

Ultranarrow-Linewidth Stimulated Intermodal Forward Brillouin Scattering

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Abstract: We demonstrate strong ($\sim 300 \text{ W}^{-1}\text{m}^{-1}$) and ultranarrow linewidth ($\sim 100 \text{ kHz}$) stimulated intermodal forward Brillouin scattering in a homogeneous multi-mode fiber optical taper. This unique combination of parameters can enable record performance Brillouin-based microwave-photonic devices.

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1. Introduction

Stimulated Brillouin scattering is a strong coherent nonlinear-optical interaction between propagating mechanical and optical fields. Brillouin processes have now been established as a valuable resource for many applications including for signal processing, narrow-linewidth lasers, and environmental sensors. In single sideband stimulated Brillouin interactions, Stokes and anti-Stokes processes are mediated by disparate acoustic waves, which enables unidirectional energy transfer from the optical pump to the Stokes wave. These interactions yield high coupling strengths, clean optomechanical responses, and are particularly desired for applications such as signal amplification, low-phase noise lasers, and filtering and signal-processing [1]. Single-sideband interactions include the well-known backward Brillouin interaction [2], as well as other intermodal interactions and platforms including birefringent fibers [3], on-chip multimode waveguides [4], and optical vortex modes [5]. While applications often benefit from large coupling and narrow linewidths [7], most current platforms supporting single-sideband processes with large coupling strengths involve GHz acoustic modes with correspondingly small acoustic lifetimes, and therefore larger linewidths ($\sim 10\text{-}30 \text{ MHz}$). Recently, strong single-sideband coupling was demonstrated with forward intermodal scattering from long-lived fundamental acoustic modes (FIM-FAM) in multimode fiber tapers [8]. However, in the initial demonstration, although the interaction was strong and involved long-lived acoustic modes, this long lifetime did not translate to narrow linewidths because geometric inhomogeneity lead to phonon self-interference and effective oscillatory spectral linewidth broadening [8].

Here, we demonstrate stimulated single-sideband Brillouin interactions with a coupling strength of $\sim 300 \text{ W}^{-1}\text{m}^{-1}$ and a linewidth response near 100-kHz based on FIM-FAM interactions in a homogeneous multimode tapered fiber. Through a combination of geometric and dispersive homogeneity improvements, the Stokes signal response is enhanced by $>1000\times$ and the effective linewidth is decreased by $>10\times$ from prior results. To our knowledge this result represents of the narrowest small-signal linewidth measured to-date from a single-sideband Brillouin active device. This interaction is ideal for microwave-photonic devices desiring high spectral resolution.

2. Principle and Device

The FIM-FAM active optical fiber taper (Fig. 1a) with a waist diameter $d = 1.2 \mu\text{m}$ and length $L = 100 \text{ mm}$ at $\lambda = 1550 \text{ nm}$ guides one Gaussian-like fundamental mode and two non-degenerate higher order optical modes (TE_{01} and TM_{01} shown in Fig. 1b). Acoustically, the taper supports three fundamental acoustic modes (flexural (F), torsional (T), and longitudinal (L)) and guided cut-off modes (Fig. 1c). A strong pump in the fundamental optical mode can

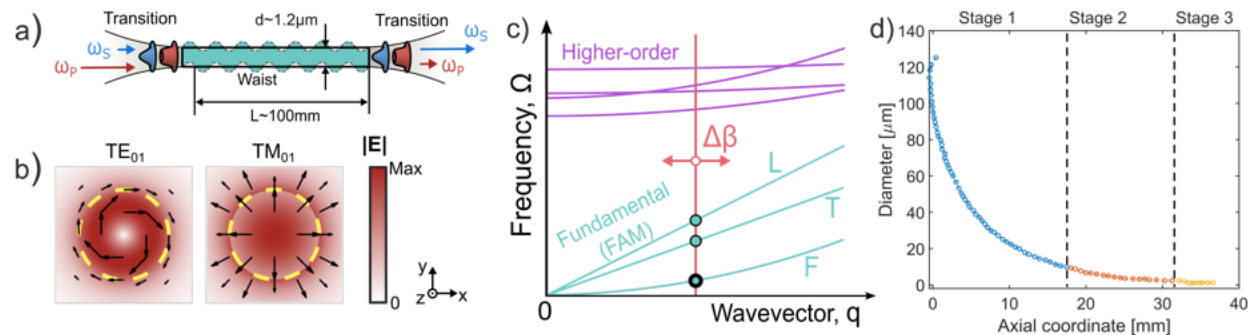


Figure 1: a) Propagating flexural mode of a FIM-FAM active fiber taper driven by phase matched pump and Stokes optical beams in separate optical modes. b) Higher order optical modes supported by the taper. c) Acoustic dispersion curves in the taper indicating the targeted interaction with the fundamental flexural mode. d) 3-stage transition region of the taper profile design.

unidirectionally amplify a co-propagating Stokes field in either of the two higher-order modes (TE_{01}/TM_{01}) through an acoustic mode, provided phase matching and energy conservation relations are satisfied (intersection points in Fig. 1c). While phase matching for intermodal interactions is possible for many modes, FIM-FAM interactions mediated by the fundamental flexural mode has the largest coupling strength. To allow for extended interactions and strong acousto-optic coupling, the FIM-FAM active fiber tapers are fabricated using a heat-brush technique to ensure a homogenous waist. The pulling process is divided into cycles. Each cycle adds a small section to the taper while the radius of the fiber cladding is reduced by a constant ratio to reach the nanofiber waist radius at the end of the last cycle. At cycle iteration number n , the heat zone length is chosen as a power law of n , enabling few-cm length tapers. Additionally, the transition regions around the taper waist are designed to be sufficiently adiabatic to minimize optical losses within the device (profile design in Fig. 1d).

3. Experimental Results

The optomechanical spectrum is measured with a sensitive phonon-mediated four-wave mixing technique, as with previous FIM-FAM measurements [8]. Two optical drive tones, which drive the fundamental flexural mode, are coupled into the optical fiber taper in distinct spatial modes with a fiber-based mode-selective coupler. A probe beam at a disparate wavelength in a higher-order optical mode scatters off the driven flexural wave into the fundamental 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 reference optical tone allowing for heterodyne detection of the frequency-resolved Stokes and anti-Stokes signals. The resultant resonances assume a Fano-like shape owing to a coherent addition of frequency-independent four-wave mixing and the optomechanical resonance. The optomechanical spectrum of the anti-Stokes response yields a strong single peaked resonant feature at 204 MHz corresponding to the $HE_{11} - TE_{01}$ FIM-FAM interaction (Fig. 2a), in good agreement with theoretical predictions. As expected of a non-reciprocal process, the corresponding Stokes response is negligible. A closer look at the resonance reveals small spectral structure resulting from some residual geometric inhomogeneity (Fig. 2b). The dominant peak consists of $\sim 50\%$ of the integrated response and has a linewidth of 113 kHz. The calculated coupling strength for the observed resonance is in excess of $300 \text{ W}^{-1}\text{m}^{-1}$. Intermodal interactions with other higher-order optical modes are suppressed through judicious taper design and polarization control, resulting in an application-desirable single peaked response.

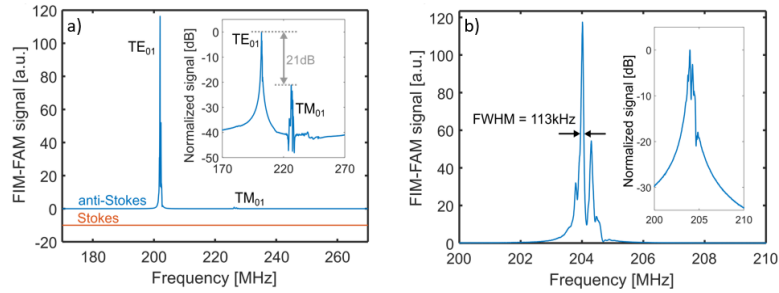


Figure 2: a) Measured optomechanical response of a FIM-FAM taper device (blue). The corresponding Stokes response shows negligible response, as predicted (red). The response from the TM_{01} optical mode is suppressed by 21 dB below the targeted TE_{01} response (inset). b) Closer view of the targeted TE_{01} Brillouin-active resonance.

In summary, here we demonstrate strong ($\sim 300 \text{ W}^{-1}\text{m}^{-1}$) non-reciprocal Brillouin interactions with an ultra-narrow linewidth ($\sim 100\text{-kHz}$) response from a long and homogeneous fiber taper device. This performance represents a linewidth reduction of more than an order-of-magnitude compared to other single-sideband high-gain interactions and therefore represents the narrowest small-signal linewidth measured to date. The frequency agility of FIM-FAM interactions along with the unparalleled combination of large coupling and ultra-narrow linewidths is desirable for microwave-photonics applications.

4. References

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Other metrics-

- 1) **Weighted Width ~ 300 kHz**
- 2) **Gain of 300 W-1m-1 is taking into account all the scattered power.**

Outline

Intro:

- 1) Brillouin optomechanics very good for a bunch of stuff.
- 2) Of which single sideband processes are uniquely advantages for all important applications like filters, lasers, on-chip isolators, reconfigurable RF photonic filters
- 3) Current optomechanical RF photonic systems are limited by linewidth
- 4) Backward Brillouin @10 GHz with linewidths ~10-30 MHz
- 5) Intermodal on-chip on silicon despite being strong still has linewidth of the order of 20 MHz
- 6) Sub-100 KHz demonstrated in micro resonators with low gain and cavity restrictions
- 7) Recent FIM-FAM can access long lived phonons, but suboptimal taper design= PSI= broadened response
- 8) Here we demonstrate Stimulated single sideband Brillouin with a near-100 KHz linewidth, for the first time + theoretical gain exceeds 500 W-1m-1
- 9) Represents a factor 100x decrease from backward, 30x decrease from intermodal, with similar gain

Theory:

- 1) Our system= 2 mode fiber + linear transition region + homogenous center
- 2) FIM-FAM between
- 3) RP+ electrostriction mediates this interaction
- 4) R=
- 5) Theoretical gains exceed 560W-1m-1 for interaction with TM01
- 6) TM01 good because of weak dependence on radius

Experiment

- 1) Technique inspired by pump-probe Brillouin spectroscopy.
- 2) Two strong pump drive, probe scatters.
- 3) Optomechanical spectrum shows sparse peaks with the strongest peak with ~100kHz linewidth
- 4) No stokes response confirming single sideband
- 5) Measured gain exceeds 300 W-1m-1

Summary

- 1) An optimized taper demonstrates world record single side band linewidth, narrower by 30x than previous ones with similar gain, for the first time
- 2) Ideal for novel reconfigurable RF photonic filters
- 3) Prospect of obtaining even narrower linewidths
- 4) Optical dispersion engineering can enable robust frequency tunability

Title Ideas:

Keywords: Single-sideband, 100-KHz, stimulated Brillouin, travelling-wave, Taper, intermodal, single-peaked, Strong, 500 W-1m-1

- 1) Strong stimulated Brillouin interaction with near 100 KHz linewidth
- 2) Single-sideband Brillouin interaction with near 100 KHz linewidth
- 3) Strong single-sideband Brillouin scattering with 100 KHz linewidth (my choice)