Slow, Superluminal and Negative Group Velocity in Optical Fibres Using Stimulated Brillouin Scattering

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Abstract *Active control of the group velocity in optical fibres is demonstrated, allowing long delays, faster-than-light propagation and even negative velocity, for which the peak of a pulse exits the fibre before entering the input end.*

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. Until recently there was no known method of realizing such an optically-controlled delay line in optical fibres, although they are believed necessary for the development of the future all-optical packet routers. Successful experiments to widely control the light group velocity has been widely reported these past few years [1]. Extreme cases like negative group velocity have even been demonstrated. But all these experiments use special media like cold atomic gases [2] or electronic transitions in crystalline solids [3] working at well defined wavelengths. We demonstrate here the possibility to optically control the signal velocity in an optical fibre. This is realized through the unprecedented approach of using the narrow band gain or loss generated by a nonlinear optical interaction, the stimulated Brillouin scattering. 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. Using stimulated Brillouin scattering 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.

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 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.

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, counterpropagating pump. Stimulated Brillouin scattering is a very convenient and flexible tool to generate a sharp spectral transition at room temperature and in a disordered medium such as amorphous silica. A monochromatic pump wave at λ=1550nm will produce a 30 MHz narrow gain/loss Lorentzian line at this wavelength. This paper not only demonstrates that optically-controlled delays can be obtained using this mechanism, but also that the extreme cases of slow and fast light propagation can be simply realized in conventional optical fibres, at room temperature and using off-the-shelf devices.

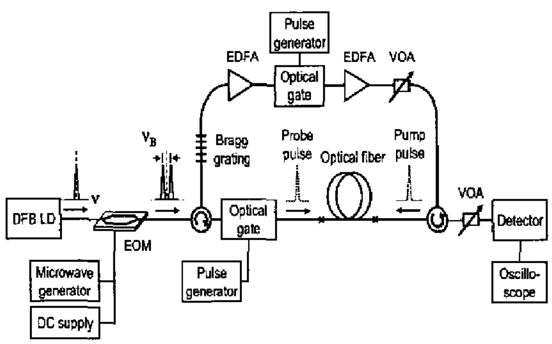

Fig. 1. Configuration to actively control the group velocity of a pulse using SBS in an optical fibre.

Fig. 1 shows our 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 distributed-feedback laser diode operating at 1552 nm was used as a light source and its output was launched into an electro-optic modulator to create two first-order sidebands. The carrier wave was suppressed by controlling the DC bias voltage delivered into the electro-optic modulator [6]. The frequency difference between the two sidebands was set to the Brillouin frequency ν_B of the test fibre.

Results

We first observed the delaying effect along a 12 km standard single mode fibre with the gain swept continuously from 0 dB to 30 dB [4]. 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 x 10^{-4} group index change and the delay varies logarithmically with the net gain with a slope of 1.07 ns/dB. Pulse advancement of -10 ns was also clearly observed in the loss configuration for a corresponding loss of -10 dB.

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 peak exiting the fibre before it actually enters the fibre.

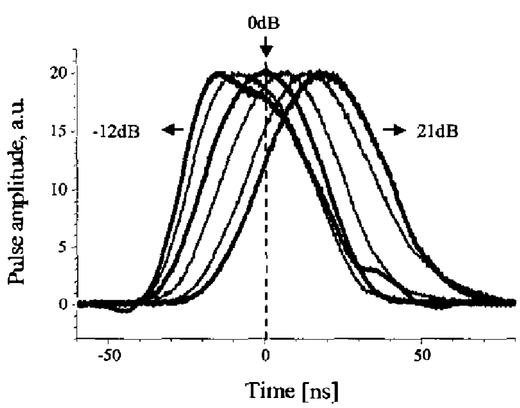

Fig. 2 Traces of the probe pulses for different Brillouin gains and losses in a 2-m test fibre, showing clear delay and advancement due to the modified group velocity.

We could experimentally verify that this extreme situation can be actually realized. The same experiment was carried out in a sample of 2 m of standard single mode fibre. Fig. 2 shows time waveforms of pulses experiencing different gains and losses in the short fibre. The observed delays are fully comparable in this 2 m sample to those obtained along several kilometres of fibre.

Fig. 3 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 4.26 under high Brillouin gain, and lowered to -0.7 under high Brillouin loss, that is a highly superluminal propagation. In other words the group velocity could be changed continuously from 70'500 km/s to infinite and further then to -428'000 km/s in the fibre sample (205'000 km/s in normal conditions), leading to the impressive delays from -14.4 ns to +18.6 ns in only 2 meter of fibre.

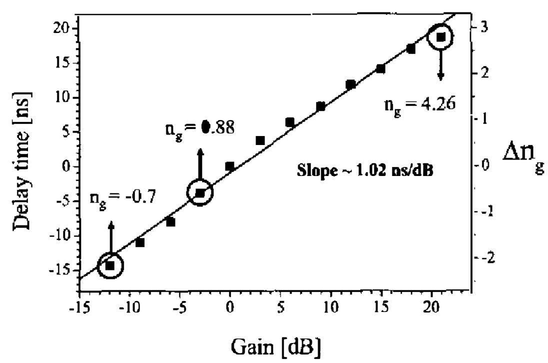

Fig. 3 Measured delay of the pulse peak as a function of gain experienced by the probe pulse through stimulated Brillouin scattering. The corresponding group index change is indicated on the right vertical axis. Some important values of the group indexes are indicated by circles.

We recently proved for 40 ns FWHM pulses that these delays can be extended to 152 ns using 4 cascaded fibre segments separated by broadband attenuators [5].

Conclusions

We have demonstrated a wide-range control of the group velocity of light signals in optical fibres using stimulated Brillouin scattering. The signal speed can be continuously varied by another light signal using this nonlinear interaction that can be readily activated in any type of fibre at any wavelength.

References

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