Stimulated Forward Brillouin Scattering from a Fundamental Acoustic Mode in a Fiber Taper

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Abstract: Strong stimulated optomechanical coupling to the fundamental flexural acoustic mode of a tapered fiber is demonstrated, broadening access to frequencies, and increasing interaction-times for applications. A theoretical model featuring unique propagation dependent behavior is introduced.

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1. Introduction

Stimulated Brillouin scattering (SBS) is a strong coherent nonlinear-optical coupling between mechanical and optical fields that has emerged as a powerful tool for optical signal processing tasks including for RF filters, optical delay lines, light storage, and sensors [1,2]. The most established backward process, through which counter-propagating optical fields couple via a GHz longitudinal acoustic wave, is strong but is limited to GHz acoustic frequencies and microsecond lifetimes by fixed material parameters. More recent studies of interactions between co-propagating optical fields and guided acoustic waves demonstrate frequency tunability, with the frequency determined by the acoustic waveguide geometry. However, since strong coupling requires the acoustic waveguide to be comparable in size to the optical waveguide, this amounts to a trade-off between accessible frequencies and the strength of the interaction. For example, in solids, weak lower-frequency interactions (e.g., in standard fiber [3]), and strong GHz-frequency interactions (e.g., in PCF fiber [4] or in integrated waveguides [1]) have been established. This trade-off could be avoided, however, if the acoustic frequency could be decoupled from the acoustic waveguide size. This is the case for fundamental acoustic modes, which have no lower frequency bound, and exist even without an acoustic waveguide (Fig. 1d). While these modes have been coupled to electrically in fibers [5] and in dual-mode fibers with a small optomechanical overlap [6], desirable strong optomechanical coupling has not been achieved with long-lived acoustic modes at lower frequencies.

Here, we demonstrate strong optomechanical coupling between two co-propagating optical modes and the fundamental flexural acoustic mode of a few-mode optical fiber taper. In contrast to prior forward Brillouin interactions featuring 'cutoff' guided acoustic modes, fundamental acoustic modes support interactions to frequencies that are at least an order of magnitude lower, with correspondingly lower dissipation. This intermodal interaction, as with backward interactions, breaks the symmetry between Stokes and anti-Stokes scattering, which allows for non-reciprocal interactions and exponential gain. Strong Brillouin processes mediated by lower frequency phonons with longer lifetimes, in addition to qualitatively new physics, could enable straightforward performance improvements for existing Brillouin devices, including for phonon-lifetime-limited Brillouin-based light storage devices [2].

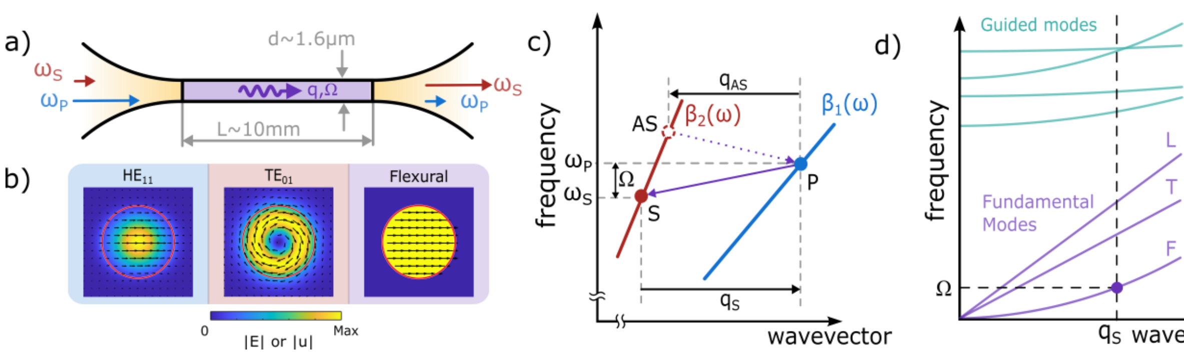

Figure 1: a) The fiber taper geometry. b) Electric field profile of the fundamental HE_{11} mode and one of the higher order modes (TE_{01}), and acoustic field profile of the fundamental flexural acoustic mode. c) Phase matching relation displayed on the optical dispersion curve, where $\beta_1(\omega)$ and $\beta_2(\omega)$ correspond to the first order and a higher order spatial mode of the taper. d) Acoustic dispersion curves of a solid cylinder depicting the phase-matched flexural mode (F) in relation to other fundamental (L and T) and guided ('cutoff') modes.

2. Theory

The optical fiber taper (Fig. 1a) with diameter $d = 1.6\ \mu m$ and length $L = 10$ mm at $\lambda = 1550$ nm guides one Gaussian-like fundamental mode (HE_{11} in fig. 1b) and three higher order optical modes (TE_{01} shown in Fig. 1b, TM_{01}, and HE_{21}), as well as three fundamental acoustic modes (flexural (F), torsional (T), and longitudinal (L)) and guided cut-off modes (Fig. 1d). A HE_{11} pump wave with frequency ω_p, and wavevector $\beta_1(\omega_p)$ can coherently couple to a co-propagating Stokes field (ω_S, $\beta_2(\omega_S)$) in any of the three higher order modes ($TE_{01}/TM_{01}/HE_{21}$) through a phase-matched acoustic mode ($q_s = \beta_1(\omega_p) - \beta_2(\omega_S)$, $\Omega = \omega_p - \omega_s$) (Fig.1c). The coupling strength is determined by the overlap of the acoustic displacement with the optical force distribution over the taper cross-section. Only the flexural acoustic mode (Fig. 1b) has a non-zero overlap with the optical forces. The three higher-order optical modes have different optical indices which through intermodal interactions will couple to three different flexural acoustic mode frequencies, 133 MHz, 208 MHz and 218 MHz for TE_{01}, TM_{01} and HE_{21} respectively. The coupling strengths are each predicted to be >10 $W^{-1}m^{-1}$ (>100 $W^{-1}m^{-1}$) assuming a conservative acoustic quality factor of 100 (1000).

3. Experimental Results

Measurements are made with a phonon-mediated four-wave mixing process related to that used in other recent studies [7,8]. The flexural mode is driven with optical drive tones separated into two distinct spatial modes with a fiber-based mode-selective coupler. A probe beam at a different wavelength in a higher-order optical mode scatters off the driven flexural wave into the fundamental optical mode. A single-mode collimator at the output of the test fiber collects scattered signal light while rejecting the probe. The scattered signal is mixed with a heterodyne optical tone allowing for frequency-resolved Stokes and anti-Stokes measurements. The resultant signal is a coherent sum $\chi^{(3)}$ of four-wave mixing and the Brillouin resonance, giving Fano-shaped resonances [7,8]. Measurement of the anti-Stokes sideband yields three distinct resonances (Fig. 2a) in excellent agreement with predictions, at 133 MHz, 208 MHz, and 218 MHz. As expected, no Stokes sideband is observed, demonstrating single sideband gain. The TE_{01} resonance exhibits additional oscillatory spectral structure at lower frequencies (Fig. 2b). To explore this feature, the coupled optomechanical equations accounting for axial variation in the taper radius (assuming a parabolic-like variation of $0.15\ \mu m$ from a minimum waist of $0.8\ \mu m$) are solved numerically (Fig. 2c). The qualitative agreement between theory and experiment suggests that the unique oscillatory structure results from fluctuations in local taper radius within the mean phonon path. The combination of long phonon lifetimes and axial profile variations results in qualitatively new spectral features compared to conventional Brillouin inhomogeneous broadening [9].

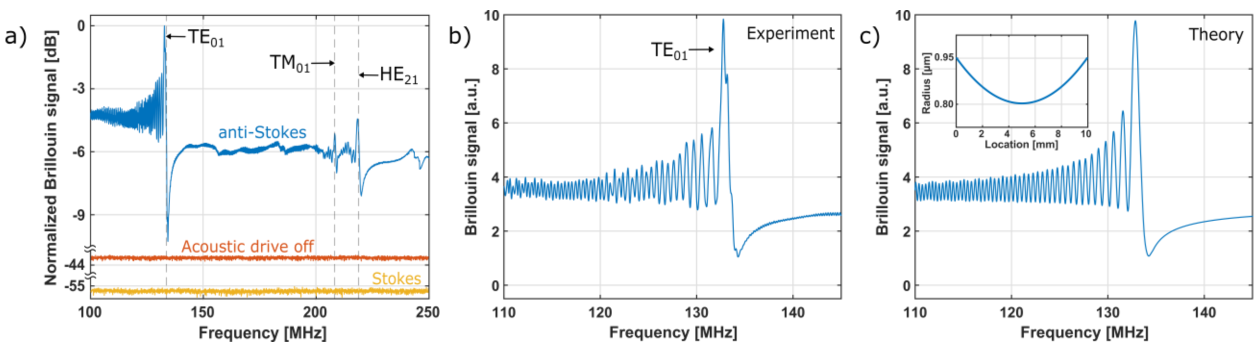

Figure 2: a) Measured intermodal response in a few-mode fiber taper, anti-Stokes (blue trace), Stokes (red) and acoustic drive off (yellow). b) The measured TE_{01} Brillouin-active resonance and c) its prediction accounting for the axial variations.

In summary, here we demonstrate a novel optomechanical interaction coupling two optical spatial modes to the fundamental flexural acoustic mode of a few-mode fiber taper. Experiments and matching predictions reveal three distinct resonances corresponding to coupling of the fundamental optical mode to three higher-order modes. A theoretical model featuring unique propagation dependent behavior agrees with measurements. This work demonstrates the potential of expanding the accessible frequencies for strong Brillouin interactions and may enable improved Brillouin signal processing, including for RF filters, optical delays, and optical information storage.

4. References

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