Observation of stimulated Brillouin scattering in silicon nitride integrated waveguides

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Abstract: We report the first observation of backward stimulated Brillouin scattering in fully cladded Si_3N_4 waveguides. The intrinsic Brillouin gain at 25 GHz and the photoelastic constant are estimated to be 4×10^{-13} m/W and $|p_{12}| = 0.047 \pm 0.004$ respectively. © 2020 The Author(s)

Introduction — Silicon nitride (Si_3N_4) [1] shows exceptional performance in integrated photonics, due to its superior optical properties such as high Kerr nonlinearity, ultralow optical losses (<1 dB/m) [2], absence of two-photon absorption, flexibility to engineer the group velocity dispersion [3], as well as wide transparency window from visible to mid-infrared. Using the CMOS-compatible wafer-scale fabrication process developed for semiconductor industry, Si_3N_4 waveguides have led to various interesting applications including microresonator-based frequency comb generation [4] and chip-based supercontinuum generation [5].

Intensive research has been dedicated to exploring the rich nonlinear phenomena in Si_3N_4, including Kerr nonlinearity, harmonic generation and Raman scattering. However, so far stimulated Brillouin scattering (SBS) in Si_3N_4 has not been reported. Since SBS is known to be the highest nonlinear effect in solid materials and is the most stringent power limitation in waveguides [6], it is therefore of central importance to characterize SBS in Si_3N_4, in order to better understand and estimate the SBS threshold power in Si_3N_4 waveguides for high-power applications.

Here, we observe, for the first time, SBS in integrated Si_3N_4 waveguides fully buried in silica. The waveguides feature tight optical confinement and anomalous GVD, which are typically used for nonlinear photonics. By developing a novel experimental setup with unprecedented sensitivity for weak gain measurements, we successfully measure the Si_3N_4 Brillouin gain spectrum. We unambiguously identify the SBS frequency shift at 25 GHz, the largest value so far reported in integrated waveguides, which corresponds to an acoustic velocity in Si_3N_4 of 10.5 km/s. The measured SBS peak gain value is 8×10^{-14} m/W, 250 times smaller than the silica gain in single-mode fibers. The photoelastic constant p_{12} has been deduced from our measurement results and analysis, which is so far absent in the literature.

Results — Figure 1(a) shows an artist view of SBS in a Si_3N_4 waveguide buried in SiO_2. Since this buried waveguide is a leaky acoustic waveguide (acoustic velocity in Si_3N_4 is much higher than in silica cladding), the Brillouin gain is expected to be weak. To separate this weak Brillouin signal from the background noise and spurious signals, a novel triple intensity modulation technique has been implemented.

Figure 1(b) shows the magnitude of the measured signal amplitude, when the pump-probe detuning frequency is scanned from 10 to 35 GHz. The left peak close to 10 GHz is the silica Brillouin gain spectrum of a 1 m long fiber patch-cords connecting to the waveguide, and the signal around 25 GHz is the 5 mm long Si_3N_4 Brillouin gain. Figure 1(c) shows the measured Si_3N_4 gain spectrum along with our simulation results. A main peak reaching $(8\pm1)\times10^{-14}$ m/W is found at 25 GHz, accompanied by other smaller peaks. Using the phase matching condition, the velocity of the main acoustic mode is calculated as 10.5 km/s, which agrees with the literature [7]. The full width at half maximum of the main peak $\Delta\nu = 390$ MHz, is obtained by a Lorentzian fitting.

Figure 1(e) shows the finite element method (FEM) simulations performed over a 3D trench of the entire chip cross-section including the SiO_2-air top interface and SiO_2-silicon-substrate bottom interface. The simulation model is built using the precisely measured parameters from SEM, as shown in Fig. 1(d). Acoustic eigenmodes, computed from 21 to 27 GHz, show that the multiple peaks in the gain spectrum originate from the hybridization with high-overtone bulk acoustic resonances (HBARs) caused by the reflection of acoustic waves at the SiO_2-air top interface and SiO_2-silicon-substrate bottom interface [8]. The temperature response of the Si_3N_4 Brillouin frequency shift is measured to 0.4 MHz/K (shown in Fig. 1(f)), 2.5 times smaller than in silica.

The measured Si_3N_4 SBS peak gain value is 8×10^{-14} m/W, 250 times smaller than that in silica. The magnitude of the photoelastic constant is estimated as $|p_{12}| = 0.047\pm0.004$ by fitting the peak heights of the FEM simulations over the measured gain spectrum. This value is 5.7 times smaller than that of silica. The intrinsic Si_3N_4 Brillouin

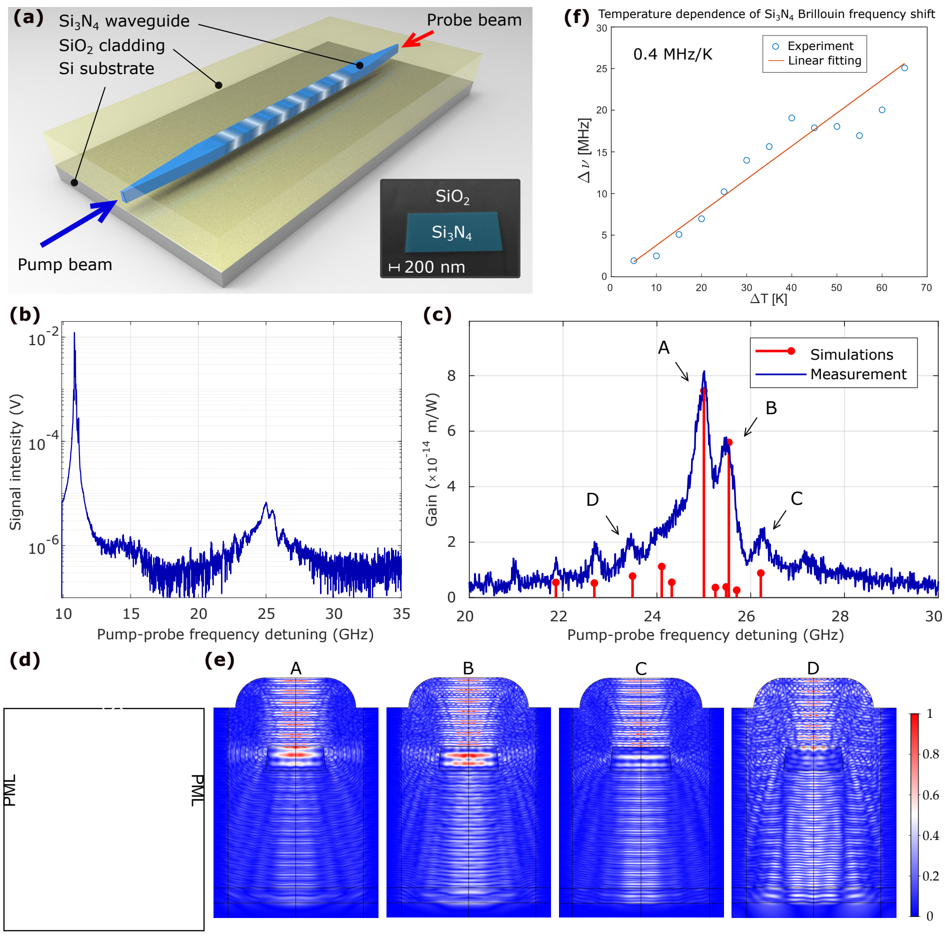

Fig. 1: **Stimulated Brillouin scattering in a Si_3N_4 waveguide.** **(a)** Artist's view of SBS in a Si_3N_4 waveguide. **(b)** Measured signal as a function of the pump-probe detuning frequency in logarithmic scale, showing the 1-m-long silica patchcord SBS to the left and Si_3N_4 SBS at 25 GHz, with more than three orders of magnitude difference. **(c)** Measured Si_3N_4 SBS gain spectrum, in agreement with the simulated eigenmodes (eigenfrequency and gain for each eigenmode). **(d)** SEM image showing the sample cross-section with precisely measured geometry parameters which are used to build the simulation model. PML, perfect-matched layer. **(e)** Four acoustic modes (A, B, C and D) marked in **(c)** with normalized acoustic displacement field norm (instantaneous value) of four peaks extracted from the simulations. The top SiO_2 dome-shaped interface is due to fabrication. **(f)** The response of the Brillouin frequency shift as a function of the waveguide temperature (relative to the room temperature of 24 °C), controlled by a Peltier cell.

gain is estimated as 4×10^{-13} m/W (51 times smaller than that of silica), when both inhomogeneous broadening and phonon leakage are absent and the acousto-optic overlap is unity.

Conclusion — We have characterized backward SBS in integrated Si_3N_4 waveguides by developing a novel experimental setup with unprecedented sensitivity for weak gain measurements. This weak gain value corresponds to an estimated SBS threshold power of 87 kW in our 5 mm long Si_3N_4 waveguides, thus demonstrating the excellent high-power handling capability of Si_3N_4, pivotal for nonlinear photonic applications.

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