Observation of 4.4 dB Brillouin gain in a silicon photonic wire

Raphaël Van Laer, Bart Kuyken, Dries Van Thourhout and Roel Baets

Photonics Research Group, Department of Information Technology, Ghent University – imec & Center for Nano- and Biophotonics, Ghent University

raphael.vanlaer@intec.ugent.be

Abstract: We report the first observation of a hypersonic mode of a small-core silicon wire. In particular, we achieve record 4.4 dB on/off continuous-wave Brillouin gain at 1550 nm. The wire is supported by a tiny oxide pillar to block the path for external phonon leakage.

1. Introduction

Stimulated Brillouin scattering (SBS) is a third-order nonlinear process that couples light to hypersound [1]. Although best known for limiting the optical power in fiber communication links, it has applications ranging from slow light [2] for lidar [3] to tunable RF notch filters [4], microwave synthesis [5] and spectrally pure lasers [6]. Fundamentally, it is a portal between the fields of photonics and phononics [7]. It can also be seen as the travelling-wave complement to cavity optomechanics [8], extending work on megahertz-optomechanics [9, 10] to the gigahertz domain. In guided-wave systems, SBS comes in two varieties: *forward* and *backward* SBS, in case the pump and Stokes wave either co- or counterpropagate. The process has been studied in a multitude of platforms [11, 12], but proved elusive in silicon wires. It was hypothesized that the elastic waves rapidly leak away to the substrate in a typical silicon-on-insulator wire [13], reducing the SBS gain coefficient drastically.

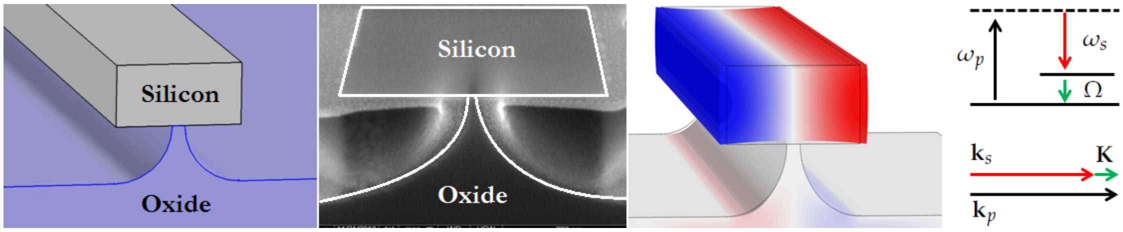
We confirm this experimentally by partially releasing a silicon wire (fig. 1) from its oxide substrate with hydrofluoric acid. By carefully controlling the etching speed, a narrow ($\approx$ 10 nm) oxide pillar is left underneath the wire. This largely blocks the external path for phonon loss, while keeping the benefits of rigidity and scalability to long interaction lengths. Finite-element simulations, based on the model of [13, 14], predict that this wire-on-a-pillar supports a mechanical mode (fig. 1) that has a large overlap with the optical forces given TE-input in the forward SBS configuration. This elastic mode can be understood as the fundamental $\lambda/2$-mode of a Fabry-Pérot cavity for hypersonic waves, formed by the silicon-air boundaries. Further, forward SBS is the acoustic equivalent of phase-matched stimulated Raman scattering. Therefore it is qualitatively different from backward SBS, allowing for comb generation even without a cavity [15].

Forward SBS in silicon was shown for the first time in a completely suspended hybrid silicon/silicon nitride waveguide [16]. However, short interaction lengths limited the on/off gain in this structure to 0.4 dB (10%) while high optical losses of 7 dB/cm precluded net gain. Here we observed 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.

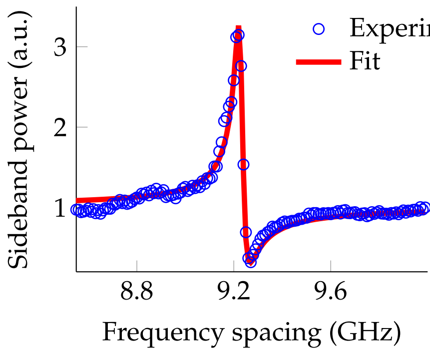
2. Findings

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.

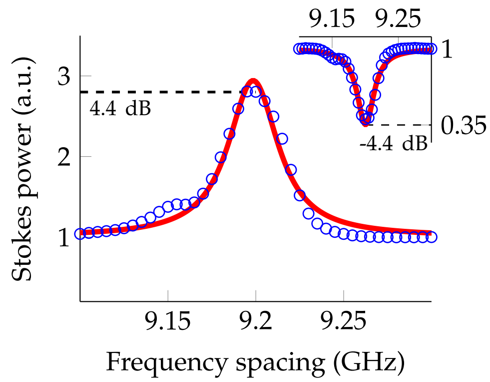
First, we calibrate the mechanical nonlinearity with respect to the Kerr effect by cross-phase modulation. The experiments yield a distinct Fano signature at 9.2 GHz (fig. 2) caused by interference between the resonant Brillouin and the non-resonant Kerr response. From this Fano resonance we extract the ratio $\gamma_{\text{SBS}}/\gamma_{\text{Kerr}} \approx 2.5$ and a linewidth of $\approx$ 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 $\approx$ 260 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.



(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.

Next, we perform a gain experiment by monitoring the power in a Stokes line 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 line. 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 22 mW c.w. pump power landed on the chip. This corresponds to gain coefficients of $\approx 2500\,\mathrm{W}^{-1}\mathrm{m}^{-1}$, which is confirmed by the cross-phase modulation experiment. At higher pump powers nonlinear absorption prevents a further increase in gain-to-loss ratio.

In conclusion, we demonstrated efficient forward SBS in a partially suspended silicon wire. Further improvements in optical or mechanical losses may bring this structure firmly into the realm of net amplification.

Acknowledgement. R.V.L. acknowledges the Agency for Innovation by Science and Technology in Flanders (IWT) for a PhD grant. This work was partially funded under the FP7-ERC-InSpectra programme and the ITN-network cQOM.

1. G. P. Agrawal, *Nonlinear fiber optics*. Academic Press, fifth ed., 2013.
2. Y. Okawachi et al. *Physical Review Letters*, vol. 153902, no. April, pp. 1–4, 2005.
3. A. Schweinsberg et al. *Optics Express*, vol. 19, no. 17, pp. 15760–15769, 2011.
4. B. Morrison et al. *Optics Communications*, vol. 313, pp. 85–89, Feb. 2014.
5. J. Li et al. *Nature Communications*, vol. 4, pp. 1–7, 2013.
6. H. Lee et al. *Nature Photonics*, vol. 6, pp. 369–373, May 2012.
7. M. Maldovan et al. *Nature*, vol. 503, pp. 209–217, Nov. 2013.
8. T. J. Kippenberg et al. *Science*, vol. 321, pp. 1172–6, Aug. 2008.
9. M. Li et al. *Nature Photonics*, vol. 3, pp. 464–468, July 2009.
10. J. Roels et al. *Nature Nanotechnology*, vol. 4, pp. 510–3, Aug. 2009.
11. A. Kobyakov et al. *Advances in Optics and Photonics*, vol. 2, p. 1, Dec. 2009.
12. B. Eggleton et al. *Advances in Optics and Photonics*, pp. 536–587, 2013.
13. P. Rakich et al. *Physical Review X*, vol. 2, pp. 1–15, Jan. 2012.
14. W. Qiu et al. *Optics Express*, vol. 21, p. 31402, Dec. 2013.
15. M. S. Kang et al. *Nature Physics*, vol. 5, pp. 276–280, Mar. 2009.
16. H. Shin et al. *Nature Communications*, vol. 4, p. 1944, Jan. 2013.