Photonic-chip-based tunable slow and fast light via stimulated Brillouin scattering

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We report the first (to our knowledge) demonstration of photonic chip based tunable slow and fast light via stimulated Brillouin scattering. Slow, fast, and negative group velocities were observed in a 7 cm long chalcogenide (As_2S_3) rib waveguide with a group index change ranging from ~-44 to $+130$, which results in a maximum delay of $\sim$23 ns at a relatively low gain of $\sim$23 dB. Demonstration of large tunable delays in a chip scale device opens up applications such as frequency sensing and true-time delay for a phased array antenna, where integration and delays $\sim$10 ns are highly desirable. © 2012 Optical Society of America

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Control over the speed of light—*slow and fast light*—in a chip scale environment is fundamental to the development of devices for applications in quantum computing and information processing, optical communications and microwave signal processing, and sensing. Slow and fast light can be realized using the large dispersion associated with an induced or structural resonance [1]. Of all these techniques, the stimulated Brillouin scattering (SBS) based approach is the most flexible and practical for slow-light-based devices due to its wavelength independent nature, large signal bandwidth range (megahertz to gigahertz), room temperature operation, and delay tunability [2–12]. However, on-chip realization of SBS slow/fast light is difficult because the large group index change (Δn_g) required to achieve a significant delay ($\Delta T_d = L\Delta n_g/c$) in a small length ($L$), where c is speed of light in vacuum, is directly related to the Brillouin gain coefficient (g_B) and pump intensity (I_p), both of which have so far been constrained due to the material choice and device geometry.

Here we report the first demonstration of on-chip SBS slow and fast light using a 7 cm long rib waveguide based on chalcogenide glass (As_2S_3). While the large refractive index (n) of chalcogenide glass [11,13,14] leads to a large Brillouin gain coefficient ($g_B \sim 100 \times$ silica) due to its strong dependence on n ($g_B \propto n^8$)), strong optical and acoustic confinement [see Fig. 1(b)] in the rib structure provides large light–sound interaction and reduced optical mode area (A_{eff}) [14], which enhance the pump intensity at relatively low power.

SBS results from the interaction of light of frequency ω_P with an acoustic mode of frequency Ω_B. For a counterpropagating signal at frequency $\omega_s = \omega_p - \Omega_B$ (Stokes frequency), the three-wave interaction satisfies energy and momentum conservation and creates a gain resonance at ω_s [Fig. 1(c)]. For a signal centered at anti-Stokes frequency $\omega_{\mathrm{as}} = \omega_p + \Omega_B$, an absorption resonance is created. Associated with these resonances is the large index change, which gives rise to slow and fast light.

Figure 1 shows the concept of on-chip SBS slow light where a pump of frequency ω_P is used to control the delay of a counterpagating Stokes wave [Fig. 1(a)]. The group delay experienced by a Stokes signal is then given by

$$\Delta T_d(\omega_s) = \frac{G}{\Gamma_B} = \frac{g_B I_p L_{\mathrm{eff}}}{\Gamma_B}, \tag{1}$$

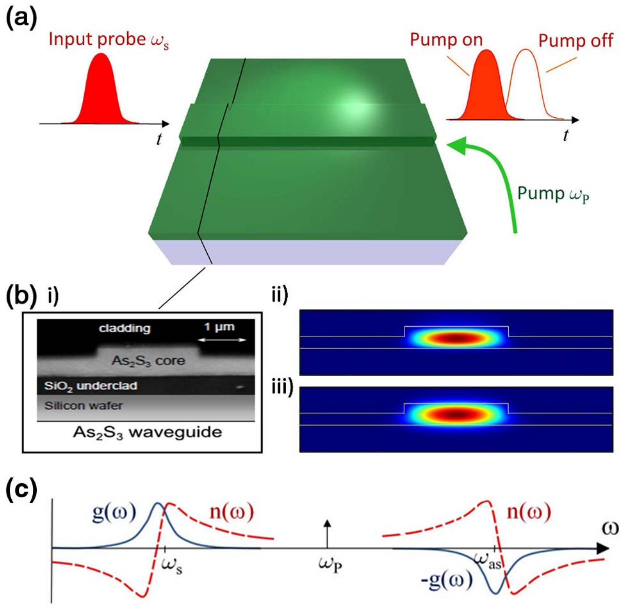

Fig. 1. (Color online) (a) Schematic of on-chip control of light pulse speed using SBS slow and fast light in a As_2S_3 rib waveguide; (b) (i) optical microscope image of a typical As_2S_3 rib waveguide and (ii) optical and (iii) acoustic modes in the rib waveguides showing strong mode confinement, which leads to strong light–sound interaction for SBS; (c) normalized gain and absorption resonances (solid blue curves) and associated dispersion (dashed red curves) demonstrating that the slope of dispersion is positive for slow light and negative for fast light.

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where Γ_B is the Brillouin linewidth and $L_{\mathrm{eff}} = (1 - e^{-\alpha L})/\alpha$ is the effective length, with L being the physical length and α being the propagation loss. From Eq. (1) it is evident that the delay can be tuned by varying the pump power (P_p). For an anti-Stokes signal, increase in P_p leads to increased absorption and thus fast light.

Figure 2 shows the experimental setup to realize on-chip SBS slow and fast light. The output delayed pulse was first filtered using an FBG setup to minimize the residual pump, which arises mainly from reflections at the lensed fiber and chip interface, and then amplified using a 200 mW, low-noise amplifier (EDFA2) before detection using a detector with 1 ns rise time. The optical chip used in the experiments had a cross-sectional area of 4 μm × 850 nm, $g_B \sim 0.74 \times 10^{-9}$ m/W [14], $A_{\mathrm{eff}} \sim 2.3\ \mu\mathrm{m}^2$, Brillouin shift of ~7.7 GHz, and linewidth of ~36 MHz. For the fast-light measurements the probe signal was amplified using a low-noise 200 mW EDFA to control the probe power, because the anti-Stokes wave is absorbed rather than amplified.

To measure the group index profile in the slow- (fast-) light regime, we modulated the probe signal centered at ω_s (ω_{as}) using a low-frequency sinusoidal wave. The probe carrier frequency was then detuned from $\omega_{s,\mathrm{as}}$, while the coupled CW P_p was kept fixed. At each frequency detuning, the measured $\Delta T_d(\omega_{\mathrm{probe}})$ was used to infer $\Delta n_g(\omega_{\mathrm{probe}}) = c\Delta T_d(\omega_{\mathrm{probe}})/L_{\mathrm{eff}}$, shown in Fig. 3; good agreement was found with theoretical calculations [9]. In the slow-light regime, we observed a maximum $\Delta n_g \sim 68$, implying a group velocity (v_g) of 4411 km/s at $P_p \sim 152$ mW. For a signal centered at ω_{as}, the slope of $n(\omega)$ is negative (see Fig. 1), leading to negative values of n_g. In the fast-light regime, a maximum $\Delta n_g \sim -44$ was measured at $P_p \sim 91$ mW, which was lower than that for the slow-light measurement, as the increased absorption at a large P_p makes the measurement difficult. From the measured $\Delta n_g(\omega_{\mathrm{as}})$ we obtain a negative $v_g \sim -6818$ km/s. To the best of our knowledge, such large slow- and fast-light group indices have never been observed using SBS.

To measure the pulse delays, we modulated the probe with a Gaussian pulse. For these experiments we used a pulsed pump to increase the on-chip pump power to ~300 mW. Pump pulses were 1 μs long with a duty cycle of 20% and were synchronized with the probe pulses.

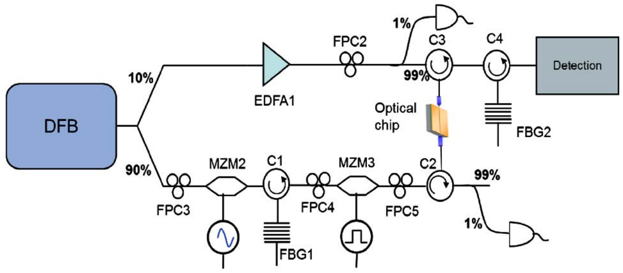

Fig. 2. (Color online) Experimental setup for SBS slow/fast light. DFB, distributed feedback laser; EDFA, erbium-doped fiber amplifier; FPC, fiber polarization controller; FBG, fiber Bragg grating; MZM, Mach–Zehnder modulator; C1–5, circulator.

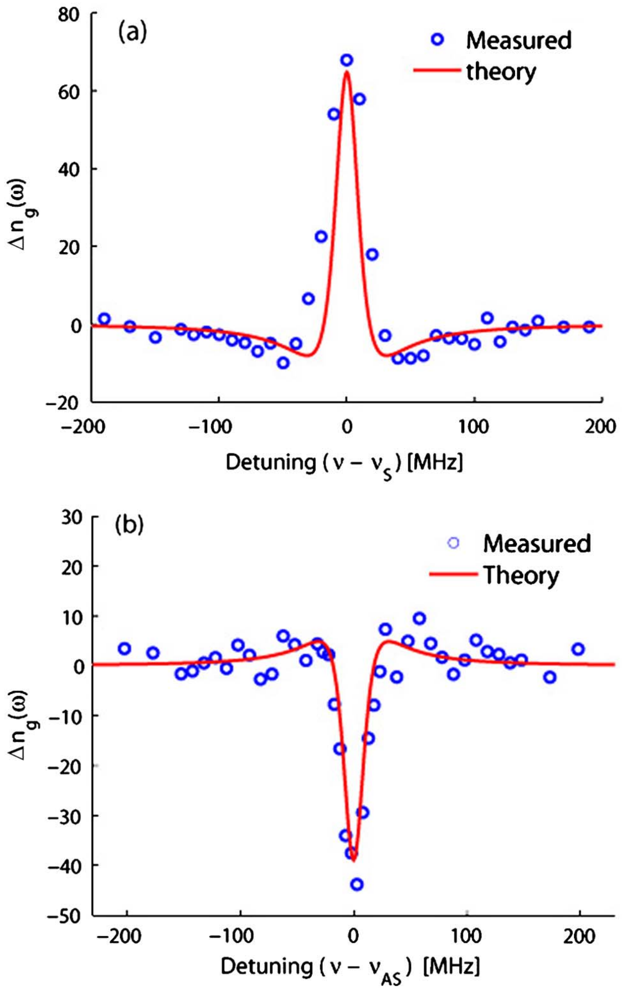

Fig. 3. (Color online) Calculated (solid curves) and measured (circles) group index profile for (a) slow light and (b) fast light. A sinusoidal modulation of 10 MHz for slow light and 3 MHz for fast light was imposed on the probe carrier wave, whose frequency was detuned from the Stokes (anti-Stokes) for slow (fast) light. The coupled CW pump powers of ~152 mW for slow light and ~91 mW for fast light were used.

Figures 4(a) and 4(b) show the delay for FWHM pulse widths of ~25 and ~100 ns, respectively, for different values of gain ($G = g_B I_p L_{\mathrm{eff}}$). As the pump power was increased, the gain (absorption) increased, and thus the group index increased (decreased) and the speed of light pulse was reduced (advanced) for pulses centered at ω_s (ω_{as}), resulting in slow and fast light. For a 25 ns long Gaussian pulse, we achieved a delay of ~22 ns at $G \sim 4.9$, while for a 100 ns long Gaussian pulse the maximum delay was ~23 ns at $G \sim 5.3$. From the measured slow-light delay for a 100 ns pulse, we calculated the maximum achieved Δn_g to be ~130, which was approximately twice the group index measured at the Stokes shift as group delay measurements at ~152 mW (see Fig. 3) and is the largest reduction ever achieved in the speed of light pulses using SBS. The total insertion loss (IL) for the 100 and 25 ns pulse delay measurements was ~10.5 and ~12.5 dB, respectively, which includes ~4 dB coupling loss at each facet and a total loss of input and output circulators ~0.8 dB. Using the loss estimate, the effective lengths for the 100 and 25 ns pulses were estimated to be ~5.5 and ~4.7 cm, respectively. We attribute the higher insertion loss for the 25 ns pulse to the

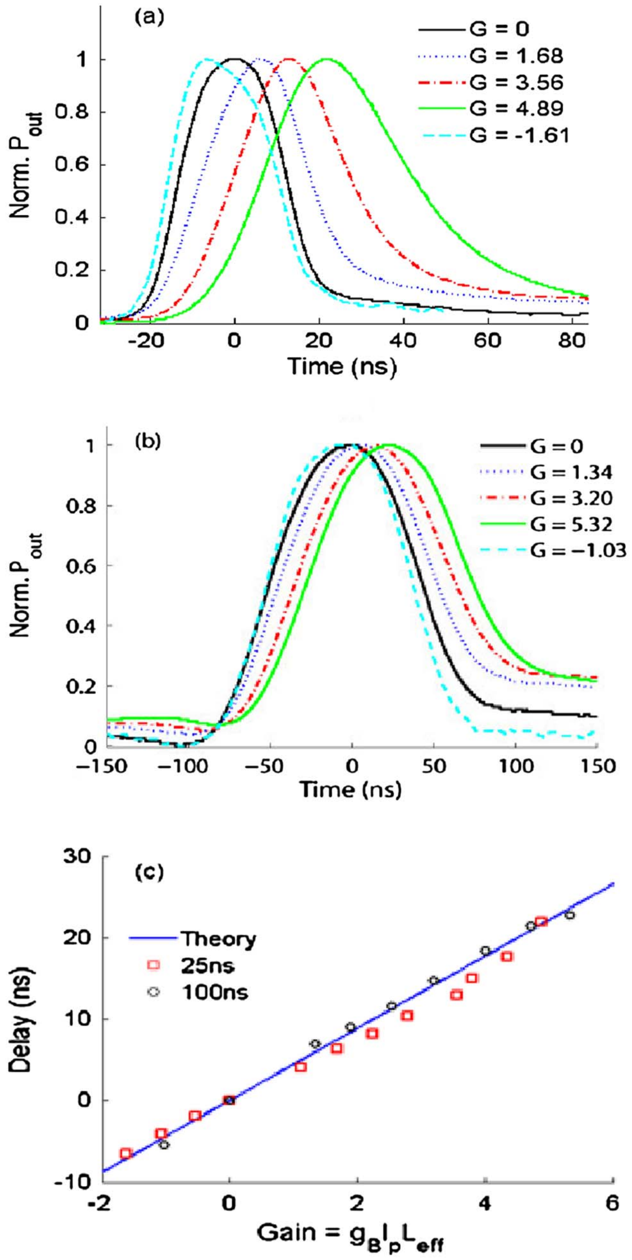

Fig. 4. (Color online) Measured output pulses for different gain values demonstrating SBS induced slow and fast light for (a) a 25 ns Gaussian pulse and (b) a 100 ns Gaussian pulse and (c) measured and theoretical delay, obtained using Eq. (1), versus gain.

alignment of the pump and probe polarizations with the increased loss of the TM mode.

For fast-light pulse delay experiments we only used a CW pump. For a 100 ns pulse, a maximum pulse advance of ~ -6 ns was obtained at $G \sim -1.03$. The output pulses for the 25 ns probe pulse exhibit significant broadening for large gain values as the different frequency components experienced different delay and gain, resulting in pulse distortion. For the 100 ns probe pulse the output pulses were nearly the same width as the input pulse. The detector response, however, introduced a long tail in the trailing edge of the input and slow/fast pulses. We attribute the origin of this tail to a diffusion current in the detector. Figure 4(c) shows a comparison of our measured delay with the theoretical delay calculated using Eq. (1), showing good agreement between theory and experiments for the 100 ns pulse, while the slow-light delay for a 25 ns pulse was slightly smaller, as would be expected.

In conclusion, we have demonstrated on-chip slow, fast, and negative group velocities using SBS where Δn_g was continuously varied from -44 to $+130$, resulting in $v_g \sim 2307$ km/s and -6818 km/s.This demonstration opens up on-chip SBS devices for applications where multiple delay lines with tunable delays of ~ 10 ns are required, e.g., phased array antenna [2]. Furthermore, the large dispersion offers increased sensitivity for ultracompact spectrometers [15].

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