Controllable optical delay line using a Brillouin optical fiber ring laser

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Received September 1, 2006

A controllable optical delay line using a Brillouin optical fiber ring laser is demonstrated and a large time delay is obtained by cascading two optical fiber segments. In experiment, a single-mode Brillouin optical fiber ring laser is used to provide Stokes wave as probe wave. We achieve a maximum tunable time delay of 61 ns using two cascading optical fiber segments, about 1.5 times of the input probe pulse width of 40 ns. In the meantime, a considerable pulse broadening is observed, which agrees well with the theoretical prediction based on linear theory.

OCIS codes: 060.2310, 060.4370, 290.5900, 350.5500.

There is a great interest in methods of controlling the propagation velocity of light pulses through material systems[1]. Specific applications in the field of high-speed all-optical signal processing that might benefit significantly from such controllable optical delay lines include random-access memory, network buffering, data synchronization, and pattern correlation[2]. To achieve controllable optical delay lines, the presence of narrow-band spectral resonance with large dispersion is required. Large normal dispersion results in a pulse group velocity v_g being much less than the speed of light in vacuum. Early electromagnetically induced transparency[3,4] or coherent population oscillations[5,6] are used in slow light research, where a narrowband transparency window is created within an absorbing resonance by an intense coupling laser field. However, all of the above systems that have been developed to generate slow light are fairly complicated and difficult to implement. Recently, people have been focusing on optically controllable slow light in optical fiber using stimulated Brillouin scattering (SBS)[7−10]. This method offers several advantages: the slow light can be created at any wavelength by changing the pump wavelength; the application of long optical fiber can reduce the power needed for the controlling beam; it is compatible with existing telecommunication technology; and the process is run at room temperature[9].

So far, Song *et al.*[8] and Okawachi *et al.*[9] have obtained Stokes wave (as probe wave) using modulation of the light from one laser and a SBS generator consisting of 1-km long open-ended fiber, respectively. However, the structure of modulation of the light from one laser is complex and the Stokes wave from open-ended fiber is instable. In this paper, we demonstrate a controllable optical delay line using a Brillouin optical fiber ring laser that has simple structure and stable emission.

SBS is usually described as the coupling interaction of three waves, in which the pump wave is coupled to both a forward traveling wave (phonon) and a backward traveling wave (Stokes wave) with inherent phase matching and thus creating an inherent spatial feedback which may lead to SBS oscillation with a distinct threshold. A ring-cavity is usually used to form a Brillouin optical fiber ring laser, in which the SBS threshold is decreased dramatically by the feedback. The notable feature of a Brillouin optical fiber ring laser is its periodic, quasi-periodic, and other irregular behaviors. The dynamics has been shown to be essentially dependent on pump power, displaying periodic, and quasi-periodic oscillation at near above the SBS laser threshold and continuous wave (CW) emission, which operates at single mode with higher pump power[11].

According to the Kramers-Kronig relation, a refractive index change is associated with the Brillouin gain process, and a substantial change of the group index $n_g = n + \omega\frac{dn}{d\omega}$ follows as a result of the sharp index transition. The slow-light time delay induced by the SBS process follows the approach described by Boyd *et al.*[2]. The maximum delay ΔT_{del} occurs at the peak of the Brillouin gain and is simply given by[9]

$$\Delta T_{del} = G/\Gamma_B, \qquad (1)$$

where G is the Brillouin gain coefficient, Γ_B is the Brillouin linewidth. Figure 1 is the typical gain and group delay curves associated with SBS. Large normal dispersion around the peak of SBS gain gives rise to a decrease in group velocity and therefore a time delay in optical fiber. A limiting process is SBS generation seeded by spontaneously scattering. For $G > 25$, photons spontaneously scattered from thermal phonons near the entrance

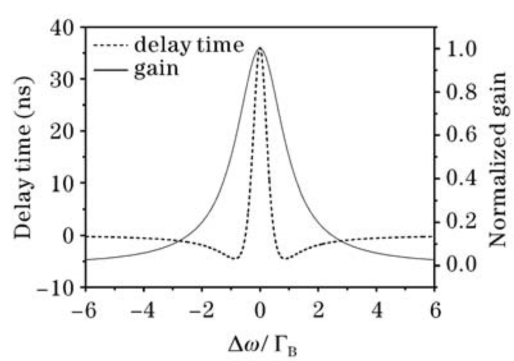

Fig. 1. Typical gain and group delay curves associated with stimulated Brillouin scattering.

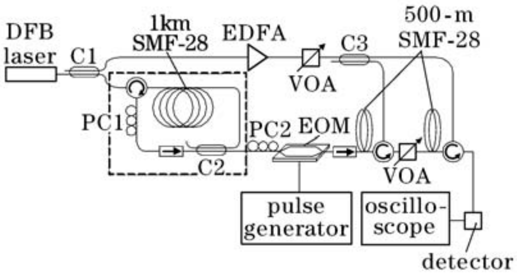

Fig. 2. Experimental setup. There is a Brillouin optical fiber ring laser in dot frame, which provides the Stokes wave to the light pulse generator.

end of the fiber are amplified by a factor of exp(25), resulting in the generation of a Stokes field at the output end which saturates the pump field in the absence of any input Stokes field. Therefore, the maximum attainable delay occurs when $G \approx 25$. To extend the time delay, there is a method using multiple cascaded fiber segments separated by attenuators. In our experiment, two fiber segments are used to extend the time delay.

Figure 2 shows the experimental setup. Light from a 100-mW, 40-kHz linewidth, 1550-nm wavelength distributed-feedback (DFB) laser was divided into two parts with a 10:90 coupler C1, in which the 90-mW beam was sent into a Brillouin optical fiber ring laser to generate the Stokes wave, while the 10-mW beam was sent into a erbium doped fiber amplifier (EDFA) as the continuous wave (CW) Brillouin pump wave. The Brillouin optical fiber ring laser was composed of a 5:95 coupler C2, an isolator, a polarization controller PC1, a circulator, and a segment of 1-km SMF-28 fiber. In the ring design, the pump sent into the ring propagating clockwise was prevented from re-circulating in the ring with an isolator, which was also used to avoid generating high order Stokes waves. When the pump intensity became large enough, the first order Stokes wave was generated, propagating in the counter-clockwise direction. Five percent of this backscattering light re-circulated in the ring as feedback with a coupler C2. PC1 was used to change the polarization state of the Stokes wave to match that of the pump in the ring-cavity and obtained the maximum gain. In experiment, the pump power was larger than two times of the threshold of lasing that was about 34 mW, and 30-mW stable and single-mode SBS laser was obtained. In order to observe the delay, we used an electro-optic modulator (EOM) to get a Gaussian-shaped Stokes pulse (as probe pulse) with an initial full-width at half maximum (FWHM) of 40 ns. The CW Brillouin pump wave from EDFA was divided into two parts equally with a 50:50 coupler C3, varying the pump power from 0 to 200 mW for each fiber segment. Before the amplified probe from the first fiber segment entering into the second one, it is attenuated with variable optical attenuator (VOA) to avoid gain saturation in the second fiber segment.

Figure 3 shows the time delay and broadening factor as a function of Brillouin gain. In Fig. 3(a), the solid line, whose slope is 1.22 ns/dB, is a theoretical curve under the condition of a 30-MHz Brillouin linewidth. The gain from 0 to 25.4 dB was obtained in the first fiber segment, inducing a delay from 0 to 28.2 ns; and the gain from 33.8 to 52.5 dB was obtained in the second fiber segment, inducing a delay from 36 to 61 ns. It is seen that the experimental spots agree well with the theoretical curve. In the meantime, a considerable broadening of the pulse from 40 to 78.8 ns was observed. It is shown in Fig. 3(b) that the experimental result agrees well with the theoretical prediction based on linear theory, where the pulse broadening factor B is given by[9]

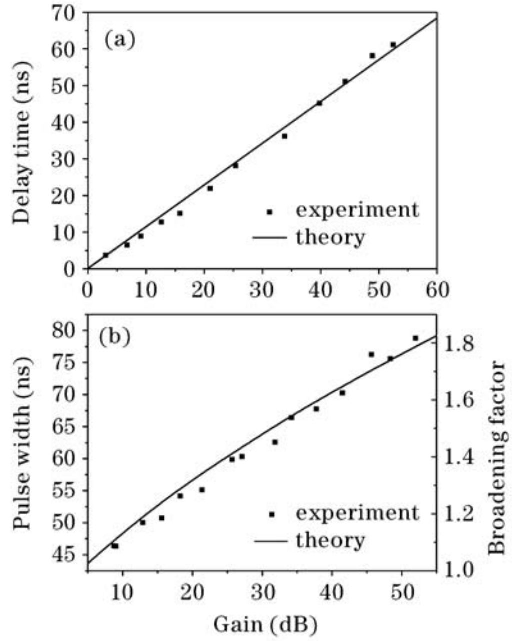

Fig. 3. (a) Measured delay as a function of Brillouin gain; (b) measured probe pulse width (FWHM) and broadening factor as a function of Brillouin gain (the initial pulse width is 40 ns).

$$B = \left(1 + \frac{16 \ln 2G}{\tau_{\rm in}^2 \Gamma_{\rm B}^2}\right)^{1/2}, \tag{2}$$

where $\tau_{\rm in}$ (FWHM) is the initial pulse width. The pulse broadening is inevitable because of the narrowband of the Brillouin gain, yet can be reduced by pump spectral broadening technique[10].

We have demonstrated a controllable optical delay line using a Brillouin optical fiber ring laser. Stable SBS laser was achieved as probe wave with the well designed Brillouin optical fiber ring laser. A continuous tunable optical delay up to 61 ns, larger than the initial pulse width of 40 ns , was obtained by cascading two fiber segments. In the meantime, a considerable broadening of the pulse from 40 to 78.8 ns was observed.

This work was supported by the National Natural Science Foundation of China under Grant No. 10476009. Z. Lü is the author to whom the correspondence should be addressed, his e-mail address is zw_lu@sohu.com.

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