Optically-controlled delays in optical fibres using Brillouin-generated slow and fast light

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ABSTRACT

We demonstrate experimentally the optical control of the group velocity along an optical fibre using Stimulated Brillouin Scattering. We have achieved pulse delaying of 30 nanoseconds and group velocity exceeding the vacuum light velocity.

Keywords: delay effects, velocity, single-mode fibres, pulses, nonlinear optics, dispersion, fibre optic sensors

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 fibres 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 optical signal processing and fibre-optic communication systems. To date, there is no known method of having such an optical delay line in optical fibres, although they are believed necessary for the development of the future all-optical packet routers.

It was recently suggested [5] that it is possible to introduce a delay in a pulse propagating in a single-mode fibre by placing it in the stimulated Brillouin gain region of a moderately powerful, counter propagating pump. In this paper we present 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 fibres. For a given fibre the optical delay experienced by the signal turns out to depend only on the total gain (loss) experienced by the signal, so that large delays can be obtained in long fibres using a few mW pump power. But the same gain using high power in short fibres results in a drastic change of the group velocity and group indices ranging from 2.7 down to 0.7 were actually observed, well above the vacuum light velocity in the latter case.

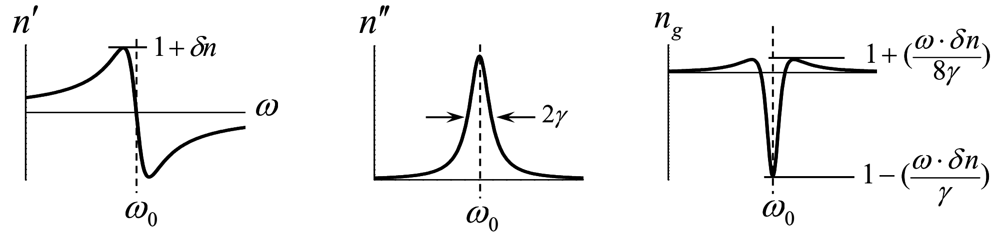

Fig. 1 Relation between the phase constant (n'), the attenuation constant (n'') and the group index (n_g) around the absorption peak centred at ω_0 for a Lorentzian absorption line. The group index change is maximised at the centre of the resonance.

2. PRINCIPLE

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 n of the material. This sharp transition induces a strong change in the group index n_g

$$n_g = n + \omega \frac{dn}{d\omega}$$

While the refractive index n is related to the propagation speed of the light wavefronts, n_g controls the speed at which the envelope of the optical carrier propagates. Hence, a large change in n_g induces large changes in the time delay

17th International Conference on Optical Fibre Sensors, Marc Voet, Reinhardt Willsch, Wolfgang Ecke, Julian Jones, Brian Culshaw, eds., Proceedings of SPIE Vol. 5855 (SPIE, Bellingham, WA, 2005) · 0277-786X/05/$15 · doi: 10.1117/12.623603

$\tau = n_g L / c$ of an optical pulse as it travels through the material. This situation is shown in Fig. 1, where the real and complex parts of the refractive index of a Lorentzian absorption have been depicted. Actually the light signal is slowed down in presence of a gain resonance and accelerated in the case of an absorption line.

In our case we use the narrowband gain and loss mechanisms of SBS to achieve strong changes in the group index of optical pulses. 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, ν_B being the Brillouin shift. We made a simple numerical estimation of the possible optical time delays by the SBS in a standard fibre and a dispersion shifted fibre (DSF). The gain spectrum was assumed Lorentzian-shaped and the FWHM ($\Delta\nu_B$) was set to 35 MHz for a standard fibre and to 50 MHz for a DSF, those are typical values for each fiber type. The expected delays are 1.04 ns per dB gain in a standard fibre and 0.73 ns/dB in a DSF. Since 30 dB gain can be easily obtained using SBS with about 10 mW pump power along a 2 km fibre, delays over 30 ns can be routinely reached, corresponding to a 6 meter optical path change. This delay can be randomly varied by just changing the pump power.

3. EXPERIMENT AND RESULTS

Figure 2 shows the experimental configuration, in which all signals are generated through the modulation of the light from one laser [6]. 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 probe 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 into 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 [6]. The frequency difference between the two sidebands was set to the Brillouin frequency (ν_B) of the test fibre.

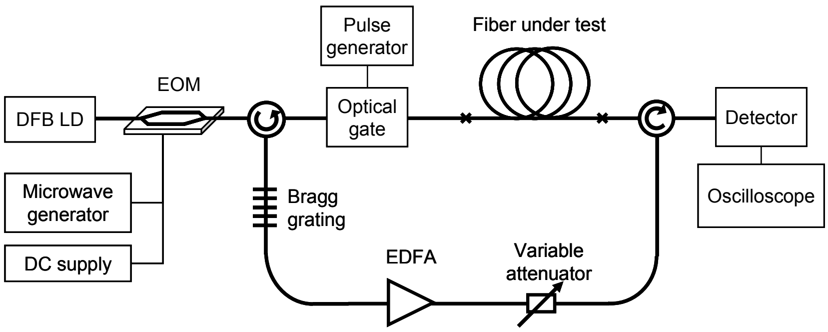

Fig. 2. Configuration to measure variable pulse delay from SBS in an optical fibre

In order to measure the effect of Brillouin gain, the lower sideband was reflected by a narrow band fibre Bragg grating and optically gated to be used as a Stokes probe pulse. Another EOM was used as a fast optical gate, resulting in clean pulses with sharp rising and trailing edges. The upper sideband was used as a CW Brillouin pump after being 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 addition the output amplitude of the probe pulse on the detector was kept constant to avoid a possible time biasing from an amplitude-dependent time response of the detector. The input pulse power on the detector for a 0 dB 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, and propagated an anti-Stokes probe pulse together with a CW pump wave. Then, the measurement was performed in the same way by varying the power of the CW pump wave and monitoring the amplitude and the time delay of the probe pulse.

We measured two kinds of test fibres for comparison - a standard fibre (length: 11.8 km, dispersion: ~ 17 ps/km/nm) and a dispersion shifted fibre (DSF, length: 6.7 km, dispersion: ~ 1.1 ps/km/nm). Their Brillouin frequencies were 10.844 GHz and 10.420 GHz, respectively.

The traces of the probe pulse in the case of the standard fibre are shown in Fig. 3-(a) 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 x 10^{-4} for standard fibre and 8.1 x 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 small gain and even narrower for higher gain. The pulse width was almost maintained nevertheless.

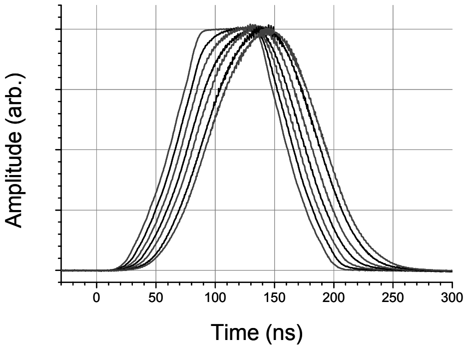

Fig. 3-(a) Traces of the probe pulses for different Brillouin gains (standard fibre), showing a clear delay due to the modified group velocity

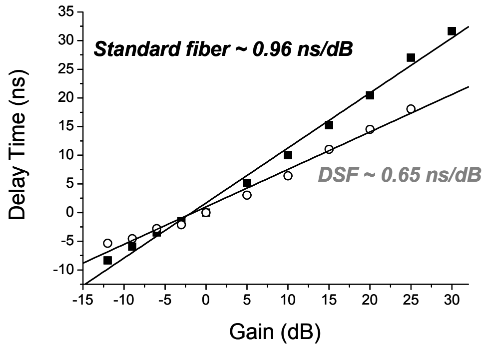

Fig. 3-(b) Delay time of the pulse as a function of Brillouin gain. In a gain situation the pulse is delayed while it is accelerated in a loss configuration.

Figure 3-(b) shows the optical delay of the pulse as a function of the Brillouin gain in the two fibres. 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 0.96 ns/dB for the standard fibre 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 fibre [6].

When the measurement was performed under large Brillouin loss (< -10dB), we observed more deviation from the fitted line. This is due to residual reflection of the other sideband (Stokes wave 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 the overall decrease of the slopes when compared to our numerical estimation. When only positive gain regions are considered, the slopes are 1.07 ns/dB for the standard fibre and 0.74 ns/dB for the DSF, which agrees well with our estimated values of 1.04 ns/dB and 0.73 ns/dB, respectively.

Since the delay (advancement) only depends on the overall gain (loss) experienced along the full fibre length for a given type of fibre, the group index change can be drastically increased by realizing the same gain (loss) over a shorter fibre using a higher pump power. In other words the index change will scale in the inverse proportion of the fibre length for a fixed gain (loss) to maintain the same delay. Actually the group index change will vary from the 10^{-3} range for kilometre-long fibres to the unity range for meter-long fibres. In this latter case it is thus possible to conceive a system with a group index smaller than 1, hence faster than the vacuum light velocity.

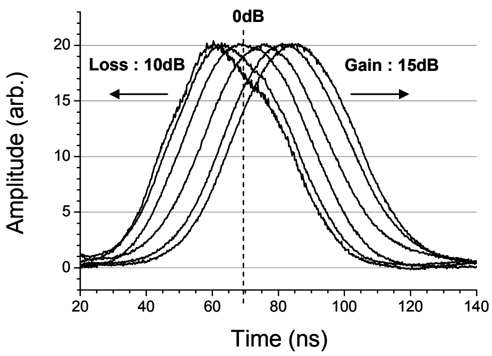

Fig. 4-(a) Waveforms of the probe pulses for different Brillouin gains and losses in a 4-m standard fibre. Considerable distortion is observed in the case of fast light (loss) to keep compliant with relativity.

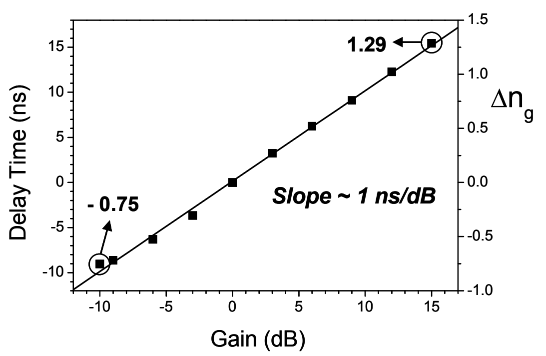

Fig. 4-(b) Peak position of the probe pulses and the equivalent group index change as a function of Brillouin gain in a 4-m standard fibre. Extreme group index changes are highlighted.

We could experimentally verify that this amazing situation can be actually realized. The same experiment was carried out in a sample of 4m of standard single mode fibre. The main issue was to raise the pump power to the 10 Watt range to achieve a 30 dB gain using SBS over a short fibre. This could be achieved by forming a pulse train with the pump wave, so that the full gain is achieved in the EDFA while the average output power is kept below the saturation power. The pulse duration is made longer than twice the propagation time in the fibre sample, so that the signal pulse sees a constant pump power while propagating throughout the entire fibre sample. This just requires a perfect synchronization of the 2 pulse trains to make them overlap during the propagation in the fibre sample.

Fig. 4-(a) shows time waveforms of pulses experiencing different gains and losses through SBS in the short fibre. The observed delays are fully comparable in this 4 m sample to those obtained along several kilometres of fibre. Fig. 4-(b) shows the pulse peak position as a function of the gain (loss) experienced by the signal and the equivalent group index change. This index could be increased continuously from 1.46 in normal conditions to 2.75 under high Brillouin gain, and lowered to 0.7 under high Brillouin loss, that is substantially *faster than the vacuum light velocity*. In other words the group velocity could be changed continuously from ~110’000 km/s to ~430’000 km/s in the fibre sample (~205’000 km/s in normal conditions), leading to the impressive delays from -10 ns to +15 ns in only 4 meter of fibre. It means that the fibre effective length can be continuously changed from 2 m to 7 m.

It must be pointed out that a group velocity faster than the vacuum light velocity *c* does not break the famous principles resulting from the theory of special relativity, as demonstrated in an excellent treatise written by Brillouin himself [7]. The information velocity cannot exceed *c* and in our case “information” means presence or vanishing of the pulse. It means that the starting point of the pulse (beginning of leading edge) and the ending point (end of trailing edge) cannot propagate faster than the speed of light, because these only 2 points are essential for determining the presence or absence of the pulse. But the pulse peak can propagate at the group velocity and thus faster than the speed of light, since the peak position is not essential for determining the presence of the pulse in the time domain and in a causal view. This leads to a severe distortion of the pulse in the case of fast light (starting and ending points at light velocity, peak point at group velocity), resulting in a steeper leading edge and a longer trailing edge. This can be clearly observed in Fig. 4-(a) in the case of strong pulse advancement.

4. CONCLUSION

We demonstrated experimentally for the first time that propagation delays can be optically controlled in an optical fibre. This opens a wide field of applications in the field of sensors and optical signal processing, such as variable delay lines, optical storage and increase of the effective length of the fibre for nonlinear effects. This has also a big interest in telecommunications for controlling the timing of signals to avoid collisions in routing applications.

Such a system also may lead to very unusual situations in which the group velocity can reach extremely large values on one hand or a superluminal situation (“faster than light”) on the other hand. These early experiments are very promising and other astonishing observations are expected in a near future. The fact that slow and fast light can be achieved in a standard single fibre, in normal environmental conditions and using off-the-shelf instrumentation, is very promising and, since stimulated Brillouin scattering (SBS) is a simple, flexible and easy-to-handle effect, it will certainly be the platform for the development of a wide range of applications in optical signal processing.

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