# Enhancement of maximum time delay in one fiber segment slow light systems based on stimulated Brillouin scattering

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**Abstract:** An effective method to enhance the time delay in SBS-based slow-light systems by decoupling the delay from the Brillouin gain is shown. A drastic improvement of the time delay in one fiber segment was achieved.
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Slow and fast light has attracted an increasing interest during the last years because it offers the potential for an all optical control of the velocity of light pulses. Especially the nonlinear effect of stimulated Brillouin scattering (SBS) has become an effective and flexible tool for the development of a number of very interesting applications in optical telecommunications and optical signal processing [1]. In [2] an extremely wide group velocity control as small as 71000 km/s and even negative group velocities were observed in a short optical fiber.

But one problem of the SBS is that in most experiments the maximum pulse delay is limited to around 30 ns [1, 3]. Most SBS-based slow light systems presented so far can be seen as a Brillouin amplifier for which 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 [4, 5]:

$$G_{dB} = 10\log\left(\frac{P_D(L)}{P_D(0)}\right) \approx 4.343\, g_0 \frac{P_P L_{eff}}{A_{eff}} \approx 4.343\, \Delta f_B 2\pi \Delta T . \qquad (1)$$

where $g_0$ is the line center SBS gain coefficient, $P_P$ the pump power, $\Delta f_B$ the Brillouin line width, $A_{eff}$ and $L_{eff}$ the effective area and length of the fiber. As can be seen from Eq. (1) the time delay $\Delta T$ increases with higher optical powers of the pump source. This is always accompanied by a higher amplifier gain and an unavoidable amplification of the delayed pulses. But if the amplification becomes too high the delay goes over into a saturation regime because the pump depletion and the amplified spontaneous Brillouin scattering limits further delay times.

One opportunity to enhance the maximum time delay is to cascade several delay lines [6] but this method is very complicated because additional equipment is required and the properties of all fiber segments have to be identical referring to the SBS. Another method which is much easier and more effective is to decouple the amplifier gain and the time delay [5, 7]. This is possible if the base line of the SBS gain is shifted into the loss region. That causes a reduction of $g_0$ whereas the shape of the Brillouin gain will remain the same in the frequency domain. Since the group velocity and hence the time delay is a function of the group index in the fiber – which in turn depends on the shape of the Brillouin gain – the time delay will also be unchanged. However, the amplifier gain is a function of the absolute height of the Brillouin gain and so the pump depletion is reduced. This results in higher usable pump powers and hence in higher time delays. The method can be achieved by superimposing a SBS gain $+G_1$ with the bandwidth $\Delta f_{B1}$ and a SBS loss $-G_2$ with the bandwidth $\Delta f_{B2}$. The resulting delay is therefore [5]:

$$\Delta T_{res} = \frac{G_1}{2\pi \Delta f_{B1}} - \frac{G_2}{2\pi \Delta f_{B2}} \qquad (2)$$

where $G_{1,2} = g_0 P_{P1,2} L_{eff}/A_{eff}$. In contrast to [5] with our method we achieved a maximum time delay which is around six times higher.

Our principle experimental setup for this method is shown in Fig. 1. We used two distributed feedback (DFB) pump lasers at a wavelength of 1550 nm to generate a Brillouin spectrum in a 50 km SSMF. Due to such a very long fiber the required pump powers can be minimized. Each pump source creates a gain at $f_P$-$f_B$ and a loss at $f_P$+$f_B$ via Brillouin scattering, with $f_P$ as the optical frequency of the lasers and $f_B$ as the natural Brillouin shift in the fiber, which is typically at around 11 GHz in a SSMF. By adjusting $f_{P1}=f_{P2}+2f_B$ the gain spectrum of the first pump laser (Pump1) superimposes with the loss of the second (Pump2). Thereby, the loss spectrum is broadened by a direct modulation of the laser with a noise signal and the power of the loss and gain spectrum is additionally controlled by an erbium-doped fiber amplifier (EDFA) and a tunable optical attenuator (TOA). The two pump waves are coupled into the SSMF via a circulator (C). From the other side a pulse signal, which is produced by a narrow bandwidth

(<1 kHz) fiber laser and a Mach-Zehnder modulator (MZM) driven by a waveform generator, is coupled into the same fiber. The pulses had a wavelength of 1550 nm, a repetition rate of 1 MHz and a temporal duration of around 35 ns. In the fiber the 25 dB attenuated (Att) pulses will be amplified and delayed by the coincided loss and gain spectrum; finally detected by a photodiode (PD) and interpreted by an oscilloscope (Osci) at port 3 of the circulator.

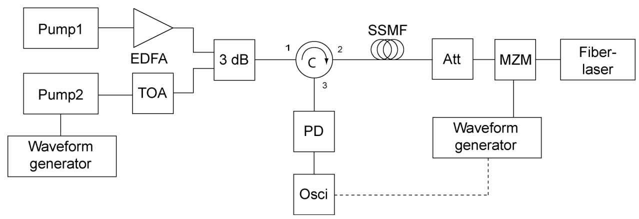


Fig. 1. Principle experimental setup.

The results for a pulse delay without and with additional loss spectrums are shown in Fig. 2. For small rising pump powers of Pump1 the delay increases linearly for all conditions. Thus, the time delay does not change by adding the loss spectrum at first. Then, the time delay reaches the saturation regime caused by the pump depletion; without a loss spectrum at around 35 ns. But, by adding the loss spectrum with a 3-dB bandwidth of around 180 MHz the pump depletion is reduced. It can be seen that with higher pump powers of the gain laser the saturation regime is reached later; with a loss spectrum of 10.5 mW at around 55 ns. Thus, increasing pump powers of the loss laser results in higher maximum time delays. Without the loss spectrum we achieved a maximum time delay of only approximately 55 ns for a gain pump power of 20 mW whereas for the loss spectrums of 4 mW, 9 mW and 10.5 mW delays of 60 ns, 67 ns and 70 ns occurred which is an unprecedented enhancement of 27 %. Nevertheless, the time delay can be further increased up to around 100 ns with a higher loss in our method [7].

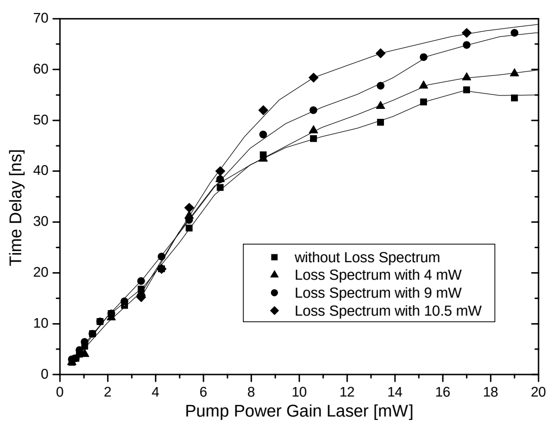


Fig. 2. Time delay against the gain laser pump power with and without an additional loss spectrum.

In conclusion we have shown how the maximum time delay can be enhanced by decoupling the delay from the Brillouin gain in a one fiber segment SBS-based slow light system. By variably reducing the line center SBS gain coefficient with an additional loss spectrum a continued adjustment above the common time delay of 30 ns is possible. With this simple and flexible method we achieved maximum pulse delays of 70 ns in a 50 km SSMF.

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