Light controlling light in an optical fibre: from very slow to faster-than-light speed

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We demonstrate a method to achieve an extremely wide and flexible external control of the group velocity of signals as they propagate along an optical fibre. This control is achieved by means of the gain and loss mechanisms of stimulated Brillouin scattering in the fibre itself. Our experiments show that group velocities below 71,000 km/s on one hand, well exceeding the speed of light in vacuum on the other hand and even negative group velocities can readily be obtained with a simple benchtop experimental setup. The experimental result shows tuneable optical delay as much as 152 ns with a 40 ns pulse.

Introduction

The active control of the speed of a light signal in an optical fibre is attracting much attention for the development of fast-access memories and optically-controlled delay lines compatible with optical computing and fibre-optic communication systems. Recently a large effort has been carried out for realizing such an optically-controlled delay line in optical fibres, since they are believed necessary for the development of the future all-optical packet routers. Successful experiments to widely control the light group velocity have been reported these past few year [1], showing the possibility to slow the speed of light up to nearly stopping it or to achieve group velocity exceeding the vacuum light velocity *c* [2,3]. Strong negative group velocities have also been demonstrated [4]. But all these experiments use special media like cold atomic gases [5-7] or electronic transitions in crystalline solids [8] working at well defined wavelengths. Previous works have demonstrated the possibility of achieving superluminal group velocities in optical fibres [9], but with no optical control. Here we summarize our work this past year demonstrating for the first time a wide optical control of the signal velocity in an optical fibre, realized with the recently suggested approach of using the narrow band gain or loss generated by a nonlinear optical interaction, the stimulated Brillouin scattering [10]. The high flexibility of this interaction makes this active control possible in any type of fibre and at any wavelength, in particular in the low loss window of optical fibres.

Theoretical background

Stimulated Brillouin Scattering (SBS) is usually described as the interaction of two counter propagating waves, a strong pump wave and a weak probe wave [11]. If particular phase matching conditions are met (namely $f_{Pump}=f_{probe}+\nu_B$, ν_B being the Brillouin shift), an acoustic wave is generated. This acoustic wave scatters photons from the pump to the probe 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 $f_{Pump}-\nu_B$.

Assuming $f_{Pump}=f_{probe}+\nu_B$ and no pump depletion, the spatial evolution of the electric field amplitudes of pump (A_p) and probe (A_s) waves under SBS is described by the following coupled equations:

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

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

where g_B is the Brillouin gain coefficient, A_{eff} the mode effective area, $\Delta\nu$ the frequency deviation from ν_B, $\Delta\nu_B$ the gain bandwidth and α the linear attenuation coefficient. The usual treatment of these equations in the literature has basically concentrated on the intensity increase of the probe wavelength, which can be described with the exponential law $I_s(L)=I_s(0)exp(g_B I_P L)$. However, while the real parts of the equations are related with gain in the probe wave or loss in the pump wave, the imaginary parts are responsible for additional phase shifts undergone by the two waves [11]. More specifically, through the SBS process the pump wave induces a propagation constant change in the probe wave given by:

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

where I_P is the pump power intensity in the fibre. This change in the propagation constant has strong frequency dependence, as shown in Fig. 1. If we consider a pulse propagating at the probe wavelength, its velocity will be related to the group velocity $v_g=(d\beta/d\omega)^{-1}$. Thus, a sudden change in the propagation constant with frequency produces a strong change in the group velocity, which in turn introduces an additional delay of the pulse at the fibre output, $\Delta t=L/v_g$. If the frequency difference between pump and probe exactly matches the Brillouin shift ($\Delta\nu = 0$), the resultant optical time delay is given by $\Delta t=g_B I_P L/(2\pi\Delta\nu_B)$. We can thus say that the delay varies logarithmically with the net gain (loss) experienced by the probe. A fast evaluation of these quantities in conventional single-mode fibres ($\Delta\nu_B \approx 35$ MHz) leads to a surprisingly simple rule-of-thumb: 1 ns delay is introduced per dB gain introduced in the probe.

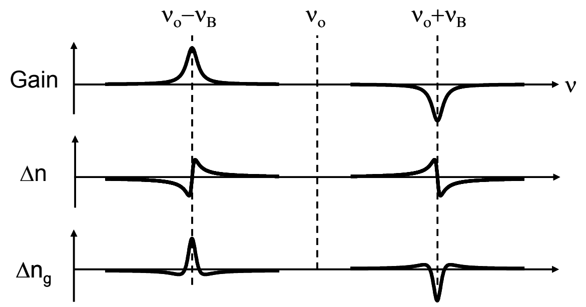

Fig. 1 Principle of signal delaying and advancement using stimulated Brillouin scattering.

So far we have treated the case of gain in the probe, this is $f_{Pump}=f_{probe}+\nu_B$. In this case, an extra delay is introduced in the probe signal with respect to the normal propagation time along the fibre. By tuning the probe wavelength so that $f_{Pump}=f_{probe}-\nu_B$ we observe loss at the probe wavelength. The treatment of the loss case is exactly the same to the gain case but changing the roles of pump and probe in the coupled equations, so the delay in this case is not positive but negative. This is viewed as an advancement of the pulse with respect to the conventional propagation along the fibre.

Experiment and results

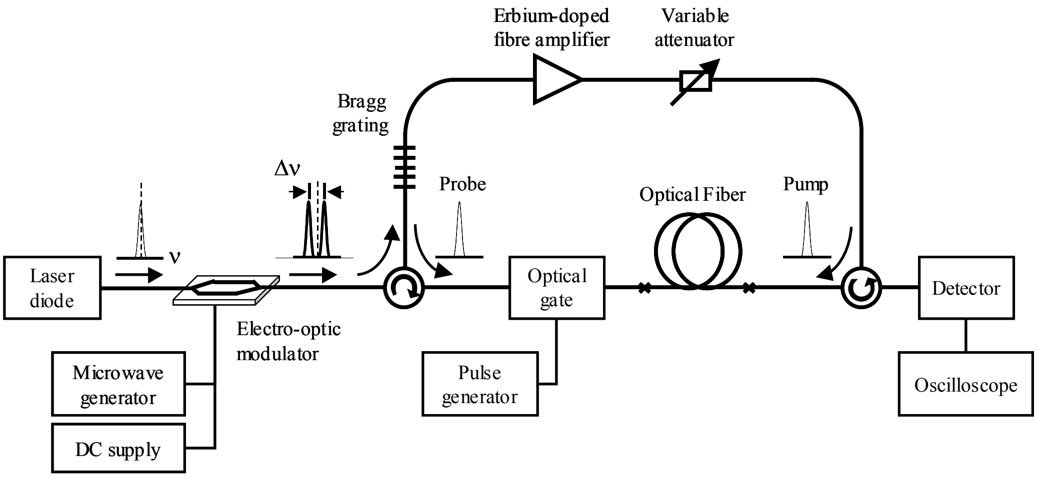

Fig. 2. Experimental configuration.

Figure 2 shows the experimental setup, in which the pump and probe signals are generated through the modulation of the light from one laser [12]. 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 and the frequency difference between the two sidebands was set exactly to the Brillouin frequency ν_B of the test fibre, that is around 10.8 GHz at this wavelength for standard fibres.

In order to measure the effect of Brillouin gain, the lower-frequency sideband was reflected by a narrow band fibre Bragg grating and optically gated to be used as a probe pulse. For this purpose another EOM was used as a fast optical gate, resulting in clean pulses with sharp rising and trailing edges. The higher-frequency sideband was used as the CW Brillouin pump after being amplitude-controlled by a broadband erbium-doped fibre amplifier and a variable attenuator. The time delay of the probe pulse was measured for different Brillouin gains by varying the pump amplitude from zero to several tens of mW. In the case of the Brillouin loss experiment, we swapped the roles of the two sidebands, so that the higher-frequency sideband was used to build the probe pulse and the lower frequency sideband was used to build the 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.

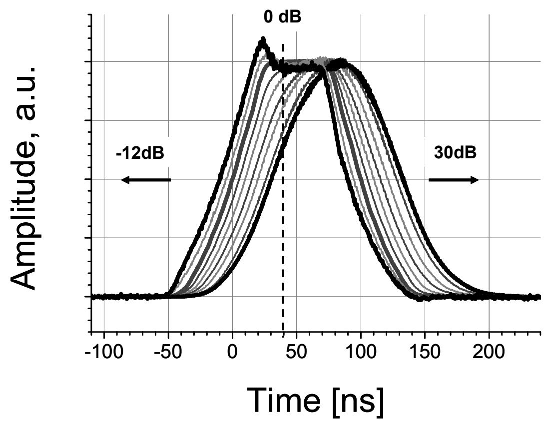

Fig. 3 Pulse waveforms and delay according to Brillouin gain and loss in 11.8 km standard fibre using 100 ns pulse.

We first observed the delaying effect along a 11.8 km standard single mode fibre with the gain swept continuously from 0 dB to 30 dB. The probe pulse width (FWHM) was 100 ns and the maximum pump power was about 40 mW, limited basically by the threshold for amplified spontaneous Brillouin emission. We could see clear retardation of the pulse as the Brillouin gain increased and the maximum delay time was close to 30 ns when the gain was 30 dB. This corresponds to a 7.6×10^{-4} group index change and the delay varies logarithmically with the net gain with a slope of 1.07 ns/dB, in good agreement with the theoretical prediction. Pulse advancement was also clearly observed in the loss configuration with a maximum value of -8.4 ns for a corresponding loss of -12 dB. A larger loss was practically difficult to obtain, non-attenuated residual signals at different wavelengths superposing with the probe pulse with comparable amplitudes. The time waveforms and the optical delay as a function of dB-gain are shown in Fig. 3. The distortion of the pulse shape came from the filtering effect due to the narrow bandwidth.

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, or even negative, with the pulse maximum emerging out of the fibre before it actually enters the fibre.

We could experimentally verify that this extreme situation can be actually realized [13]. The same experiment was carried out in a sample of 2 m of standard single mode fibre. The main issue was to raise the pump power to 10 Watt range to obtain a 30 dB gain using stimulated Brillouin scattering over the short fibre. This could be achieved by forming a pulse train with the pump wave, so that the full gain is available in the erbium-doped fibre amplifier while the average output power is kept below the saturation power. Thus an additional electro-optic modulator was used to gate the pump pulse. This gating was synchronized with the probe pulse and the pump pulse was 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.

Fig. 4-(a) shows time waveforms of pulses experiencing different gains and losses through stimulated Brillouin scattering in the short fibre. The observed delays in this 2 m sample are fully comparable 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. As it can be seen, the group index

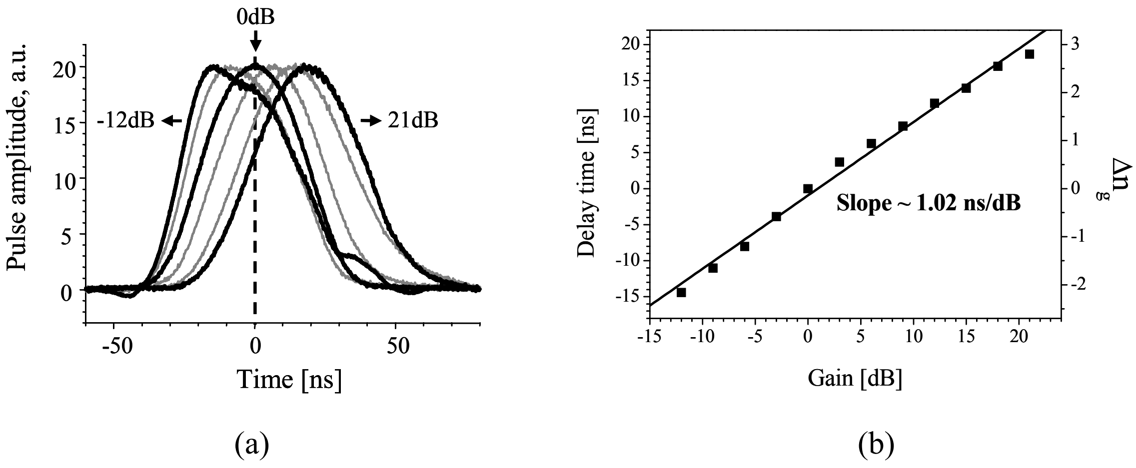

Fig. 4. (a) Pulse waveform at the fibre output; (b) Pulse delay and group index modification achieved using 2-m standard fibre with 40 ns pulse.

could be increased continuously from 1.46 in normal conditions to 4.26 under high Brillouin gain, and lowered to -0.7 under high Brillouin loss, a negative group index meaning that the pulse peak exits the fibre before it enters. In other words, the group velocity could be changed continuously from 70’500 km/s to infinite and then to -428’000 km/s (~205’000 km/s in normal conditions), leading to impressive delays from -14.4 ns to +18.6 ns in only 2 meter of fibre. In terms of length, this means that the fibre effective length can be continuously changed from -3 m to 3.8 m.

It must be pointed out that a group velocity faster than the vacuum light velocity *c* or even negative does not break the famous principles resulting from causality and relativity. The fact that the spectral transition is narrowband prevents all frequency components from experiencing the same group velocity and amplitude response, so that the information cannot finally propagate at a speed faster than *c* [5]. This leads to a severe distortion of the pulse in the case of fast light (starting and ending points at normal light velocity in the medium and non-attenuated, peak point at modified group velocity and attenuated), 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. In the case of pulse delaying, the peak of the pulse is substantially amplified with respect to the leading and trailing edges, and the symmetry of the pulse appears better preserved.

In order to extend the time delay, we introduced a new configuration composed of cascaded fibre segments including unidirectional optical attenuators in the fibre junctions as shown in Fig. 5 [14]. Four uniform fibre spools with the same Brillouin frequency and length of 1.1 km were used as gain media, and they were cascaded using unidirectional variable attenuators as shown in the inset.

In this configuration, the amplification of the probe pulse

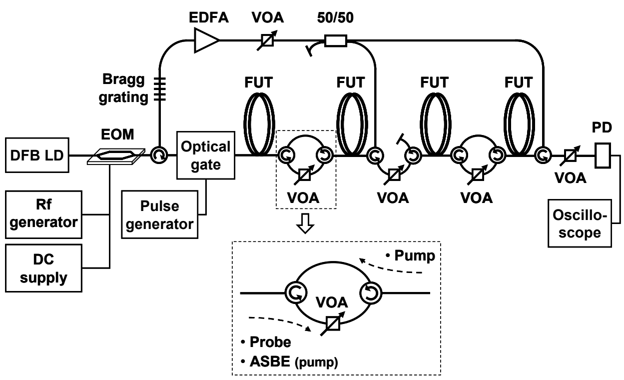

Fig. 5 Experimental setup using cascaded fibre structure and unidirectional attenuators.

was periodically compensated by the variable optical attenuator (VOA), while the counter-propagating pump wave did not experience the attenuation. This feature helped avoiding the gain saturation coming from large amplification of the pulse, maintaining the induced optical delay. In addition, the depletion of the strong pump wave due to ASBE was also avoided by the periodic step absorption of the CW backscattered wave.

The time waveforms of the probe pulses are shown in Fig. 6 according to the gain swept from 0dB to 120dB. A Gaussian-shaped pulse was used as the probe with an initial pulse width (FWHM) of 42 ns. Clear time delay was observed as the gain increased and the maximum delay of 152 ns was achieved when the gain was 120dB, which corresponds to 3.6 times the initial pulse width. In the mean time, a considerable broadening of the pulse from 42 ns to 102 ns was also observed which is attributed to the narrow gain.

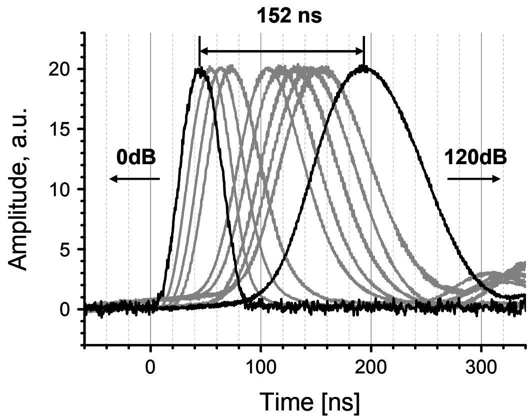

Fig. 6 Time waveforms of the probe pulses for different Brillouin gains, showing a time delay much exceeding the initial pulse width (42 ns)

To summarize, we have demonstrated a wide control of the group velocity of light signals in optical fibres using stimulated Brillouin scattering. With this effect we have achieved nearly all results obtained using atomic transitions, from delays widely exceeding the optical pulse duration to superluminal propagation and even negative group velocity. This experiment can be realized on a tabletop in normal environmental conditions, so that it could be the platform for the development of a wide range of applications.

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