Highly efficient light-sound interaction in silicon photonic nanowires

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Abstract: We study the interaction between light and gigahertz sound in small-core silicon wires. The wires are supported by a tiny pillar to improve sonic confinement, thus compressing both photons and phonons to the silicon core. The 10 GHz sound is generated optically. We detect its presence by the Doppler-shift it induces on the light. This sets the stage for a feedback loop known as stimulated Brillouin scattering, in which an optical beat note generates sound that reinforces the initial beat note. We report the first demonstration of this nonlinear process in silicon wires, with all-optical applications in microwave photonics, spectrally pure lasers and delay lines.

1. Introduction

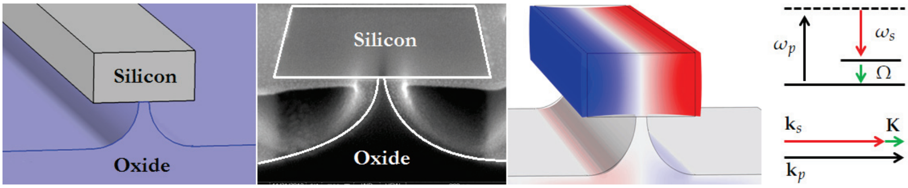
Stimulated Brillouin scattering (SBS) is a third-order nonlinear process that couples light to sound [1]. The hallmark of this process is the interaction between two optical waves called the *Stokes* and *pump* field. The weak Stokes seed gets amplified when it is red-detuned from the strong pump by precisely the mechanical resonance frequency. The amount of amplification is determined by the pump power, the light-sound overlap and the effective waveguide length. Although best known for limiting the optical power in fiber communication links, SBS has applications ranging from slow light [2] for lidar [3] to tunable RF notch filters [4], microwave synthesis [5] and spectral purification [6]. It can be seen as the travelling-wave complement to cavity optomechanics [7], extending work on megahertz-optomechanics [8, 9] to the gigahertz domain. The process has been studied in a multitude of platforms [10, 11], but proved elusive in silicon nanowires. It was hypothesized that the elastic waves rapidly leak away to the substrate in a typical silicon-on-insulator wire [12], drastically reducing the phonon lifetime.

We confirm this experimentally by partially releasing a silicon wire (fig. 1) from its oxide substrate with hydrofluoric acid. By carefully controlling the etching speed, a narrow ($\approx$ 15 nm) oxide pillar is left underneath the wire. This largely blocks the external path for phonon loss, while keeping the benefit of scalability to long interaction lengths. This wire on a pillar supports a mechanical mode (fig. 1) that has a large overlap with the optical forces given TE-polarized optical input. The elastic mode can be understood as the fundamental mode of a Fabry-Pérot cavity for hypersonic waves, formed by the silicon-air boundaries. Therefore, its frequency can be estimated as $\frac{\Omega_m}{2\pi} = \frac{v}{2w} = 9.4\,\text{GHz}$ with $v = 8433\,\text{m/s}$ the longitudinal speed of sound in silicon and $w = 450\,\text{nm}$ the waveguide width.

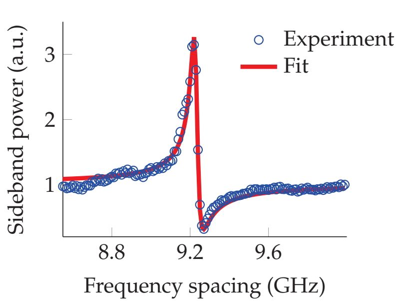
Previously, SBS was shown in a completely suspended hybrid silicon/silicon nitride waveguide [13]. However, short interaction lengths limited the on/off gain in this structure to 0.4 dB while high optical losses of 7 dB/cm precluded net gain. Here we observe gain of 2.3 dB/cm in a wire with 2.6 dB/cm linear loss. This represents a ninefold improvement in the gain-to-loss ratio. Moreover, we improve the maximum SBS gain by a factor 20 to 175 %. The light-sound overlap is a factor 10 larger than in any other waveguide, and the gain coefficient is more than a thousand times larger than in highly nonlinear and photonic crystal fibres.

2. Findings

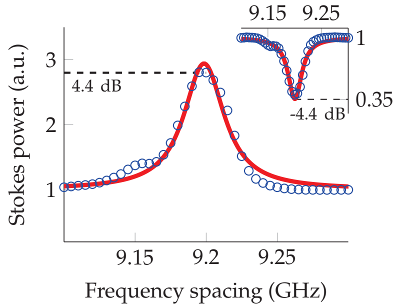
We investigate straight and low-footprint spiral waveguides with a 450 nm $\times$ 220 nm cross-section and lengths from 1.4 mm to 4 cm. We couple 1550 nm TE-light to the waveguides through curved grating couplers and perform both cross-phase modulation and gain experiments.



(1) A drawing, SEM-image and mechanical mode profile of the silicon wire on an oxide pillar. The color of the mechanical mode indicates the horizontal displacement (red: $+$, blue: $-$). The energy diagram and phase-matching condition of forward SBS are depicted on the right.



(2) Fano signature obtained from the cross-phase modulation experiment.



(3) Lorentzian gain profile on a Stokes line. Inset: depletion profile on an anti-Stokes line.

First, we calibrate the mechanical nonlinearity with respect to the Kerr effect by cross-phase modulation. The experiments yield a distinct Fano signature at 9.2 GHz (fig. 2) caused by interference between the resonant Brillouin and the non-resonant Kerr response. From this Fano resonance we extract the ratio $\gamma_{\text{SBS}}/\gamma_{\text{Kerr}} \approx 2.5$ and a linewidth of ≈ 35 MHz. The center frequency is highly tunable (20 MHz/nm) by changing the waveguide width. The experiments also show that the linewidth increases strongly with pillar size. The quality factor of ≈ 300 is consistent with a finite-element model of phonon leakage through the pillar. Remarkably, there is no large increase in the linewidth even in the long 4 cm spirals. Therefore there is, if at all, only limited line broadening caused by inhomogeneities in the waveguide width.

Next, we perform a gain experiment by monitoring the power in a Stokes seed as a function of frequency spacing with a pump wave. We obtained the highest on/off gain of 4.4 dB in a 4 cm long spiral waveguide (fig. 3). The experiments yield similar values for on/off loss on an anti-Stokes seed (inset of fig. 3). In a 2.7 mm long straight wire with 0.7 dB linear loss, we find up to 0.6 dB on/off gain with an estimated 20 mW c.w. pump power landed on the chip. This corresponds to gain coefficients of $\approx 3000\,\text{W}^{-1}\text{m}^{-1}$, which is confirmed by the cross-phase modulation experiment. This implies that the optomechanical nonlinearity is stronger than both the Kerr and Raman effect in these wires. At higher pump powers two-photon and free-carrier absorption prevent a further increase in Brillouin gain.

3. Conclusion

In conclusion, we have demonstrated efficient interaction between near-infrared light and gigahertz sound in a small-core silicon photonic wire on a pillar. The structure exhibits an extremely large light-sound overlap, at the same time allowing for a centimeter-scale Brillouin-active interaction length. The combination of both opens the door to practical Brillouin devices, including optically-driven lasers/sasers, microwave filters and comb generators, integrated on a CMOS-compatible silicon chip.

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