Observation of pulse delaying and advancement in optical fibers using stimulated Brillouin scattering

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Abstract: We demonstrate experimentally that it is possible to control optically the group velocity of an optical pulse as it travels along an optical fiber. To achieve this control we use the effect of Stimulated Brillouin Scattering. In our experiments we have achieved changes in the group index of 10^{-3} in several kilometer-length fibers, thus leading to pulse delaying and advancement in the range of tens of nanoseconds. We believe that this is the first evidence of such optically-controlled strong delay changes in optical fibers. In this paper we derive the basic theory behind these group-delay changes and we demonstrate the effect in two kinds of fibers which are conventionally used.

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

References and links

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1. Introduction

Recent experiments have demonstrated the possibility of optically changing the group velocity of an optical pulse as it travels through a material [1-4]. These experiments have shown that it is possible to slow the speed of light up to nearly stopping it [2] and also faster-than-light propagation of the pulse envelope (although not its information) has been demonstrated [3]. The possibility of slowing or advancing light in optical fibers is very interesting since it can be potentially used for the development of fast-access memories and optically-controlled delay lines which would be compatible with fiber-optic communication systems. To date, there is no known method of having such an optical delay line in optical fibers, although they are believed necessary for the development of the future all-optical packet routers.

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It was recently suggested [5] that it is possible to introduce a delay in a pulse propagating in a single-mode fiber by placing it in the stimulated Brillouin gain region of a moderately powerful, counter propagating pump. In this paper we develop the basic theory behind this phenomenon and we demonstrate this effect experimentally. We also demonstrate fast light propagation in the spectral region of Brillouin loss of the spectrum. To our knowledge, this is the first experimental demonstration of optically-controlled pulse advancement and delaying in optical fibers. Although the changes in the refractive index introduced in our experiments are quite modest (in the order of 10^{-3}), we achieve large pulse delays because of the long lengths of fibers.

From the point of view of applications, stimulated Brillouin scattering (SBS) is a simple, flexible and easy-to-handle effect. Thus, we believe it will be the platform for the development of a wide range of applications in optical signal processing.

2. Theory

In all the experiments of slow and fast light, the presence of narrowband spectral resonances is required. Spectral resonances have a complex response function, so that they introduce an extremely narrowband peak in the absorption/gain characteristics of the medium while there is also a sharp transition in the effective refractive index of the material. This sharp transition induces a strong change in the group index, which is responsible for large changes in the relative delay of an optical pulse as it travels through a material. This situation is depicted in Fig. 1, where the real and complex parts of the refractive index of a Lorentzian absorption have been depicted.

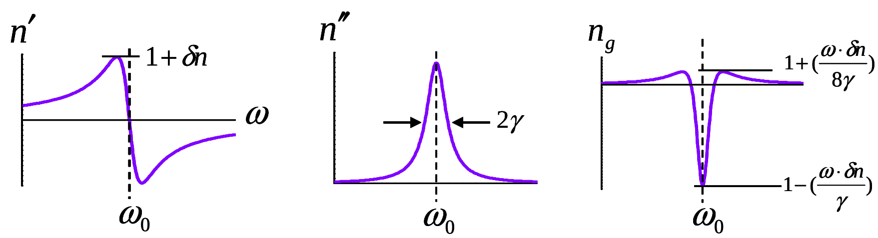

Fig. 1. Relation between the phase constant (n'), the attenuation constant (n'') and the group index (n_g) around the absorption peak centered at ω_0.

In our case we use the narrowband gain and loss mechanisms of SBS to achieve strong changes in the group index of optical pulses. The effect of SBS is usually described as the interaction of two counter propagating waves, a pump wave and a Stokes wave. If particular phase matching conditions are met (namely $f_{Pump}=f_{Stokes}+\nu_B$, ν_B being the Brillouin shift), an acoustic wave is generated. This acoustic wave scatters photons from the pump to the Stokes wave, stimulating the process. From a practical point of view, the process of SBS can be viewed as a narrowband amplification process, in which a continuous-wave pump produces a narrowband (30-50 MHz) gain in a spectral region around f_{Pump}-ν_B.

Assuming $f_{Pump}=f_{Stokes}+\nu_B$, the spatial evolution of the electric fields of pump (A_p) and probe (A_s) waves under SBS is described by following coupled equations [6]:

$$\frac{dA_p}{dz}=-\frac{g_B}{2A_{eff}}\frac{|A_s|^2}{1-2j\left(\frac{\Delta\nu}{\Delta\nu_B}\right)}A_p-\frac{\alpha}{2}A_p \tag{1}$$

$$\frac{dA_s}{dz}=\frac{g_B}{2A_{eff}}\frac{|A_p|^2}{1+2j\left(\frac{\Delta\nu}{\Delta\nu_B}\right)}A_s+\frac{\alpha}{2}A_s \tag{2}$$

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where g_B, A_{eff}, $\Delta\nu$, $\Delta\nu_B$, and α are Brillouin gain coefficient, mode effective area, frequency deviation from ν_B, gain bandwidth and attenuation coefficient, respectively. While the real parts of the equations are related with gain in the Stokes wave or loss in the pump wave, the imaginary parts are responsible for additional phase shifts of the two waves. More specifically, through the SBS process the pump wave induces a phase constant change in the probe wave given by:

$$\Delta\beta = \mathrm{Im}\left(\frac{g_B}{2A_{eff}} \frac{P_P}{1+2j\left(\frac{\Delta\nu}{\Delta\nu_B}\right)} \right) \tag{3}$$

where P_P is the pump power. This change in the phase constant has strong frequency dependence, as shown in Fig. 1. If we consider a pulse propagating at the Stokes wavelength, its velocity will be related to the derivative:

$$v_g = \left(\frac{d\beta}{d\omega}\right)^{-1} \tag{4}$$

Thus, a sudden change in the phase constant with frequency produces a strong change in the group velocity (see Fig. 1). This group velocity change can also be viewed as a group index change (n_g). The group index is related to the phase index (n_p) by:

$$n_g = n_p + \omega \frac{dn_p}{d\omega} \tag{5}$$

and the resultant optical time delay (Δt) described by:

$$\Delta t = \frac{n_g L}{c} \tag{6}$$

where L is the fiber length and c is the speed of light in vacuum. A brief inspection of the equations in this case ($f_{Pump}=f_{pulses}+\nu_B$) reveals that a positive delay is introduced at the pulse wavelength.

By tuning the pulse wavelength so that $f_{Pump}=f_{pulses}-\nu_B$ we would have the case of loss in the pulse. The treatment of the loss case is similar to the gain case but reversing the signs in the coupled equations, so the delay in this case is not positive but negative. This is viewed as certain ‘advancement’ of the pulse with respect to the conventional propagation along the fiber.

We made a simple numerical estimation of the possible optical time delays by the SBS in a standard fiber and a dispersion shifted fiber (DSF). The gain spectrum was assumed Lorentzian shape and the FWHM ($\Delta\nu_B$) was set 50 MHz for DSF and 35 MHz for standard fiber, those are typical values for each kind. The lengths of the fibers were 11.8 km (standard fiber) and 6.7 km (DSF) respectively, which were the same as those used in the experiment. The results are depicted in Fig. 2. The group index variation as a function of the frequency deviation from ν_B is shown in Fig. 2-(a), where Brillouin gain is 20dB. Figure 2-(b) represents the delay time according to Brillouin gain in two kinds of fibers. The negative gain means the situation of loss. It is notable that the delay time is proportional to the total Brillouin gain in logarithmic scale, and the different results of the two fibers come from their different $\Delta\nu_B$’s. Therefore, one can easily control the delay time by changing the Brillouin pump power.

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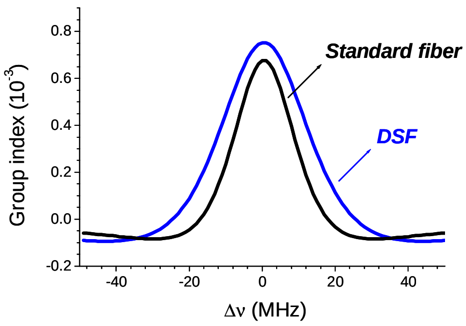

Fig. 2-(a) Group index variation according to frequency deviation from Brillouin frequency. The gain is 20dB when Δν = 0

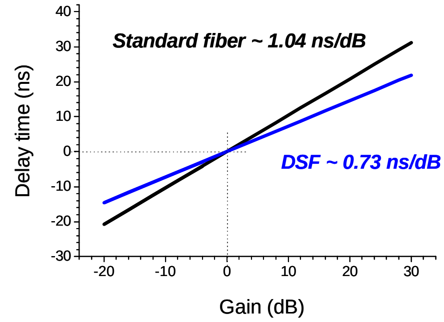

Fig. 2-(b) Delay time as a function of Brillouin gain..

3. Experiment

Figure 3 shows the experimental configuration, in which all signals are generated through the modulation of the light from one laser [7]. This results in an ideal stability as far as the frequency difference between pump and signal is concerned, that is essential regarding the narrow spectral width of the Brillouin gain. To properly observe the delay, a pulse signal is generated while the pump is a continuous wave (CW). A DFB laser diode operating at 1552 nm was used as a light source, and its output was launched to an electro-optic modulator (EOM) to create two first-order sidebands. The carrier wave was suppressed by controlling the DC bias voltage delivered into the EOM with a feedback circuit [7]. The frequency difference between the two sidebands was set to the Brillouin frequency (ν_B) of the test fiber.

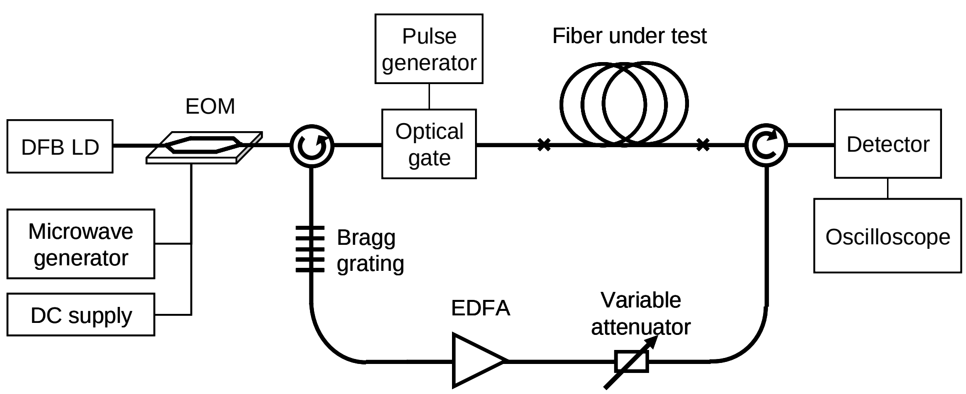

Fig. 3. Configuration to measure variable pulse delay from SBS in an optical fiber

In order to measure the effect of Brillouin gain, the lower sideband was reflected by a narrow band fiber Bragg grating and optically gated to be used as a probe pulse (Stokes wave). As a fast optical gate another EOM was used, resulting in clean pulses with sharp rising and trailing edges. The upper sideband was used as a cw Brillouin pump after amplitude-controlled by an EDFA and a variable attenuator. The time delay of the probe pulse was measured using a digital oscilloscope for different Brillouin gain by varying the pump amplitude from zero to several tens of mW. In the mean time, the output amplitude of the probe pulse on the detector was kept constant to avoid a possible time biasing from an

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amplitude-dependent time response of the detector. The input pulse power on the detector for a 0dB gain was 12 μW and was decreased for higher gain to keep the output amplitude constant, so that the pump is subject to no depletion.

In the case of Brillouin loss experiment, we swapped the roles of the two sidebands, so that the probe pulse has a higher frequency and is therefore an anti-Stokes wave. Then, the measurement was performed in the same way by varying the power of cw pump wave and monitoring the amplitude and the time delay of the probe pulse.

We measured two kinds of test fibers for comparison - a standard fiber (length : 11.8 km, dispersion ~ 17 ps/km/nm) and a dispersion shifted fiber (DSF, length : 6.7 km, dispersion ~ 1.1 ps/km/nm). Their Brillouin frequencies were 10.844 and 10.42 GHz respectively.

4. Result

The traces of the probe pulse in the case of the standard fiber are shown in Fig. 4 with the gain swept from 0dB to 30dB with a step of 5dB. The pulse width (FWHM) was 100 ns. We could see clear retardation of the pulse as the Brillouin gain increased and the maximum delay time was 30 ns when the gain was 30dB. In the case of the DSF, the maximum delay time of 18 ns was observed when the gain was 25dB. In terms of the group index change, they correspond to 7.6×10^{-4} for standard fiber and 8.1×10^{-4} for DSF. A smoothing of the pulse shape was also observed, which is attributed to a low-pass filtering effect resulting from the narrow Brillouin gain bandwidth, that is about 35 MHz for a small gain and even narrower in case of a strong gain. The pulse width was almost maintained nevertheless.

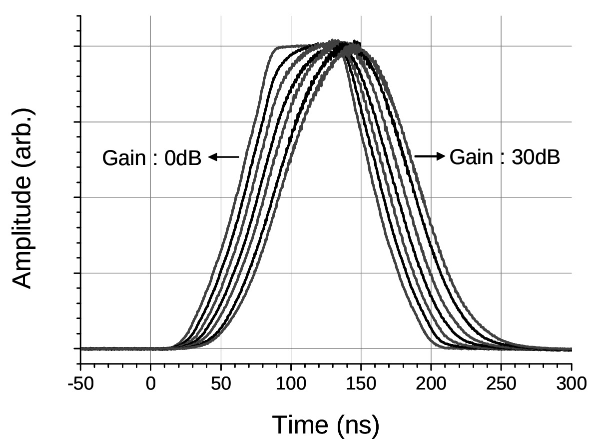

Fig. 4. Traces of the probe pulses for different Brillouin gains (standard fiber), showing a clear delay due to the modified group velocity.

Figure 5 shows the optical delay of the pulse as a function of the Brillouin gain in two fibers. The negative gain indicates the situation of a Brillouin loss measurement. For the determination of the time delay, we measured the delay times of both rising and falling edges at FWHM, and made an average of them. The results match well with a linear fit with slopes of 0.97 ns/dB for the standard fiber and 0.65 ns/dB for the DSF. The smaller delay time and slope of the latter seem to come from its broader Brillouin gain bandwidth due to higher dopant concentration in the core compared to a standard fiber [7].

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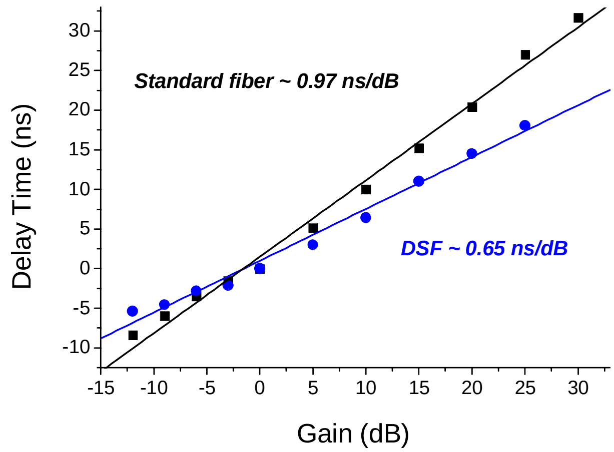

Fig. 5. Delay time of the pulse as a function of the Brillouin gain. In a gain situation the pulse is delayed while it is accelerated in a loss configuration.

When the measurement was performed under large Brillouin loss (< -10dB), we observed more deviation from the fitted line. This is due to unwanted reflection of the other sideband (lower sideband at the pump frequency in the case of Brillouin loss) by the Bragg grating, which turns out to have comparable amplitude for high loss and to superpose with the probe pulse. We also believe this is the origin of overall decrease of the slopes when compared to our numerical estimation shown in Fig. 2. When only positive gain regions are considered, the slopes are 1.07 for the standard fiber and 0.74 for the DSF, which agrees well with our estimated values of 1.04 and 0.73, respectively.

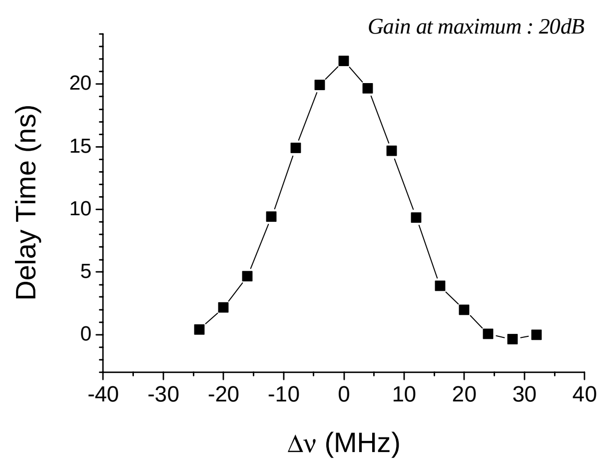

Fig. 6. Delay time of the probe pulse as a function of the modulation frequency deviation ($\Delta\nu$) from ν_B. The pump and the probe powers were fixed.

We also measured the time delay of the pulse while sweeping the modulation frequency on the EOM with the powers of both the cw pump and the probe pulse fixed. This is to confirm that there is no other power-dependent cause to the optical delaying than the Brillouin gain.

The standard fiber was used, and the pump power was set to give 20dB gain at ν_B. The result is depicted in Fig. 6.

One can observe sudden change of delay time around ν_B ($\Delta\nu$=0) with a FWHM of about 25 MHz, and the shape reflects very faithfully the Brillouin gain spectrum in this optical fiber. This is reasonable result when we consider the close relation between the Brillouin gain and the delay time depicted in Fig. 5. We believe this is clear evidence of the role of Brillouin gain as an origin for the optical time delay in the pulse propagation.

The only inconvenience of this optically-controlled delaying method is that the pulse experiences strong amplitude changes depending upon the introduced delay. Further investigations should provide engineering mechanisms to compensate for these amplitude changes while preserving the delay.

5. Conclusion

We have experimentally demonstrated, for the first time to our knowledge, pulse delaying and advancement in optical fibers using stimulated Brillouin scattering. The narrow Brillouin gain produces a rapid variation of the phase constant with frequency, which in turn causes a rather visible modification of the group index of the fiber at the Stokes wavelength. We have measured changes in the group index of 10^{-3}, in good connection with our theoretical estimation. The main limit of this technique for delaying pulses is that it is limited by the Brillouin bandwidth, some 30-50 MHz in usual fibers. This limitation might be easily solved by dithering the pump. However, to obtain the same amount of delay as we presently have, more pump power will be needed. We believe that this optical delaying method will have important implications in all-optical signal processing.

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