

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.

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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 memory, network buffering, data synchronization, and pattern correlation [1].

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 group velocity v_g that is much less than the speed of light in vacuum c . Early slow-light research used, for example, electromagnetically induced transparency [3–5] or coherent population oscillations [6,7], where a narrow transparency window is created within an absorbing resonance by an intense coupling laser field. Slow light is also possible using the dispersion associated with a laser induced amplifying resonance such as that arising from stimulated Raman scattering [8,9] and stimulated Brillouin scattering (SBS).

In this Letter, we demonstrate optically controllable slow-light delays at telecommunication wavelengths via stimulated Brillouin scattering in a conventional single-mode optical fiber. The fiber is pumped by a continuous wave laser beam (frequency ω_p) that counterpropagates through the fiber with respect to the delayed pulse (carrier frequency ω). The pulse delay is largest when ω is set to the peak of the Brillouin resonance ($\omega = \omega_p - \Omega_B$, where

Ω_B is the Brillouin frequency shift), and it can be varied quickly and in a linear fashion by adjusting the intensity I_p of the pump laser beam. We observe pulse delays as large as 25 ns for a 63 ns long (full width at half maximum) Gaussian-shaped optical pulse with only modest pulse distortion. We also observe a pulse delay of 1.3 pulse widths for 15 ns long input pulses. Our approach offers several advantages: the slow-light resonance can be created at any wavelength by changing the pump wavelength; the use of an optical fiber allows for long interaction lengths and thus low powers for the control beam; it is compatible with existing telecommunication technology; and the process is run at room temperature.

The SBS process leads to strong coupling between pump and Stokes fields via an acoustic wave, which results in exponential amplification of the Stokes field [10,11]. For the case in which the Stokes field is traveling in the $+z$ direction and the pump field is traveling in the $-z$ direction, the slowly varying amplitude of the Stokes field $E_s(z, \omega)$ at frequency ω is given by

$$E_s(z, \omega) = E_s(0, \omega) e^{g I_p z}, \quad (1)$$

where

$$g = g_0 \frac{1}{1 + 2i(\omega - \omega_p + \Omega_B)/\Gamma_B} \quad (2)$$

is the complex SBS gain factor, Γ_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 $v_g = (dk_s/d\omega)^{-1} = c/n_g$ is determined through the relation

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

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., $\omega = \omega_s$), $v_g^{-1} = n_{fg}/c + g_0 I_p/\Gamma_B$. 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

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

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/Γ_B . On resonance and for a long Gaussian-shaped Stokes pulse of duration τ_{in} (full width at half maximum), the pulse emerging from the fiber is also Gaussian shaped with a longer pulse length τ_{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 ΔT_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 τ_{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 Ω_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 $\sim 1 \mu\text{W}$.

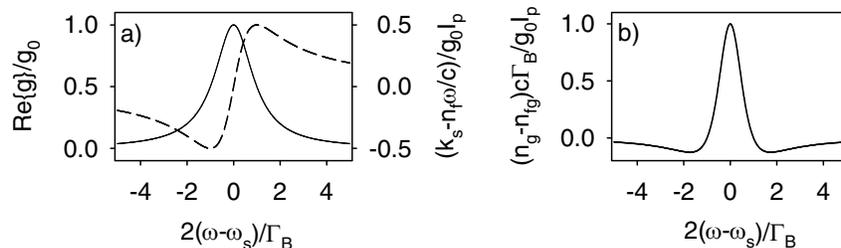


FIG. 1. Large dispersion of the SBS resonance. (a) Gain (solid line) and refractive index (dashed line) of the resonance. (b) Normalized group index of the resonance.

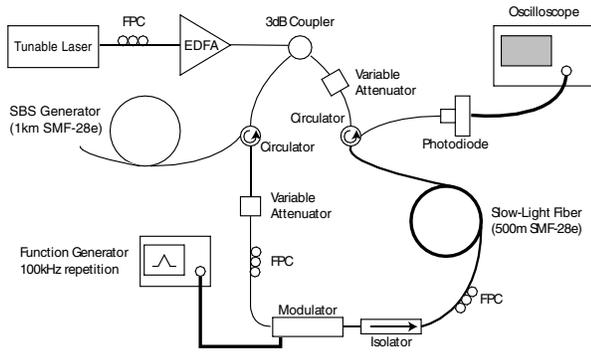


FIG. 2. Experimental setup: FPC, fiber polarization controller; EDFA, Erbium doped fiber amplifier.

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 $\Gamma_B/2\pi \approx 70$ 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 ΔT_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 $\Gamma_B/2\pi \approx 70$ 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 ($2.5 \mu\text{s}$ for our conditions) or the SBS lifetime ($1/\Gamma_B = 2.3$ ns).

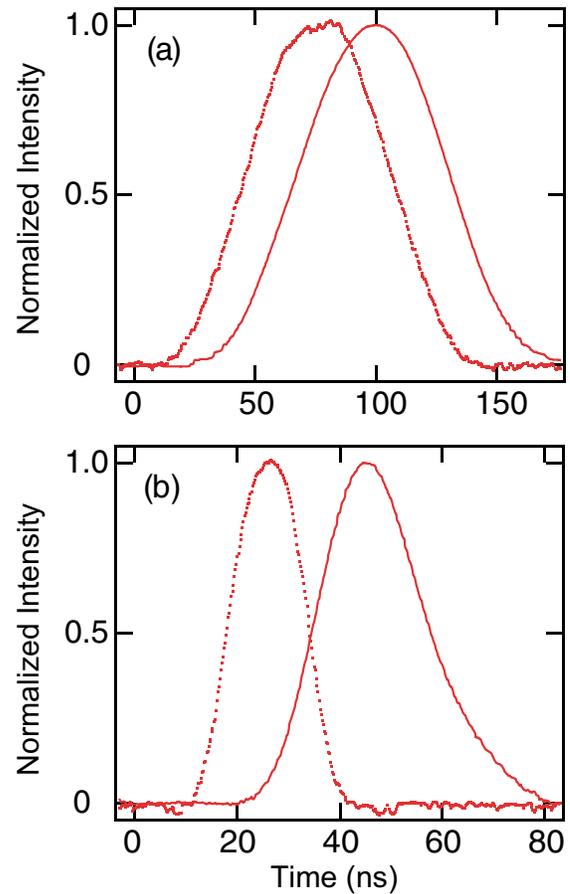


FIG. 3 (color online). Observation of slow light via SBS in a room temperature optical fiber at telecommunication wavelengths. Temporal evolution of the Stokes pulses (with a gain parameter $G = 11$) emitted from the fiber in the absence (dotted) and presence (solid) of the pump beam for (a) 63 ns long and (b) 15 ns long input Stokes pulses.

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 ΔT_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

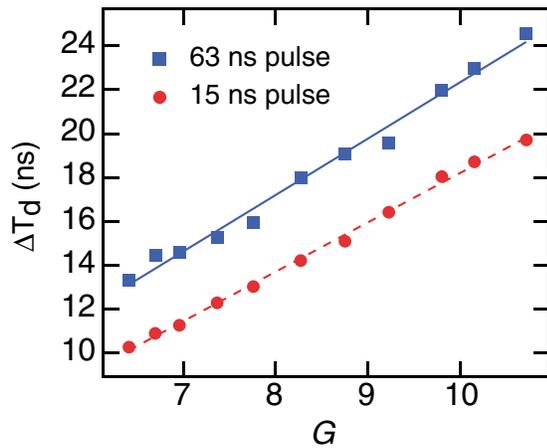


FIG. 4 (color online). Demonstration of optically controllable slow-light pulse delays. Induced delay as a function of the Brillouin gain parameter G for 63 ns long (square) and 15 ns long (circle) input Stokes pulses.

pulse length for pulses as short as 15 ns. We are not constrained 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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