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

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ABSTRACT

The ability to control the speed of light on an optical chip is fundamental to the development of nanophotonic components for all-optical signal processing and sensing [1-7]. However this is a significant challenge, because chip-scale waveguides require very large changes in group index (Δn_g) to achieve appreciable pulse delays. Here, we use Stimulated Brillouin Scattering (SBS) to report the demonstration of on-chip slow, fast and negative group velocities with Δn_g ranging from -44 to $+130$, and delays of up to 23ns at a pump power of ~ 300 mW and propagation length of 7cm. These results are obtained using a highly-nonlinear chalcogenide (As_2S_3) rib waveguide, in which the confinement of both photons and phonons results in strong interaction. SBS can be used to achieve controllable pulse delays at room temperature over a large wavelength and signal-bandwidth [5]. These results open up a new set of photonic applications ranging from microwave photonics [8] to spectrometry [4].

Keywords: stimulated Brillouin scattering, on-chip, slow light, group index, chalcogenide, tunable delay

1. INTRODUCTION

Controlling the speed of a light pulse entails changing the group index n_g : *slow light*, for which $n_g > 1$, and *fast light*, for which $n_g < 1$, can be obtained by centering a pulse near a material [2, 3, 5, 7, 9, 10] or structural resonance [1, 6, 11, 12] where the induced change in dispersion gives rise to a large index slope [13]. The challenge in achieving *on-chip* slow and fast light is that the short interaction length requires a very large value of n_g to achieve an appreciable pulse delay. Thus far, large values of group index have been obtained using resonances of atomic transitions [3, 7] or optical cavities [6, 11, 14] and multi-structured waveguides [1], however these techniques are fixed in frequency and/or limited in signal bandwidth, constraints which put severe restrictions on the maximum achievable pulse delay. In addition, the atomic transitions for which the largest values of n_g are attained require specialized hardware, and have applications mainly in quantum information processing. An alternative approach for situations where integration or tunability (of wavelength, signal bandwidth and delay) is important involves Stimulated Brillouin Scattering (SBS), in which the photons interact coherently with phonons in an optical waveguide. Application of SBS on the chip-scale would provide a flexible, dynamically tunable system that can work at almost any wavelength of interest at room temperature and accommodating signal bandwidths covering MHz to tens of GHz [5]. However, the opto-acoustic interaction that drives the SBS process is typically extremely weak, leading to low values of n_g for realistic pump powers, and so SBS experiments have invariably been performed in optical fibers several meters long. Application in a chip-scale device, which is important for the integration of delay components, requires at least a 10-fold increase in the strength of the underlying interaction.

Here, we report on-chip control of the speed of a light pulse using SBS. We have observed slow (~ 2307 km/s), fast and negative group velocities ($v_g \sim -6818$ km/s) in a 7 cm long chalcogenide (As_2S_3) rib waveguide, corresponding to group index changes ranging from ~ -44 to $+130$ with the largest n_g achieved at a low gain of ~ 23 dB [15]. To the best of our knowledge, this is the record n_g in a SBS slow-light system and is 13-fold larger than the previous value of $n_g \sim 10$ which was achieved in a 2 m long Erbium-

doped Tellurite fiber at a gain of ~ 53 dB [16]. We exploited the SBS process in our optical chip to tune the delay of a 25 ns long Gaussian pulse from -7 ns to ~ 22 ns (nearly one pulse width delay) while a 100 ns Gaussian pulse was delayed from -6 ns to 23 ns. The modification of the group index is large enough for us to directly measure it by tracking the phase of a narrow band signal. We present such measurements here for both slow and fast light regimes.

2. ON-CHIP SBS SLOW AND FAST LIGHT

To obtain slow light using SBS, a pump wave (ω_p) must interact coherently with an acoustic wave at frequency (Ω_B) and a counter-propagating wave at the Stokes frequency (ω_s) (see Figure 1). A pulse in the counter-propagating wave then experiences a delay according to [17]

$$\Delta T_d(\omega_s) = \frac{L_{\text{eff}} \Delta n_g(\omega_s)}{c} = \frac{g_B I_p L_{\text{eff}}}{\Lambda} \quad (1)$$

where L_{eff} is the effective length, g_B is the Brillouin gain coefficient, I_p is the pump intensity, and Γ is the Brillouin linewidth. This delay can be tuned by changing the pump power, and fast light can be obtained by shifting the frequency of the signal to the anti-Stokes line. However, obtaining large values of ΔT_d on a chip, where L_{eff} is small, is difficult because the best values of Γ for optical materials are on the order of tens of MHz; this means that large delays require a very large $g_B I_p$ product. We approached this difficulty using a combination of materials and geometry. The Brillouin gain g_B can be enhanced using high refractive index materials, provided other material parameters are comparable, because the coefficient of electrostriction scales with n^8 . Further enhancement can be gained by ensuring that the photons and phonons are both guided within the same structure. A material satisfying all the right conditions is chalcogenide glass, with refractive index $n=2.4$ at 1550nm and a longitudinal sound velocity of ~ 2600 m/s (compared to ~ 5971 m/s for silica). Chalcogenide glass has been shown to have both large Brillouin gain and Kerr nonlinear coefficients (~ 100 times that of silica) [18-20], and the use of a microstructure waveguide, for which the mode area is small and hence I_p is large, means that the power required to achieve the same delay in a given length is dramatically reduced.

Our device consisted of a 7cm-long chalcogenide (As_2S_3) rib waveguide on a silica substrate (see Figure 1). The optical chip used in the experiments has a cross-sectional area of $4 \mu\text{m} \times 850$ nm, $g_B \sim 0.74 \times 10^{-9}$ m/W [21], $A_{\text{eff}} \sim 2.3 \mu\text{m}^2$, Brillouin shift of ~ 7.7 GHz and linewidth of ~ 36 MHz. Because of the large contrast in phase velocity of both sound and light between the waveguide and cladding, the acoustic and optical modes are both confined within the rib (Fig. 1b). We first measured the change in group index profile of the counter-propagating wave in the slow (fast) light regime. To do this we modulated the probe signal at the Stokes (anti-Stokes) frequency using a sinusoidal wave; the probe signal frequency was then detuned from centre of the Stokes (anti-Stokes) line while the coupled CW pump power was kept fixed. At each detuning, we measured the group delay of the sinusoidal signal and calculated the group index profile, shown in Fig. 2; good agreement was found with theoretical calculations using a Lorentzian model for the interaction. In the slow-light regime, we observed a maximum group index change of ~ 68 , implying a reduction of the group velocity of light to 4411 km/s at a pump power of

Figure 1. a) Schematic of on-chip control of light pulse speed using SBS slow- and fast-light in a As_2S_3 rib waveguide (b) scanning electron microscope image (i) of a typical As_2S_3 rib waveguide and optical (ii) and acoustic (iii) 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) and associated dispersion (dashed) demonstrating that the slope of dispersion is positive for slow-light and negative for fast light.

152mW. For a signal centered at ω_{as} the slope of $n(\omega)$ is negative (see Fig. 1), leading ultimately to negative values of n_g . We use the negative change in group index to demonstrate fast and negative group velocities: a group index change of $\Delta n_g \sim -44$ was measured at a power of ~ 91 mW, resulting in a negative group velocity (~ -6818 km/s). This implies that the body of the pulse exits the medium before entering it, causality being preserved because the information in the pulse is carried by the signal velocity.

Fig 2. Calculated (solid) 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 power of ~ 152 mW for slow light and ~ 91 mW for fast light were used.

Fig 3. Measured output pulses for different gain values demonstrating SBS induced slow- and fast light for (a) 25ns Gaussian pulse (b) 100 ns Gaussian pulse and (c) measured and theoretical delay, obtained using Eq. (1), vs. gain.

We then measured the delays directly by modulating the counter-propagating signal with a Gaussian pulse. For these experiments we used a pulsed pump to increase the on-chip peak pump power to ~ 300 mW. Pump pulses were $1\mu\text{s}$ long with a duty cycle of 20% and were synchronized with the probe pulses. Figures 3(a) and 3(b) show the delay for pulse-widths of ~ 25 ns and ~ 100 ns, respectively, for different values of gain ($G = g_B I_p L_{eff}$). As the pump power was increased (decreased) the group index increased (decreased) according to Eq. (1) 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 25ns long Gaussian pulse, we achieved a delay of ~ 22 ns at a peak pump power of ~ 300 mW whilst for a 100 ns long Gaussian pulse the maximum delay was ~ 23 ns. From the measured slow light delay for a 100 ns pulse we calculated the maximum achieved n_g to be ~ 130 , which was approximately twice the group index measured at the Stokes shift from group delay

measurements at ~152 mW (see Fig. 2) and implies that the speed of light was 130 times smaller than that in vacuum. This is the largest reduction ever achieved in the speed of light pulses using SBS.

For fast light pulse-delay experiments we only use 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 there was almost no distortion; the output pulses were nearly the same width as the input pulse. Figure 3(c) shows a comparison of our measured delay with the theoretical delay calculated using Eq. (1) showing a good agreement between theory and experiments for 100 ns pulse while the slow-light delay for a 25 ns pulse was slightly smaller as would be expected.

3. CONCLUSION

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 group velocities of 2307 km/s and -6818 km/s for slow- and fast-light respectively. Such a wide variation allowed continuously tunable, on-chip delays ranging from -6 ns to +23 ns in a 7cm long photonic chip with the maximum delay achieved at the relatively low pump power of ~300 mW. The importance of this demonstration is that it opens up the SBS process to the scalability of on-chip devices: for applications such as true-time delay for phased array antenna and microwave filters where multiple delay lines with tunable delays of 1-10 ns are required to control multiple Radar elements, the integration and operation flexibility afforded by on-chip slow and fast light is highly desirable [8]. Furthermore, the large dispersion offers increased sensitivity for ultra-compact spectrometers [4]. The ability to control light speed on a chip using the phonon modes leads not only to these new applications and technologies, but also provides a new platform for exploring fundamental interactions between sound and light.

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