the amplitude of the delayed pulse and A_R as the amplitude of the reference pulse, both measured with the photodiode, was around 16 dB (dashed curve in the inset of Fig. 5). Then we generated an additional loss spectrum of around 15.8 dBm and adjusted the power of the gain laser (16.7 dBm) so that the amplification gain was the same as without the loss spectrum. Because the absolute gain remains the same while the group velocity index is increased, we achieve a much higher pulse delay of 97 ns (dashed–dotted curve in Fig. 5). To the best of our knowledge this is the highest pulse delay ever reported in just one fiber spool.

We believe that with a higher loss the change of the group velocity index can be further increased, which would result in higher pulse delays. In principle, the limit up to which the loss can be increased is the Brillouin threshold of the pump laser f_P. In this case the change of the group velocity index, which is produced by f_{P2}, can be nearly doubled. The threshold of f_P will be determined by the gain at $f_P - f_B$. With a third laser at a frequency $f_P - 2f_B$, the gain at $f_P - f_B$ can be decreased, which allows a higher loss at $f_P + f_B$ and therefore a further increase of the slow-light delay.

In conclusion, we have shown a SBS slow-light concept in which the amplitudes of the delayed or accelerated pulses do not depend on the delay or acceleration time and can be adapted to any given application. We have shown that with this approach the pump depletion can be reduced significantly, leading to a drastic enhancement of the maximum delay.

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