Arbitrary-bandwidth Brillouin slow light in optical fibers

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Abstract: Brillouin slow light in optical fibers is a promising technique for the development of all-optical buffers to be used in optical routers. The main drawback of this technique up to now has been its narrow bandwidth, normally restricted to 35 MHz in conventional single-mode optical fibers. In this paper we demonstrate experimentally that Brillouin slow light with an arbitrary large bandwidth can be readily obtained in conventional optical fibers using a simple and inexpensive pump spectral broadening technique. In our experiments, we show the delaying of 2.7 ns pulses over slightly more than one pulse length with only some residual broadening (<25%) of the pulse width. We see no limit to extend this technique to the delaying of GHz-bandwidth signals.

OCIS codes: (060.2310) Fiber optics; (290.5900) Scattering, stimulated Brillouin; (060.4370) Nonlinear optics, fibers; (070.6020) Signal processing; (350.5500) Propagation

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1. Introduction

The optical control of the delay of light signals in room-temperature solids is currently viewed with great interest by the scientific community [1-3]. In particular, the possibility of exerting this delay control in optical fibers seems particularly attractive in optical communications [4,5], where fiber-based optically-controlled delay lines could be of interest in many signal processing devices, including all-optical routers [6-8]. Recent experiments have demonstrated the possibility to achieve a wide group delay control in optical fibers by use of the stimulated Brillouin scattering (SBS) effect [9,10]. In these experiments, the amount of delay achieved was limited to roughly 30 ns in several km-long fibers, and the group delay changes induced in the fiber were in the order of 10^{-3}. In Ref. [11] it was experimentally demonstrated that arbitrarily large optically-controlled delays can be obtained by preventing pump depletion and amplified spontaneous Brillouin scattering. This simply requires the insertion of unidirectional broadband attenuators in the signal path, leaving the pump path lossless. A more recent paper [12] has also shown that an extremely wide group velocity control in the fiber is possible using the same Brillouin principle, simply by using a shorter fiber and much higher pump powers. Group velocities as small as 71000 km/s, superluminal and even negative group velocities were observed. Up to now, however, the main limitation of this all-optical delaying technique has been its bandwidth, the natural Brillouin bandwidth being restricted to approximately 35 MHz in conventional single-mode fibers. Thus, the temporal width of the optical pulses that can be delayed with this technique has so far been restricted to about 20 ns. Similar restrictions hold for other slow-light configurations [13].

Previous works have proposed schemes for achieving optically-controlled delays of broadband pulses in media exhibiting electromagnetically-induced transparency (EIT) [14]. In [15], Stenner *et al*. described a method to optimize the SBS-induced slow light pulse delay with a given distortion constraint for the cases of a single lorentzian line and for the case of a gain doublet. It was shown that a careful spectral engineering could provide an increase in the achievable fractional delay, although the pulse width used was still in the order of magnitude of the characteristic gain bandwidth of the SBS in optical fibers. In this paper we demonstrate experimentally a method to overcome the bandwidth limitation in SBS-based optical fiber slow light, thus opening the possibility to exploit slow light for the development of high-speed all-optical routers. The bandwidth of the pulses used in our experiments well exceeds that of the characteristic Brillouin gain spectrum. Our procedure is simple, inexpensive, uses off-theshelf materials, and ensures that the bandwidth of the slow light can be matched to that of the signal. We believe that these results offer a basis for a technological application of this effect.

2. Theory

The process of SBS is usually described as the interaction of two counterpropagating waves, a strong pump wave and a weak probe wave. If a particular phase matching condition is satisfied (namely $f_{pump}=f_{probe}+\nu_B$, ν_B being the Brillouin shift), an acoustic wave is generated which scatters photons from the pump to the probe wave, stimulating the process. SBS can be regarded as a narrowband amplification process, in which a strong pump wave produces a narrowband gain in a spectral region around $f_{pump}-\nu_B$ and a loss around $f_{pump}+\nu_B$. According to the Kramers-Kronig relations, a refractive index change is associated with the Brillouin gain/loss process and a substantial change of the group index $n_g=n+\omega\, dn/d\omega$ follows as a result of the sharp index transition. When a perfectly coherent pump is used in the stimulated Brillouin interaction, the gain window appearing in the fiber transmission spectrum has a Lorentzian shape whose characteristic spectral width is around 35 MHz in conventional single-mode fibers pumped at 1.55 μm. However, when the pump is modulated the gain bandwidth is given by the convolution of the pump spectrum and the Brillouin gain curve. Hence the effective Brillouin gain spectrum $g(\Delta\nu)$ is given by [16]:

$$g(\Delta\nu) = P(\Delta\nu) \otimes g_B(\Delta\nu) \tag{1}$$

where $\otimes$ denotes convolution, $P(\Delta\nu)$ is the normalized pump power spectral density (so that its integral is unity) and $g_B(\Delta\nu)$ is the characteristic Lorentzian gain of the Brillouin amplification process:

$$g_B(\Delta\nu) = g_B \frac{1}{1-2j(\Delta\nu/\Delta\nu_B)} \tag{2}$$

for which g_B is the linear Brillouin gain coefficient and $\Delta\nu_B$ is the characteristic Brillouin width. Hence an adequate pump modulation can be used to broaden at will the Brillouin interaction. A particularly useful case arises if the pump spectrum can also be approximated by a Lorentzian. In such conditions, the effective Brillouin gain shape remains Lorentzian, but shows a width equal to the sum of the characteristic Brillouin gain width and the pump spectral width. In this particular case, the delay obtained is given by $\Delta\tau=G/[2\pi(\Delta\nu_B+\Delta\nu_P)]$, where G is the logarithmic gain suffered by the signal and $\Delta\nu_P$ is the pump spectral width. With no pump broadening $(\Delta\nu_P=0)$ the delay obtained amounts to 1 ns per dB gain[9]. Thus, for the same amount of signal gain, a tenfold increase of the bandwidth of the interaction comes at the expense of a tenfold reduction of the achieved delay. Since $G=g_B I_P L_{eff}\Delta\nu_B/(\Delta\nu_B+\Delta\nu_P)$, achieving the same absolute delay with a tenfold increase in the bandwidth of the interaction requires a 100-fold increase in the power of the pump or the effective length. More importantly, however, in terms of fractional delay (i.e., the delay divided by the pulse length) the same fractional delay with a tenfold increase in the bandwidth only requires a tenfold increase of the pump power.

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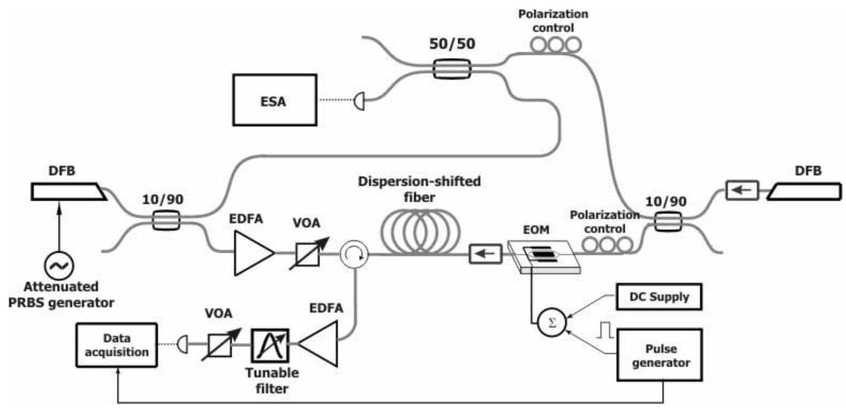

Fig. 1. Experimental setup. DFB, distributed feedback laser diode; VOA, variable optical attenuator; EOM, electro-optic modulator; EDFA, erbium-doped fiber amplifier.

3. Experiment and results

Figure 1 depicts the experimental setup. Two conventional temperature and current-controlled distributed feed-back (DFB) lasers are used to generate the pump and the probe, respectively. The frequency difference between the pump and probe lasers is set to the Brillouin shift of the fiber by adjusting the temperature and current settings of both lasers. To broaden the pump, the signal from a strongly attenuated pseudorandom binary sequence (PRBS) with a bit rate of 38 Mbit/sec is used to slightly modulate the current of the pump laser (< 1%), yielding a smooth bell-shaped broadening of the pump spectrum. The width of the pump spectrum is basically controlled by the amplitude and the bit rate of the modulating signal. A simple increase in the amplitude of the modulation could produce a broader pump spectrum and hence broader-bandwidth slow light with no need of increasing the bit rate. The high bit rate used in the modulation simply ensures that the pump spectrum seen by the pulse is homogeneous over the full length of fiber. Hence the modulation bandwidth limit of the pump laser does not seem an issue to increase the slow light bandwidth further. The broadened pump is amplified with an erbium-doped fiber amplifier (EDFA) and its intensity is controlled with a variable optical attenuator (VOA). The spectrum of the pump is monitored by the use of a fast detector connected to an electrical spectrum analyzer (ESA). The probe laser is modulated with an external electro-optic modulator to produce a 40-MHz train of smooth 2.7-ns wide pulses. A 6.7-km-long dispersion-shifted fiber with a Brillouin shift of 10.5 GHz and a gain bandwidth of approximately 50 MHz is used as the gain medium, in which the pump and probe are launched in opposite directions. The probe pulse train at the fiber output is amplified to a comfortable level using another EDFA, filtered and amplitude-controlled before being measured by another fast detector and a sampling oscilloscope. We tested our detection scheme for several probe powers with the pump turned off so as to ensure that there was no amplitude-dependent delaying measured by the detection scheme.

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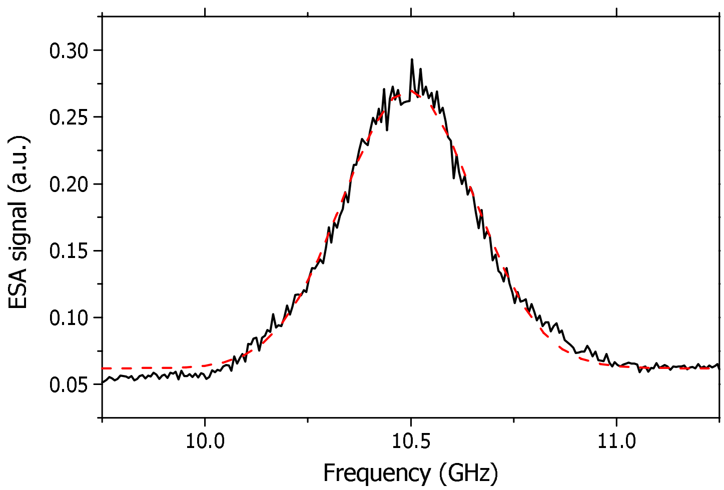

Fig. 2. Pump-probe beating spectrum as recorded in the electrical spectrum analyzer

Figure 2 shows the pump-probe beating as seen in a fast detector. We observe that the broadening is smooth and it can be well approximated by a Gaussian distribution. The relatively high bit rate of the PRBS generator ensures that the effective gain seen by the signal after propagation over the entire fiber length is effectively the convolution of the Brillouin gain of the fiber and the pump spectrum depicted in Fig 2. The pump spectrum fits to a gaussian with a width of approximately 325 MHz. We evaluate the convolution of this gaussian with the lorentzian Brillouin gain and estimate that in this case the delay introduced per logarithmic gain corresponds to approximately 0.092 ns/dB, in good agreement with the analytical prediction made in the previous section.

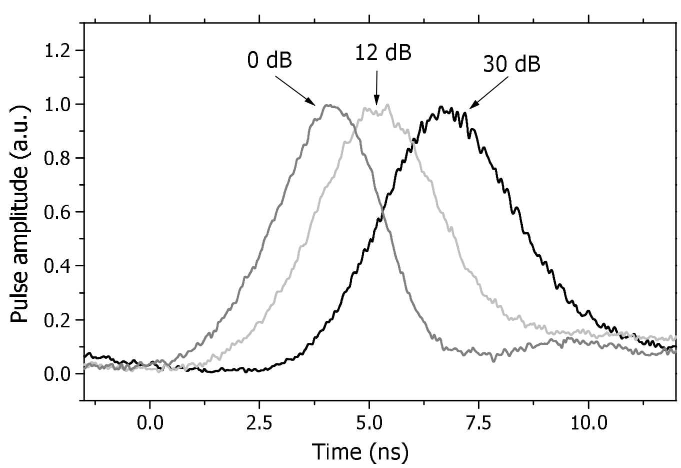

Fig. 3. Pulse waveforms at the fiber output for different gain values.

Figure 3 shows the delaying results of 2.7-ns pulses for several gain values, and Fig. 4 shows the achieved delay values as a function of the gain. We observe a linear dependence of

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the delay with the logarithmic gain with a slope of approximately 0.092 ns/dB, as expected from the theory. By tuning the probe frequency appropriately, we also performed measurements in the Brillouin loss region, obtaining pulse advancement with the same linear dependence on the logarithmic gain. The achievable gain is limited to 30 dB due to the onset of spontaneous Brillouin scattering (the maximum achievable pump power in the fiber is approximately 30 mW). Note that the threshold for amplified spontaneous Brillouin emission appears in this case for a power value that is roughly ten times bigger than in the non-broadened pump case. Although in this configuration the delay is limited to the tenth of the delay achieved in the non-broadened pump configuration, it must be pointed out that the maximum achievable fractional delay (i.e., the delay divided by the pulse length), which is the parameter of interest for real applications, is fully maintained (≈1.1) and can be arbitrarily extended using the method described in reference 11. A small residual broadening of the pulse is also observed for large gain values (≈25%), as expected from the linear theory.

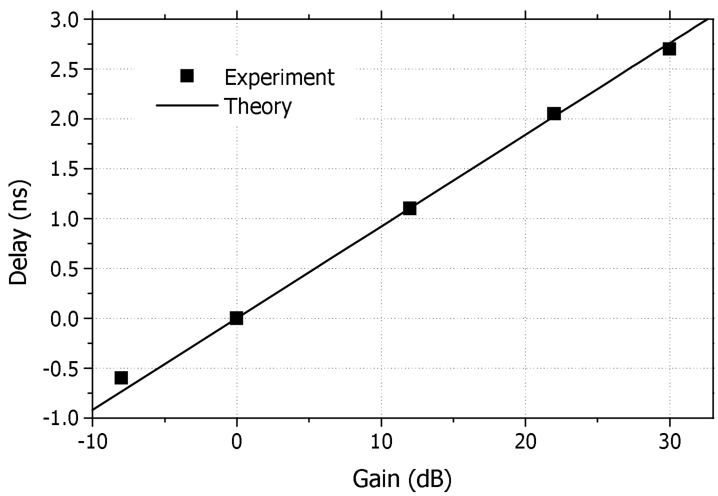

Fig. 4. Delay as a function of the gain achieved in the fiber.

4. Conclusions

We have demonstrated experimentally a method for performing all-optical delaying and advancement of optical pulses of arbitrary bandwidth using stimulated Brillouin scattering that is based on the broadening of the pump spectrum. We have demonstrated a tenfold increase in the available bandwidth of the interaction, and we see no restriction to push this limit beyond to match telecommunication data rates (up to tens of Gbit/s). Furthermore, we see no theoretical drawback to extend this idea to other slow light setups, like those based on population oscillations [17].

Acknowledgments

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