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On-Chip Backward Stimulated Brillouin Scattering in Lithium Niobate Waveguides

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Abstract: We report on the first experimental demonstration of backward stimulated Brillouin scattering (SBS) in Lithium Niobate on Insulator (LNOI) waveguides. Performing polarization-dependent pump-probe experiments, we successfully quantified both intramodal and intermodal scattering among fundamental modes, showcasing substantial gains up to $G_B = 10 \text{ m}^{-1} \text{W}^{-1}$. Such large gains on simple waveguides open a pathway for unlocking novel opto-electro-mechanical phenomena within the LNOI platform.

Lithium niobate (LN), a material with an extensive historical presence in bulk optics and telecom components, has only recently gained attention for its potential in high confinement integrated photonics, thereby enhancing the interaction between optics and acoustics [1, 2]. A major challenge when tailoring LN structures to enhance the optomechanical interaction lies in achieving simultaneous confinement of both optical and mechanical waves. Current strategies involve either fully suspended structures [3] or exploring surface acoustic waves (SAW) [4] excited through interdigital transducers (IDT) that explores the unique piezoelectric properties of LN. Here we demonstrate a substrate-anchored LNOI waveguide that leverages the simultaneous guidance of light and shortwavelength surface acoustic waves [5], enabling the optical excitation of these acoustic waves through backward stimulated Brillouin-Mandelstam scattering (SBS) [6–8].

The waveguide has w = 700 nm top width, a wedge angle of $\phi = 65^{\circ}$ and is patterned on a t = 400 nmthick Z-cut LNOI atop a 4.7 µm silica (SiO₂) substrate, as schematically illustrated in Fig.1(a,e). The waveguide is 8.68 mm long, aligned parallel to the Y-axis of the material. To enhance SAW confinement [5], the surrounding LN layer was entirely etched away, resulting in a rib-like configuration. The design is optimized to support only the fundamental transverse electric (TE) and transverse magnetic (TM) optical modes, as depicted in Fig.1(b,c).

The SBS response of our system is characterized using a pump-probe scheme previously reported [9], as depicted in Fig.1(d), where the interference between a fixedwavelength pump at $\lambda_{\rm p} = 1550 \,\mathrm{nm}$ and a probe laser, which is piezo-scanned around the pump frequency, excites the acoustic grating. Given that SBS is inherently a nonlinear and typically weak phenomenon, both the pump and probe lasers are intensity modulated at slightly different frequencies $(f_{\rm s} = f_{\rm p} + \Delta, \text{ where } f_{\rm p} = 3 \,\text{MHz}$ and $\Delta = 40 \, \text{kHz}$, which allows us to detect the signal at the difference frequency (Δ) using a lock-in amplifier (LIA). This approach enhances the signal-to-noise ratio by mitigating low-frequency noise, while also allowing us to utilize high-gain narrow bandwidth optical receivers. SBS manifests when the optical force generated by the beating of these two counter-propagating lasers excites



FIG. 1. (a) Waveguide's profile and material axes orientation; (b,c) Norm of electric field for TE and TM modes; (d) Schematic pump-probe experimental setup; (e) SEM top view of the waveguide; (f) RMS power at 40 kHz measured by the LIA; (g) Anti-Stokes spectrum; (h) Stokes spectrum.

an acoustic mode satisfying energy and momentum conservation [10]. These criteria are satisfied when the pump and probe laser detuning matches the acoustic frequency $\Omega_m/2\pi \approx 2v_{\rm qs}(n_{\rm p} + n_{\rm s})/\lambda_{\rm p}$, where $v_{\rm qs}$, ranging between 3577 m/s and 3940 m/s, represents the speed of quasishear waves in LN, and $n_{\rm p,s}$ denote the effective refractive indices of the pump and probe modes, respectively. Given the strong polarization dependence of the waveguide and the inherent birefringence of the material, we anticipate Brillouin frequencies to be influenced by the polarization states of both the pump and probe lasers.

A sample raw data from our experiment is shown in Figure 1(f), displaying the backward SBS signal power measured by the LIA (40 kHz) for pump and probe launched at TM-TM polarizations. At a frequency of $\pm 10.8 \,\mathrm{GHz}$, we observe a Brillouin peak originating from a 6.3 m long optical fiber pigtails, along with two distinct mechanical modes within the LNOI waveguide, centered at ± 7.54 GHz and ± 8.13 GHz, each exhibiting linewidths of 66 MHz and 183 MHz. The symmetrically located peaks correspond to Stokes and anti-Stokes Brillouin scattering. To investigate the polarization dependence, we measured the SBS gain spectra under three different polarization configurations for the pump-probe pair: TE-TE, TE-TM, and TM-TM. The polarization states were configured by maximizing the extinction of either TM- or TE-polarized modes within a coupled microring (not shown), a determination based on a comparison of measured free spectral ranges with numerical simulations. We observed three distinct mechanical frequencies originating from the LN waveguide, as shown in Fig.1(g,h). The Brillouin gain spectra exhibited peaks at identical frequency detuning on both the Stokes and anti-Stokes sides for all frequencies, displaying an asymmetry in amplitude, a characteristic feature of SBS. As anticipated, the Brillouin gain spectra exhibit notable sensitivity to polarization states. In the TE-TE configuration, a singular mode emerges at 8.5 GHz, effectively suppressing the 7.54 GHz and 8.13 GHz modes. However, in both the TM-TM and TM-TE configurations, these modes are not entirely suppressed. We attribute this behavior to the potential misalignment of the pump and probe beams along the entire optical waveguide, as well as possible polarization rotation due to birefringence. Notably, the mode displaying the most substantial Brillouin gain (G_B) corresponds to the 7.54 GHz mode in the intermodal TE-TM configuration, exhibiting a Brillouin gain as high as $G_B = 9.4 \text{ m}^{-1} \text{W}^{-1}$.

To investigate the observed acoustic modes, we employed a simplified clamped waveguide as a toy model. We conducted simulations to analyze its mechanical dispersion (Fig.2(a)) and, for modes spanning from 7 GHz to 9 GHz, we numerically computed the normalized Brillouin gain (G_B/Q_m) for all the polarization configurations (Fig.2(b)), with Q_m representing the mechanical quality factor. Remarkably, the simulations revealed substantial G_B/Q_m values not only for the two intramodal interactions (TE-TE and TM-TM) but also for the intermodal interaction (TE-TM), aligning with our experimental findings (Fig.2(c)). Upon scrutinizing the simulation results, we observed a close resemblance in mode structure between the experimental traces and simulations. Notably, the three modes identified in the experimental data exhibited consistent normalized Brillouin gain values in good agreement with the simulations. The frequency mismatch between the experimental and simulated data can be attributed to uncertainty in optical

and mechanical velocities, particularly in the case of SAW modes, which are highly sensitive to small fluctuations in geometric and material parameters. The absence of certain modes, such as mode 1 in the TE-TE interaction, can be explained by a potentially lower Q_m and consequently a reduced G_B compared to mode 2. This difference may result in a situation where they are scarcely distinguishable, even in the parallel TE-TE configuration.



FIG. 2. (a) Mechanical dispersion diagram for a bottomclamped LN waveguide oriented along the Y-axis. The colors represent a weighting of mechanical polarizations; (b)-(c) Simulated and experimental normalized Brillouin gain (G_B/Q_m) for the different pump/probe polarization choices, respectively; (d) Mechanical mode profiles of the modes labeled in (a).

In summary, this study reports experimental demonstration of on-chip backward stimulated Brillouin scattering within the LNOI platform. Through a comprehensive investigation of the polarization states of our pump and probe signals, we not only observed robust intramodal Brillouin scattering but also, surprisingly, even more pronounced intermodal Brillouin scattering. This discovery holds the potential to pave the way for a multitude of innovative Brillouin-based applications, harnessing the well-established SBS capabilities in conjunction with the advanced maturity of LNOI piezoelectric devices within anchored waveguides.

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Disclosures. The authors declare no conflicts of interest. During the preparation of this manuscript, we became aware of the work by Kaixuan Ye et al. [11] also reporting SBS in LNOI.

Data Availability Statement. The data reported in the manuscript is available online at ZENODO (10.5281/zenodo.10059309).

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