Gain-independent SBS based Slow Light in optical Fibers

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Abstract: We show a simple method to decouple the delay in SBS-based slow-light systems from the Brillouin Gain. With this approach the maximum time delay can be enhanced to more than 100ns in one fiber segment.

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During the last few years the concept of slow and fast light is of increasing interest since it is a fascinating field of optics. But, it offers a number of very interesting applications in optical signal processing and optical telecommunications as well. Especially slow and fast light based on the nonlinear effect of stimulated Brillouin scattering (SBS) has the potential to develop practical devices such as optical delay lines, optical buffers and optical equalizers for telecommunications systems [1]. Stimulated Brillouin scattering in optical fibers has several advantages over other slow light methods. With rather low pump powers high delays can be achieved, off the shelf telecom equipment can be used, the SBS works in all fiber types and in the entire transparency range of the fiber. With SBS in optical fibers group velocities as small as 71000 km/s and even negative group velocities were observed [2].

On the other hand, the SBS has several serious problems. The bandwidth of the natural Brillouin gain is limited to about 30MHz, leading to a maximum data rate of around 15Mbit/s which can be delayed. Accompanied with the small bandwidth is a strong distortion of the delayed pulses. This problem can be circumvented by a modulation of the pump source since the Brillouin bandwidth can be drastically enhanced [3]. Another problem is that the maximum delay, which can be achieved in several km long optical fibers, is limited to roughly 30ns [1, 4]. By a cascading of several delay lines the maximum delay can be enhanced. Since in this case the pump depletion and amplified spontaneous Brillouin scattering will be prevented [5]. Both depend on the amplifier gain whereas the delay time is a function of the group index in the fiber. So, the decoupling between the gain and the alteration of the group velocity is a much easier way to increase the maximum achievable delays.

In conventional SBS-based slow light systems the difference between the transit times of the pulse with and without a pump beam is in the peak of the Brillouin gain given by [1]

$$\Delta T \approx g_0 \frac{PL}{A_{eff}\, 2\pi f_B} \tag{1}$$

With g_0 as the linecenter SBS gain coefficient for a narrow-band pump, f_B is the intrinsic SBS resonance linewidth, A_{eff} and L are the effective area and length of the fiber, respectively and P is the optical power of the pump source. All SBS-based slow light systems presented so far can be seen as a Brillouin amplifier. If the pump depletion and the fiber loss can be neglected the amplifier gain is the logarithmical relation between the optical power of the delayed pulse at the output $P_D(L)$ and the input $P_D(0)$ of the amplifier [6]

$$G_{dB} = 10\log\left(\frac{P_D(L)}{P_D(0)}\right) \approx 4.343 g_0 PL / A_{eff} \approx 4.343 f_B\, 2\pi \Delta T \tag{2}$$

As can be seen from Eq. (2), higher pulse delays are always accompanied by a higher amplifier gain and therefore an unavoidable amplification of the delayed pulses. If the amplification becomes too high the pump depletion and the amplified spontaneous Brillouin scattering limits their further delay.

On the other hand, the group velocity and hence the delay is a function of the group index in the fiber which in turn depends on the shape of the Brillouin gain whereas the amplifier gain is a function of its absolute height. So, if the shape and the absolute height of the Brillouin gain are decoupled from each other much higher delays can be achieved. Such a decoupling is possible if the base line of the Brillouin gain is shifted into the loss region. In this case the linecenter SBS gain g_0 is reduced but the shape remains the same.

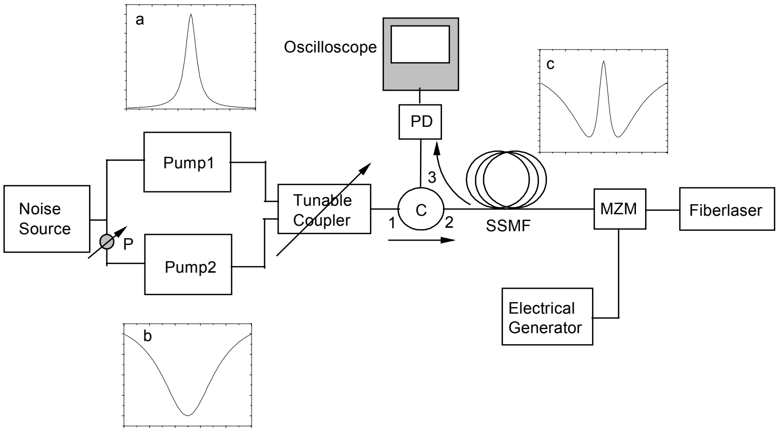

Figure 1: Principle experimental set up. P: potentiometer, SSMF: standard single mode fiber, MZM: Mach Zehnder modulator, C: circulator.

The principle experimental set up is shown in Fig. 1. For the base line shift we use two distributed feedback (DFB) pump lasers. Each pump laser with an optical frequency f_P produces a gain at $f_P–f_B$ and a loss at f_P+f_B via Brillouin scattering. Where f_B is the natural Brillouin shift in the fiber, which is typically at around 11GHZ in SSMF. From the first laser (Pump1) we use the gain (inset a) and from the second the loss (inset b). The DFB lasers are adjusted by their temperature in such a manner that gain and loss coincide in the fiber (inset c). The bandwidth of each laser is broadened by a direct modulation of their current with a 24 MHz Gaussian noise signal. The bandwidth of the Brillouin gain and loss in the fiber can be controlled independently for each laser by the potentiometer P. The relation between the output powers of the pump lasers can be controlled with a tunable coupler. The amplified pump waves (the required erbium doped fiber amplifier is not shown in the figure) 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 narrow wave (<1MHz) of a fiber laser was coupled into the same fiber via a Mach-Zehnder modulator. The MZM was driven by a waveform generator to produce pulses with a FWHM width of around 35ns and the amplified or delayed signal is detected by a photodiode and interpreted by an oscilloscope.

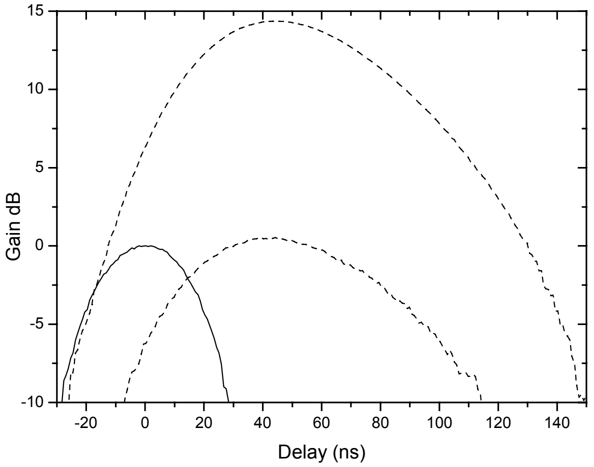

Fig. 2. Delayed pulses for two different gains in the fiber. Please note that the fiber loss is neglected in the gain calculation.

The result for a pulse delay of around 40ns is shown in Fig. 2. The solid curve shows the reference signal, which can be seen at the fiber output when no pump signal is present. If the pulse is delayed in a conventional manner its amplification is around 14dB, which comes near the pump depletion regime. If we include the 10.85dB loss of our fiber we can calculate a Brillouin gain bandwidth of around 23MHz from Eq. (2). This is unnaturally small since we measured a bandwidth of around 30MHz for our SSMF. We address this discrepancy to the case that the equations (1) and (2) are valid for short fibers only.

If the pulse is delayed with an additional loss spectrum we achieve a gain of 0dB for the same delay. This means that with our method the delay process will not change the amplitude of the delayed pulse.

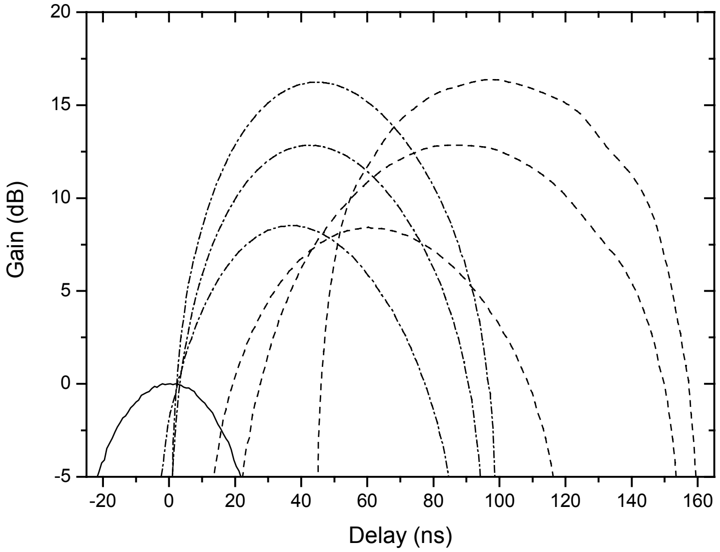

Fig. 3. Delayed pulses with and without an additional loss spectrum as a function of the amplifier gain. The solid curve shows the reference, the dashed lines show the delayed pulses with and the dashed-dotted without an additional loss spectrum. Please note that here again the fiber loss is neglected in the gain calculation.

A comparison between the pulse delays with and without an additional loss spectrum for three different gains can be seen in Fig. 3. For a gain of 8.5dB the pulse delay is around 37ns when no additional loss spectrum is present. With such a loss spectrum the delay is increased to 60ns for the same gain. For a gain of around 13dB we achieve 43ns and 88ns and for a gain of 16dB the delays are 46ns and nearly 100ns. Since for such high gains we are already in the pump depletion regime a drastically further increase of the delay times is not possible if the pulses are delayed in a conventional manner. But if we increase the loss in our method we can expect even higher delays.

In conclusion we have shown a simple method for the gain-independent pulse delay in SBS-based slow light delay systems. It is based on the reduction of the linecenter SBS gain coefficient by a loss spectrum produced by an additional pump laser. With this method we achieved pulse delays up to 100ns in a 50km SSMF.

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