Tunable All-Optical Delays via Brillouin Slow Light in an Optical Fiber

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We demonstrate a technique for generating tunable all-optical delays in room temperature single-mode optical fibers at telecommunication wavelengths using the stimulated Brillouin scattering process. This technique makes use of the rapid variation of the refractive index that occurs in the vicinity of the Brillouin gain feature. The wavelength at which the induced delay occurs is broadly tunable by controlling the wavelength of the laser pumping the process, and the magnitude of the delay can be tuned continuously by as much as 25 ns by adjusting the intensity of the pump field. The technique can be applied to pulses as short as 15 ns. This scheme represents an important first step towards implementing slow-light techniques for various applications including buffering in telecommunication systems.

A fundamental building block of communication networks or signal processors is a device that can buffer or delay the arrival of information. For operation at ultra high speeds, it is often desirable to use all-optical devices, where information is encoded with pulses. Thus, it is important to realize buffers where information is delayed via light by light interactions in a nonlinear material. Many potential applications require pulse delays of one to several times the pulse duration in a tunable and controllable fashion. Specific applications include random access memories, network buffering, data synchronization, and pattern correlation.

One promising new approach to achieve all-optical buffering with a simple device is to control the propagation velocity of optical pulses using the large dispersion associated with laser induced resonances, so called slow and fast light [2]. Large normal dispersion results in a pulse correlation [1].

We demonstrate a technique for generating tunable all-optical delays in room temperature single-mode optical fibers at telecommunication wavelengths using the stimulated Brillouin scattering process. This technique makes use of the rapid variation of the refractive index that occurs in the vicinity of the Brillouin gain feature. The wavelength at which the induced delay occurs is broadly tunable by controlling the wavelength of the laser pumping the process, and the magnitude of the delay can be tuned continuously by as much as 25 ns by adjusting the intensity of the pump field. The technique can be applied to pulses as short as 15 ns. This scheme represents an important first step towards implementing slow-light techniques for various applications including buffering in telecommunication systems.

Equation (2) is valid under conditions when

\[ g = g_0 \left( 1 + 2i(\omega - \omega_p + \Omega_B)/\Gamma_B \right) \]

is the complex SBS gain factor, \( \Gamma_B \) is the Brillouin linewidth, and \( g_0 \) is the line center gain factor. Equation (2) is valid under conditions when \( \Omega_B \gg \Gamma_B \), which is the case for standard optical fiber at telecommunication wavelengths.

The intensity dependent refractive index associated with the SBS process is related to the imaginary part of the gain factor. From the refractive index, we find that the Stokes
field wave vector magnitude is given by

\[ k_s = \frac{n_f \omega}{c} + g_0 I_p \frac{2(\omega - \omega_s)/\Gamma_B}{1 + [2(\omega - \omega_s)/\Gamma_B]^2}, \quad (3) \]

where \( \omega_s = \omega_p - \Omega_B \) is the Stokes frequency at the peak of the Brillouin gain, and \( n_f \) is the fiber modal index of refraction. The group velocity \( v_s = (dk_s/d\omega)^{-1} = c/n_g \) is determined through the relation

\[ v_s^{-1} = \frac{n_{fg}}{c} + \frac{g_0 I_p}{\Gamma_B} \frac{1 - [2(\omega - \omega_s)/\Gamma_B]^2}{1 + [2(\omega - \omega_s)/\Gamma_B]^2}, \quad (4) \]

where \( n_g \) is the total fiber group index and \( n_{fg} \) is the group index in the absence of any fiber nonlinearity. At the peak of the Brillouin gain (i.e., \( \omega = \omega_s \)), \( v_s^{-1} = n_{fg}/c + g_0 I_p/\Gamma_B \). Figure 1 shows the frequency dependence of the SBS gain, wave vector magnitude, and group index.

The slow-light delay induced by the SBS process can be predicted using the approach described by Boyd et al. [12]. For a medium of length \( L \) and a narrow bandwidth pulse \[ 4(\omega - \omega_s)^2/\Gamma_B^2 \ll 1 \], the difference between the transit times of the pulse with and without a pump beam is given by

\[ \Delta T_d = \frac{G}{\Gamma_B} \left[ 1 - 3(2(\omega - \omega_s)/\Gamma_B)^2 \right], \quad (5) \]

where \( G = g_0 I_p L \) is the gain parameter. The maximum delay occurs at the peak of the Brillouin gain and is equal to \( G/\Gamma_B \). On resonance and for a long Gaussian-shaped Stokes pulse of duration \( \tau_{in} \) (full width at half maximum), the pulse emerging from the fiber is also Gaussian shaped with a longer pulse length \( \tau_{out} \), where the pulse broadening factor \( B \) is given by

\[ B = \frac{\tau_{out}}{\tau_{in}} = \left[ 1 + \frac{16 \ln 2 G}{\tau_{in}^2 \Gamma_B^2} \right]^{1/2}. \quad (6) \]

Equations (5) and (6) clearly illustrate that the optically induced delay can be controlled through the intensity of the pump field and that the pulse delay is always accompanied by some pulse distortion. Using the relation between pulse broadening and delay, we find that the relative time delay for a fixed value of \( B \) is given by

\[ \frac{\Delta T_d}{\tau_{in}} = \left[ \frac{B^2 - 1}{16 \ln 2} \right]^{1/2} / \sqrt{G}. \quad (7) \]

In an experiment, both \( \Delta T_d \) and \( B \) can deviate from the values predicted by Eqs. (5) and (6) because of several factors. Deviations occur, for example, due to higher-order dispersion when \( \tau_{in} \) is too short and due to gain saturation when the input Stokes pulse intensity is too high. Another limiting process is SBS generation seeded by spontaneous Brillouin scattering. For \( G > 25 \), photons spontaneously scattered from thermal phonons near the entrance face of the fiber are amplified by a factor of \( \exp(25) \), resulting in the generation of a Stokes field at the output which saturates the pump field in the absence of any input Stokes field [10,11]. Therefore, the maximum attainable delay occurs when \( G \sim 25 \). For \( G = 25 \) and \( B = 2 \), we find that \( \Delta T_d/\tau_{in} = 2.6 \). Ultimately, a similar limit will apply to all schemes that use frequency dependent amplifiers to achieve controllable delays. This limitation could be circumvented, for example, by using multiple fibers separated by attenuators.

Our experimental setup for observing slow light via SBS consists of an optical fiber, a pump laser, and a Stokes pulse, as shown in Fig. 2. To generate a Stokes pulse that is shifted precisely by \( \Omega_B \), we used a single laser to generate both the pump beam and the Stokes pulse [11]. Light from a 3 mW, 300 kHz linewidth, 1550 nm wavelength laser is sent into a 1 W Erbium doped fiber amplifier. The amplified continuous wave signal is divided equally into two 250 mW beams which are sent to high power circulators. The output from the one of the circulators is sent to an SBS generator consisting of a 1 km long fiber (Corning SMF-28e) to produce the Stokes shifted light. Reflections from the fiber ends provide feedback to produce Brillouin lasing near the peak of the Brillouin gain spectrum, where the linewidth of the emitted beam is comparable to the linewidth of the pump beam [13]. The amplitude of the generated beam is modulated to form the Stokes pulse. Fiber polarization controllers (FPC) are inserted at various locations to optimize the extinction ratio of the Stokes pulse. The pulses have a peak power of \( \sim 1 \) mW.

**FIG. 1.** Large dispersion of the SBS resonance. (a) Gain (solid line) and refractive index (dashed line) of the resonance. (b) Normalized group index of the resonance.
The Stokes pulse enters a 500 m long laser-pumped optical fiber which serves as the slow-light medium, where the fiber (Corning SMF-28e) has angled ends to prevent SBS laser oscillation. From measurements described below, we find that $\Gamma_B/2\pi = 70$ MHz, which is about a factor of 2 larger than that measured in SMF-28 fibers [14]. The origin of the broader SBS linewidth in SMF-28e fibers is under investigation. The output from the other circulator counterpropagates through the slow-light fiber and serves as the SBS pump beam, where a FPC is used to optimize the gain. The delayed and amplified pulses emerging from the slow-light fiber are recorded using an InGaAs photodiode (35 ps rise time) and a digital oscilloscope. The value of $G$ is obtained by measuring the continuous wave gain of Stokes light propagating through the slow-light fiber.

Figure 3 shows our observation of SBS mediated slow light at telecommunications wavelengths for the case of a long ($\tau_{in} \Gamma_B/4 \gg 1$) and a moderately short ($\tau_{in} \Gamma_B/4 \approx 1$) input Stokes pulses. Figure 3(a) shows the temporal evolution of a Gaussian-shaped pulse with $\tau_{in} = 63$ ns in the presence and absence of the pump beam with $G = 11$, corresponding to a gain of 48 dB. We observe $\Delta T_d = 25$ ns, or a relative delay of $\Delta T_d / \tau_p = 0.4$, and a small amount pulse broadening ($B = 1.05$). The observed values compare favorably with those predicted by Eqs. (5) and (6): $\Delta T_d = 25$ ns and $B = 1.07$.

To demonstrate all-optical controllable slow-light delays, we vary the pump beam power. Figure 4 shows $\Delta T_d$ as a function of the gain parameter $G$ for $\tau_{in} = 63$ ns. It is seen that the slow-light delay varies linearly with the pump beam power, as expected from Eq. (5). The slope of the line reveals that $\Gamma_B/2\pi = 70$ MHz, from which we infer the relatively broad SBS linewidth for the SMF-28e fiber. Although we vary the pump power slowly using a manually adjusted attenuator, the reconfiguration time of the delay can, in principle, be much faster and is limited by the longer of either the transit time of the pump beam through the fiber ($2.5 \mu$s for our conditions) or the SBS lifetime ($1/\Gamma_B = 2.3$ ns).

We find that it is possible to induce larger relative slow-light pulse delays using an input pulse width that is moderately short ($\tau_{in} > 1/\Gamma_B$). Figure 3(b) shows the temporal evolution of Gaussian-shaped pulses with $\tau_{in} = 15$ ns. We observe that $\Delta T_d = 20$ ns, which is less than that obtained for $\tau_{in} = 63$ ns and predicted by Eq. (5). However, the relative delay is $\Delta T_d / \tau_p = 1.3$, which is a factor of 3.3 times larger than that obtained for the longer pulse. The improvement in relative pulse delay comes at the price of increased pulse broadening; we find that $B = 1.4$ for the 15 ns long input pulse. Figure 4 shows the variation in $\Delta T_d$ as a function of $G$, where it is seen that the broader spectral bandwidth of the pulse yields smaller delay for all $G$ in comparison to the case of the longer pulse and the slope is slightly shallower. We observe significant pulse distortion when $\tau_{in} < 10$ ns.

In conclusion, we have demonstrated that SBS in a single-mode fiber can be used to induce tunable all-optical slow-light pulse delays with a relative delay greater than a
pulse length for pulses as short as 15 ns. We are not con-
strained to work near any material resonance to achieve the
delays because the greatest delays occur at the peak of the
Brillouin resonance, whose location can be controlled by
changing the pump frequency. Therefore, delays can be
induced at any wavelength, including those within the
telecommunication band. Our observations represent a
significant improvement in terms of relative delay and
bandwidth over previous demonstrations of slow light
in solids. In addition, these results strongly suggest that
analogous delays can be achieved using stimulated
Raman scattering at telecommunication data rates
(>10 Gbits/s).

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