Long optically controlled delays in optical fibers

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Optically controlled delay lines in optical fibers are demonstrated by use of the group-velocity control of signal pulses based on stimulated Brillouin scattering. We achieve continuous time delay within the range of 150 ns, much larger than the width of the 40 ns signal pulse, using cascaded fiber segments joined by unidirectional optical attenuators. In the meantime, we also observe a large amount of pulse broadening, which agrees well with a theoretical prediction based on linear theory. © 2005 Optical Society of America

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The development of optically controlled delay lines in optical fibers is one of the key challenges in the field of all-optical signal processing and all-optical fiber-optic communication systems. To date, there has been no known method of realizing such optically controlled delay lines in optical fibers, although they are believed necessary for the development of future applications such as all-optical packet routing and random access memories. Several experiments to widely control the light group velocity have been variously reported these past few years based on electromagnetically induced transparency[1,2] (EIT) or stimulated scattering processes.[3,4] Although most of the research up to now has focused on a wide group-velocity control, few experiments have actually shown delays larger than a pulse width. Kasapi *et al.*[5] demonstrated time delays as large as four pulse widths with no lengthening of the pulse by use of EIT in a lead vapor cell. Several papers have also explored the fundamental limits of the slow-light time delay and the relation between delay and pulse distortion.[6–8]

Up to now, most of the slow-light experiments have been performed in special media like atomic vapors[2,5] or specific crystalline solids,[3,4] working at well-defined wavelengths. In a previous work,[9] we reported the first experimental demonstration of optically controlled pulse advancement and delay in optical fibers by use of the stimulated Brillouin scattering (SBS) effect. Modest changes in the group index of the order of 10^{-3} were introduced in long lengths of fiber ($\sim$10 km), resulting in overall delays of up to 30 ns. Reference 9 was the realization of the recently suggested approach[10] of using the narrowband gain of SBS to achieve noticeable changes in the fiber group index. The delays that we achieved, however, were practically limited by pump depletion and amplified spontaneous Brillouin emission (ASBE).

In this Letter we demonstrate tunable, optically controlled time delays within the range of 150 ns by use of SBS in optical fibers, nearly four times larger than the initial pulse width that we use experimentally. To avoid the limiting effects of pump depletion and ASBE, we use a delaying structure composed of cascaded fiber segments joined by unidirectional optical attenuators. In the meantime, we also observe a large amount of pulse broadening, which agrees with a theoretical prediction based on linear theory.[6–8] To our knowledge, this wide-range optical control of the delay time—much larger than the pulse width—is unprecedented in optical fibers.

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 a 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. In our case, we use the narrowband gain mechanism of the SBS to achieve strong changes in the group index of optical pulses.

Figure 1 shows the relation between Brillouin gain, the phase-index change (Δn), and the resultant group-index change (Δn_g) generated by SBS in an optical fiber. 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, $f_{\text{Pump}}=f_{\text{probe}}+\nu_B$, ν_B being the Brillouin shift), an acoustic wave is generated and it scatters photons from the pump to the probe wave, stimulating the process. From a practical point of view, the SBS can be regarded as a narrowband amplification process, in which a strong pump wave produces a narrowband gain in a spectral region around $f_{\text{Pump}}-\nu_B$ and a loss around $f_{\text{Pump}}+\nu_B$. A refractive-index change is associ-

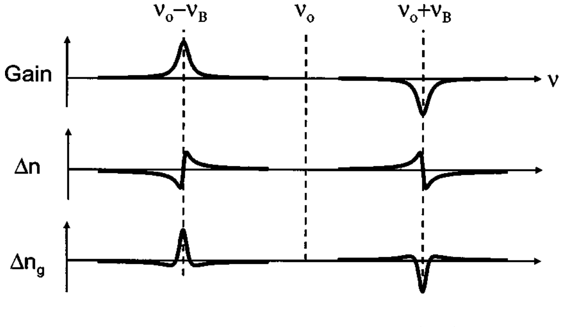

Fig. 1. Gain, refractive-index change (Δn), and group-index change (Δn_g) generated by SBS in an optical fiber. ν_0 and ν_B are the optical frequencies of the Brillouin pump wave and the Brillouin shift of the fiber, respectively.

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ated with the Brillouin gain–loss process, and a substantial change of the group index $n_g = n + \omega \mathrm{d}n/\mathrm{d}\omega$ is acquired as a result of the sharp index transition, as depicted in Fig. 1.

The optical time delay induced by a pump on a counterpropagating signal at $f_{\mathrm{Pump}} - \nu_B$ depends only on the overall gain experienced by the signal. The relation between gain and delay is logarithmic, and the slope in standard fibers is around 1 ns/dB.[9] In our previous SBS-based delay setup,[9] there was a practical limitation of ~30 dB in the achievable Brillouin gain that came from pump depletion due to large amplification of the pulse and the ASBE of the strong pump wave. Considering the width of the signal pulses (~30 ns) that could be used without serious broadening due to the limited Brillouin gain bandwidth ($\Delta\nu_B \sim 30$ MHz), the delay limitation was close to only one pulse length.

To extend the time delay, we introduced a new configuration composed of cascaded fiber segments including unidirectional optical attenuators in the fiber junctions as shown in Fig. 2. Four uniform fiber spools with the same ν_B of 10.736 GHz and length of 1.1 km were used as gain media, and they were cascaded with unidirectional variable attenuators as shown in the inset. In this configuration, the amplification of the probe pulse was periodically compensated by the variable optical attenuator (VOA), whereas the counterpropagating pump wave did not experience the attenuation (except the insertion loss of the circulators). This feature helped avoid the gain saturation coming from large amplification of the probe 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.

A distributed-feedback laser diode operating at 1552 nm was used as the 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 with a feedback circuit.[11] The frequency difference between the two sidebands was set to the ν_B of the fiber by applying a cw microwave signal at $\nu_B/2$. The lower-frequency sideband (Stokes wave) was reflected by a narrowband fiber Bragg grating and optically gated to be used as a probe pulse. As a fast optical gate, another EOM was used, resulting in clean pulses with no ripple. The other sideband (anti-Stokes wave) was amplified to be used as a Brillouin pump wave with a high-power Er-doped fiber amplifier, and a VOA was used to control the amplitude of the pump wave. We split the Brillouin pump in two by use of a 50/50 directional coupler, and each fraction of the pump was used to pump two fiber segments. This configuration is better than plainly introducing the pump through the last fiber segment because it keeps better uniformity of the Brillouin gain through the fiber segments. The time delay of the probe pulse was measured with a digital oscilloscope for different Brillouin gain values, varying the pump power from 0 to ~100 mW for each segment. In the meantime, we applied the same amount of loss to each unidirectional attenuator to compensate the Brillouin gain, and the output amplitude of the probe pulse on the detector was kept constant with another VOA to avoid a possible time biasing from an amplitude-dependent time response of the detector.

The time waveforms of the probe pulses are shown in Fig. 3 according to the gain swept from 0 to 120 dB. 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 a maximum delay of 152 ns was achieved when the gain was 120 dB, which corresponds to 3.6 times the initial pulse width. In the meantime, a considerable broadening of the pulse from 42 to 102 ns was also observed. According to the usual linear theory,[6–8] there is an intimate relationship between the pulse broadening and the pulse delay, and this broadening is the result of the bandpass filtering caused, in our case, by the limited bandwidth of the SBS amplifying chain. The pulse width W is given by

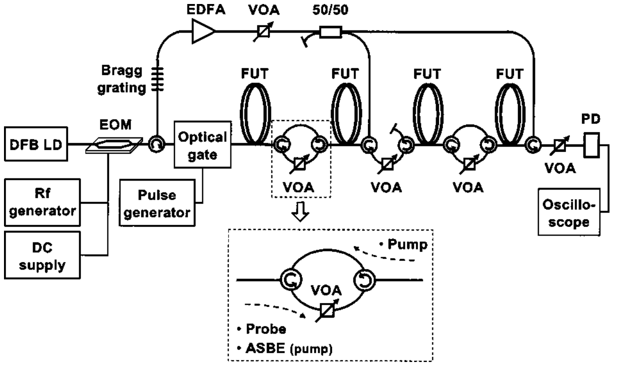

Fig. 2. Experimental setup for optically controlled delay lines based on SBS by use of cascaded fiber segments. Inset, unidirectional attenuator located in the junction of the segments: DFB LD, distributed feedback laser diode; FUT, fiber under test; EDFA, Er-doped fiber amplifier; PD, photodetector.

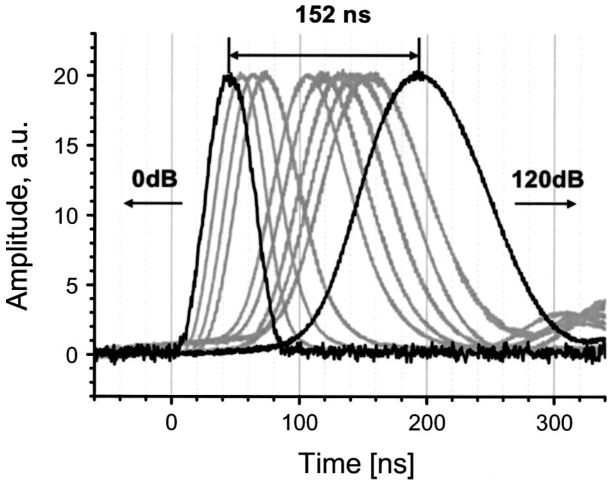

Fig. 3. Traces of the probe pulses for different Brillouin gains, showing a time delay much exceeding the initial pulse width (42 ns).

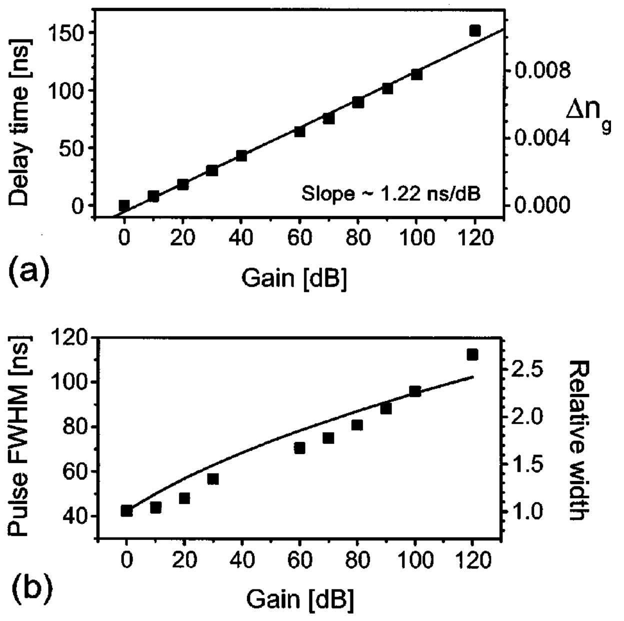

Fig. 4. (a) Measured delay as a function of the Brillouin gain experienced by the probe pulse in four 1.1 km fiber segments. The corresponding group-index change is indicated on the right vertical axis. (b) Measured pulse width (FWHM) with respect to Brillouin gain. The relative width (indicated on the right axis) is the ratio between the output and the input pulse widths (input pulse width is 42 ns). Solid curve, theoretical broadening expected from linear theory.

$$W = W_0 \sqrt{1 + \frac{0.93(\ln 2)G}{\pi^2 W_0^2 \Delta\nu_B^2}}, \qquad (1)$$

where G is the gain in dB, W_0 is the initial pulse width, and $\Delta\nu_B$ is the gain bandwidth. Although broadening is inevitable in the medium, it has also been shown that pulse broadening can be kept small if a probe pulse with more duration is used, resulting in no theoretical limitation in terms of fractional delay.[8]

Figure 4(a) shows the optical delay and the equivalent group-index change as a function of the gain. For the determination of the time delay, we measured the delay times of both rising and trailing edges at FWHM and made an average of them. The results matched well with a linear fit with a slope of 1.22 ns/dB, and the maximum group-index change was about 0.01, an order of magnitude larger than our previous result.[9] Figure 4(b) is the comparison between the measured and the theoretical pulse widths (FWHM) with respect to Brillouin gain, where the relative width on the right axis means the ratio of the pulse width to the initial value of 42 ns. The broadening of the pulse agrees reasonably well with the theoretical expectation from Eq. (1), where $\Delta\nu_B$ is set to 30 MHz.

In conclusion, we have demonstrated a wide-range optical control of the time delay of optical signals in fibers by use of the stimulated Brillouin scattering. The amount of the optical delay was controlled with the power of the Brillouin pump wave and could be easily extended by cascading fiber segments joined by unidirectional optical attenuators. A continuous optical delay of more than 150 ns on a 42 ns signal pulse was achieved with four fiber segments of 1.1 km, and larger delays can be obtained with no difficulty by cascading more delay segments. We believe that this may be an important step toward making fiber-based slow and fast light a real technological tool, although further research should be done to minimize the signal distortion while maintaining the overall delay.

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