Interaction between light and highly confined hypersound in a silicon photonic nanowire

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In the past decade there has been a surge in research at the boundary between photonics and phononics. Most efforts have centred on coupling light to motion in a high-quality optical cavity, typically geared towards manipulating the quantum state of a mechanical oscillator. It was recently predicted that the strength of the light–sound interaction would increase drastically in nanoscale silicon photonic wires. Here we demonstrate, for the first time, such a giant overlap between near-infrared light and gigahertz sound co-localized in a small-core silicon wire. The wire is supported by a tiny pillar to block the path for external phonon leakage, trapping 10 GHz phonons in an area of less than 0.1 μm². Because our geometry can also be studied in microcavities, it paves the way for complete fusion between the fields of cavity optomechanics and Brillouin scattering. The results bode well for the realization of optically driven lasers/sasers, isolators and comb generators on a densely integrated silicon chip.

The large SBS strength was thus thought to be accessible only in silicon waveguides that are fully suspended in air20,28–32. This requirement severely compromises the ability to make centimetre-scale interaction lengths, which are essential to reduce the required pump power. Hence, Brillouin scattering has remained elusive in silicon photonic nanowires.

**Results**

Here, we take the middle ground between these conflicting demands. By partially releasing a silicon wire from its substrate we drastically improve acoustic confinement (Fig. 1a–c). There is still some leakage through the pillar, but it is sufficiently limited to tap the large overlap between the optical forces and the hypersonic mode (Fig. 1d). Moreover, in this way it is straightforward to increase the interaction length. Building on this compromise, we demonstrate an order-of-magnitude performance leap in the light–sound coupling strength.

The observed mechanical mode strongly interacts with the fundamental quasi-transverse electric (TE) optical mode (Fig. 1e). The main contribution to the coupling stems from the good overlap between the horizontal optical forces and the horizontal displacement profile. In particular, the bulk electrostrictive forces \( f_0 \) and the boundary radiation pressure \( f_p \) both point in the same direction as the acoustic field \( u \) (Fig. 1d), so they interfere constructively, leading to a total overlap \( \langle f_0, u \rangle + \langle f_p, u \rangle \) that is up to twice as large as each individual component. Because the SBS gain \( G_{\text{SBS}}(fm) \) at the phonon resonance frequency \( \Omega_m \) scales as \( \langle f_0, u \rangle^2 \), the total scattering from pump to Stokes photons may be up to four times as efficient as by electrostriction or radiation pressure individually.

Such force interference20,30 was previously studied in hybrid silicon nitride/silicon waveguides33. In that case, the light was confined to the silicon core but the sound to the silicon nitride membrane. In the present work, both light and sound are compressed to the same silicon core. The elastic mode (Fig. 1d) can be understood as the fundamental mode of a Fabry–Pérot cavity for hypersonic waves (Fig. 1b) formed by the silicon/air boundaries. Its frequency can therefore be estimated as \( \Omega_m/2\pi = \nu/2\omega = 9.4 \text{ GHz} \),

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where $v = 8,433 \text{ m s}^{-1}$ is the longitudinal speed of sound in silicon and $w = 450 \text{ nm}$ is the waveguide width.

To create the pillar structure we began with an SOI wire fabricated by deep-ultraviolet lithography using the silicon photonics platform ePIXfab (www.epIXfab.eu). We next performed an additional oxide etch with hydrofluoric acid. By carefully controlling the etching speed, a narrow pillar was left under the wire (Fig. 1a–c). With this simple fabrication method we obtained wires up to 4 cm in length. To retain compactness, wires longer than 3 mm were coiled into a low-footprint spiral (Supplementary Fig. 2). Despite the additional etch, the wires still exhibited optical losses of only $2.6 \text{ dB cm}^{-1}$.

In the experiments (Fig. 2) we investigated straight and spiral waveguides with lengths $L$ ranging from 1.4 mm to 4 cm. We coupled 1,550 nm TE light into the waveguides through focusing grating couplers and performed both gain (Fig. 2a,b) and cross-phase modulation (Fig. 2c,d) experiments. The resonances (Fig. 2a,c) observed in these experiments thus allowed characterization of the photon–phonon coupling in two independent ways.

We first monitored the power in a Stokes seed as a function of frequency spacing $\Omega/2\pi$ with a strong co-propagating pump wave (Fig. 2a,b). We observed a Lorentzian gain profile at $\Omega_m/2\pi = 9.2 \text{ GHz}$, as expected in the low-cascading regime (see Supplementary Information). Similarly, we observed an identical depletion profile on an anti-Stokes seed (Fig. 2a). The Stokes seed experiences amplification as long as the pump remains undepleted. Exactly on resonance, the on/off gain is given by $2g_{\text{SBS}}P_pL_{\text{eff}}$, where $2g_{\text{SBS}} = G_{\text{SBS}}(\Omega_m)$ is the Brillouin gain coefficient, $P_p$ is the input pump power and $L_{\text{eff}} = (1 - \exp(-\alpha L))/\alpha$ is the effective interaction length. The effective length has an upper limit of $1/\alpha = 1.7 \text{ cm}$ in our wires. To extract the Brillouin parameter $g_{\text{SBS}}$ we swept the pump power in a 2.7-mm-long wire (Fig. 3a). Above 25 mW on-chip power, nonlinear absorption saturates the on/off gain. Free carriers, created by two-photon absorption (TPA), then result in a power-dependent optical loss $\alpha(P_p)$. We extracted $g_{\text{SBS}} = 3,218 \text{ W}^{-1}\text{m}^{-1}$ below this threshold. The Lorentzian fit yielded an acoustic linewidth of $\Gamma_m/2\pi = 30 \text{ MHz}$ and thus a quality factor of $Q_m = \Omega_m/\Gamma_m = 306$ and a phonon lifetime of $\tau = 1/\Gamma_m = 5.3 \text{ ns}$ in the same short wire. The largest on/off gain of 0.6 dB below the TPA threshold falls narrowly short of the linear loss $\alpha L = 0.7 \text{ dB}$ (Fig. 3a). The wire is therefore close to net optical amplification, which is necessary for lasing. The on/off gain reached 175% in the 4-cm-long wires (Fig. 2a), an improvement of a factor of 19 on previous results in silicon.

Similarly, we observed backward SBS (see Supplementary Information) for counter-propagating pump and Stokes waves, which generate elastic waves with a large wavevector $K = 2k_0$ (where $k_0$ is the pump wavevector). However, we achieved the giant light–sound overlap only for forward SBS, for co-propagating pump and Stokes waves that generate low-group-velocity acoustic phonons with small wavevector $K < 2\Omega/v_g$ (where $v_g$ is the optical group velocity). Therefore, we focus on forward SBS here.

We next measured the strength of the cross-phase modulation (XPM) imprinted on a weak probe by a strong intensity-modulated pump (Fig. 2c,d). The experiment yielded a distinct asymmetric Fano signature at $\Omega_m/2\pi = 9.2 \text{ GHz}$ caused by interference between the resonant Brillouin and the non-resonant Kerr response (see Supplementary Information). The lineshape follows $\gamma_{\text{XPM}}(\Omega) = 2g_{\text{Kerr}} + g_{\text{SBS}}(\Omega) = 2g_{\text{Kerr}} + 2g_{\text{SBS}}(\Omega)$ for counter-propagating pump and Stokes waves that generate low-group-velocity acoustic phonons with small wavevector $K < 2\Omega/v_g$ (where $v_g$ is the optical group velocity).

We deduced the ratio $g_{\text{SBS}}/g_{\text{Kerr}}$ to be 2.5 and $Q_m = 249$ from the fit. The Kerr parameter $g_{\text{Kerr}}$ of similar silicon wires has been studied extensively, with values reported at $g_{\text{Kerr}} = 566 \text{ W}^{-1}\text{m}^{-1}$ for our cross-section. Because of the pump etch, the light is more confined to the high-index silicon core. In simulations we found that this yields a slight increase in the Kerr effect (by 8%) to $g_{\text{Kerr}} = 611 \text{ W}^{-1}\text{m}^{-1}$. Thus, we have $g_{\text{SBS}} = 3,055 \text{ W}^{-1}\text{m}^{-1}$, within 5% of the value obtained from the gain experiments. This nonlinearity is roughly a factor of 10$^4$ stronger than in photonic crystal and highly nonlinear fibres.

Furthermore, the resonance frequency, quality factor and interaction strength are in good agreement with the models. To study the frequency we performed the XPM experiment for waveguide widths from 350 nm to 500 nm (Fig. 3b). Both a simple Fabry–Pérot ($\Omega_m/2\pi = v/2w$) and a sophisticated finite-element model match the observed resonances. The finite-element model takes into account the exact geometry of the wires (obtained from scanning electron microscopy; Fig. 1c). This includes the waveguide...
Figure 2 | Experimental characterization of photon-phonon coupling. a, Typical Lorentzian gain profile on a Stokes seed. In both cases, the interaction generates acoustic phonons and redshifted photons (energy diagram). Such resonances are observed in wires as short as 2.7 mm (see Supplementary Information) with a highest on/off gain of 175% (4.4 dB) in the 4 cm spiral (L<sub>eff</sub> = 1.5 cm) with 35 mW on-chip pump power. There is a remnant of a second resonance at 9.15 GHz (see Supplementary Information). The normalized Stokes power is to the chip. The pump is removed at the output by a bandpass filter (BPF). The phase modulation on the probe wave is transduced to intensity modulation by filtering out the redshifted sideband. Finally, an electrical spectrum analyser (ESA) is used to observe the beat between the probe and the imprinted blue sideband.

Figure 3 | Analysis of Brillouin gain and phononic resonance frequency. a, Scaling of the on/off Brillouin gain with input pump power. Above a power threshold of 25 mW, the on/off gain saturates because of nonlinear absorption. A fit is performed to obtain the Brillouin nonlinearity below that threshold. b, Phononic resonance frequency for different waveguide widths. Error bars indicate an estimate of the uncertainty on the waveguide width. The uncertainty on the resonance frequency (y axis) is smaller than the size of the points. Both a simple Fabry-Pérot and rigorous finite-element model agree with the data.

height, pillar size, sidewall angle and the (110) crystal orientation of our wires (see Methods). We found that the waveguide width alone pins down the resonance frequency, with other geometrical parameters inducing only minor shifts. For a 450-nm-wide waveguide, the frequency sensitivity to width changes is 19.2 MHz nm<sup>-1</sup> (Fig. 3b). In contrast, the calculated sensitivity to height changes is only 2.3 MHz nm<sup>-1</sup>. This supports the intuitive Fabry–Pérot view, in which the height does not appear at all.

The large sensitivity to waveguide width implies that a 2 nm width fluctuation shifts the resonance by more than a linewidth. Accordingly, inhomogeneous broadening may affect both the line-shape and linewidth, similar to Doppler broadening in gain media. Surprisingly, we achieve acoustic quality factors above 250, even in the 4-cm-long wires (Fig. 4a). This suggests that there is, if at all, only limited length-dependent line broadening (see Supplementary Information). This large sensitivity can be exploited to tailor the resonance frequency.

By sweeping the pillar size in a short 450-nm-wide waveguide we established leakage through the pillar as the dominant phononic loss mechanism (Fig. 4b). The pillar acts as a channel for elastic waves that propagate down into the substrate. We rigorously modelled this mechanism by adding an artificial absorbing layer at the
boundary of the simulation domain (see Methods). As predicted by such a model, the observed quality factors diminish rapidly with increasing pillar size. The pillar should be seen as a moving acoustic membrane, not as a fixed point. It therefore affects neither the acoustic field profile nor its associated stiffness $k_{\text{eff}}$ to any great extent. We regard a short phonon lifetime as the prime reason why SBS has not been observed so far in typical SOI nanowires.

Finally, we show that the photon–phonon coupling is a constructive combination of bulk (electrostriction) and boundary (radiation pressure) effects (Fig. 4c). The resonant Brillouin gain coefficient is given by $G_{\text{SBS}}(Q_m) = 2y_{\text{SBS}} = \omega_0 Q_m(f, u)^2/(2k_{\text{eff}})$ (see Supplementary Information), so the non-resonant part $2y_{\text{SBS}}/Q_m$ is a direct measure of the photon–phonon overlap $\langle f, u \rangle$. In our finite-element simulations of $\langle f, u \rangle$ and $k_{\text{eff}}$, we take into account the mechanical anisotropy of silicon but not the pillar. We also approximate the cross-section as rectangular, neglecting the small sidewall angle. Even so, the simulations match the experimentally determined coupling strength. Neither electrostriction nor radiation pressure separately explain the experimental results, indicating that the effective interaction strength must be enhanced. Currently, we attribute a short phonon lifetime as the prime reason why SBS has not been observed so far in typical SOI nanowires.

### Discussion

Our observations provide robust evidence for incredibly strong photon–phonon coupling in silicon nanowires. The simulations of the interaction strength match the experiments, indicating that the new nanoscale SBS theory is on the right track. Moreover, simple finite-element models accurately capture both the phononic resonance frequency and lifetime.

Building on the good light–sound overlap, some typical SBS applications are now squarely in reach. For lasing, the gain must exceed the loss over an optical cavity roundtrip. Currently, we achieve 0.6 dB on/off gain in a wire with 0.7 dB propagation loss (Fig. 3a). We note that lasing—as opposed to sasing—also requires a resonator that is less optically than acoustically damped. Another example is the microwave filter, as such filters can be driven by even sub-1 dB gain.

For other devices, such as isolators and slow light, the performance in terms of optical losses and SBS strength must be improved more substantially. Optical losses below 1 dB cm$^{-1}$ have already been demonstrated in comparable silicon wires, by moving from a 200 nm to a 300 nm wafer CMOS pilot line with more advanced lithography tools. Significant net gain should be accessible in such low-loss wires, in which effective interaction lengths up to $L_{\text{eff}} = 5$ cm may be obtained.

Furthermore, free-carrier absorption saturates the SBS gain above a pump power of 25 mW (Fig. 3a). This means that the SBS gain has to be improved by other means, and either the phonon lifetime $\tau$ or the photon–phonon overlap $\langle f, u \rangle$ should be enhanced. Currently limited by the phonon leakage, the lifetime could be increased—at the cost of smaller bandwidth—by exciting asymmetric elastic modes. It has been predicted that such modes can be generated efficiently by cross-coupling between the quasi-TE and quasi-transverse magnetic (TM) optical modes. Alternatively, the overlap $\langle f, u \rangle$ may be increased by trapping light in a narrow horizontal air slot between two specially designed silicon wires. Such ideas may further boost the Brillouin nonlinearity to a level sufficient for milliwatt-threshold lasing, frequency comb generation and fully non-resonant optomechanics.

In fact, each application comes with a specific figure of merit. For comb generation with a dual pump, the forward SBS gain is critical. It is then equivalent to increase the lifetime $\tau$ or the overlap $\langle f, u \rangle$. In other cases, such as for slow light, the bandwidth is equally important. Furthermore, it is often desirable to have the acoustic resonance in the gigahertz range, which implicitly sets the stiffness $k_{\text{eff}}$ given a certain mass. Even so, a large light–sound overlap $\langle f, u \rangle$—clearly manifested in this work—is greatly beneficial in all cases.

In conclusion, we have demonstrated efficient interaction between near-infrared light and gigahertz sound trapped in a small-core silicon photonic wire. The structure exhibits an extraordinary light–sound overlap, at the same time allowing for a centimetre-scale Brillouin-active interaction length. The combination of both opens the door to practical Brillouin devices integrated on a CMOS-compatible silicon chip.

### Methods

**Device fabrication and characterization.** The SOI wires were fabricated by 193 nm deep-ultraviolet lithography on a 200 nm wafer CMOS pilot line at imec. The wires were undrenched with 2% diluted hydrofluoric acid at an etching rate of 10 nm min$^{-1}$. Platinum (Pt) was deposited on the wire and the cross-section (Fig. 1c) was milled by a focused ion beam. Platinum deposition ensured a straight cross-section and prevented charging effects when the cross-section was viewed by a scanning electron beam. The straight wires had lengths of 1.4 and 2.7 mm, and the spirals were 1, 2 and 4 cm long (Supplementary Fig. 2). The 1, 2 and 4 cm spirals had footprints of 275 μm × 100 μm, 775 μm × 90 μm and 1,570 μm × 90 μm, respectively. Adjacent wires were spaced by 1.55 μm inside the spiral. We found a propagation loss $\alpha$ of 2.6 dB cm$^{-1}$ and a coupling loss of 6 dB per grating coupler by the cut-back method.

**Experimental set-up.** The following abbreviations are used (Fig. 2): erbium-doped fibre amplifier (EDFA); band-pass filter (BPF); fibre polarization controller (FPC); intensity modulator (IM); electrical spectrum analyser (ESA); light trap (LT); fibre Bragg
grating, FBG; photodetector, PD. The FBGs were a crucial part of the set-up. Produced by Temixion, these filters were custom-designed to have a flat response within the passband and to drop to ~30 dB within 2.5 GHz. The steep flanks were used to filter out either the red- or blueshifted sidebands (bandwidth, 60 GHz). In addition, a pair of perfectly aligned FBGs were used for the gain experiment (Fig. 2b).

Finite-element modelling. We obtained the photonic and phononic modes from the finite-element solver COMSOL. These were exported to MATLAB to calculate the photon–phonon coupling\(^{26-28}\). Because the wires were aligned along a (110) axis, both the elasticity \(v_{\text{ph}}\gamma_{\text{ph}}\) = (166, 64, 79) GPa and photoelasticity \(p_{\text{ph}}|\gamma| = (0.0, 0.0, 0.017, -0.051)\) matrices were rotated by \(\pi/4\). To simulate the clamping loss, an artificial silica matching layer with Young’s modulus \(c = \frac{E}{3(1-\nu)}\) and density \(\rho\) was added. The layer absorbed incoming elastic waves without reflection. In a frequency-domain simulation, we then found the quality factor from \(Q_{\text{ph}} = (\omega/2\pi)\zeta\) was optimized for minimal \(Q_{\text{ph}}\). A typical value was \(\zeta = 2\) for a 420-nm-thick matching layer.

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Competing financial interests
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Additional information
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In the version of this Article originally published, in the expression for $L_{\text{eff}}$ on page 200 the exponential should have contained a minus sign and the expression should have read $L_{\text{eff}} = (1 - \exp(-\alpha L))/\alpha$. This has been corrected in the online versions.