Tunable Brillouin-based Microwave Photonic Bandpass Filter with sub-MHz Bandwidth

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Abstract: A continuously tunable microwave-photonic filter with ultranarrow bandwidth is enabled by forward inter-modal Brillouin interactions with a fundamental acoustic mode of a fiber taper. Sub-MHz bandwidth is demonstrated over >10 GHz, limited by current components.

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1. Introduction

Microwave filters based on photonic systems offer several advantages over traditional approaches, including low loss, reconfigurability, tunability, immunity to electromagnetic interference, high spectral resolutions, and large instantaneous bandwidths [1,2]. Filters leveraging stimulated Brillouin scattering have garnered considerable attention, in particular, due to their unique potential for enabling wideband and continuously tunable filters with the high spectral resolutions inherent to Brillouin interactions [1,3]. However, current Brillouin-based microwave photonic filters are limited to spectral resolutions of around several MHz due to the short lifetimes of the GHz phonons typically associated with Brillouin interactions [4–7]. Recently, Forward Inter-Modal Brillouin interactions with the Fundamental Acoustic Modes (FIM-FAM) have been shown in optical fiber tapers to enable efficient access to low-frequency phonons with ultranarrow Brillouin linewidths nearing ~100 kHz [8,9]. If these interactions can be translated to an effective and flexible microwave-filtering platform, the achievable filter bandwidth for Brillouin-based filters could be reduced by more than an order of magnitude, which would be valuable for microwave applications with demanding spectral resolution requirements.

Here, we demonstrate a continuously tunable, ultranarrow bandwidth photonic bandpass filter based on FIM-FAM in a few-mode fiber taper. Wideband frequency tunability is experimentally demonstrated by tuning the filter response over 10 GHz (7-19 GHz), limited only by current component constraints, with an out-of-band rejection ratio exceeding 25 dB. The filter bandwidth at the 3-dB point is demonstrated to be approximately 270 kHz at all measured frequencies, which, to the best of our knowledge represents an order of magnitude bandwidth improvement for Brillouin-based continuously tunable photonic bandpass filters.

2. Filter Design and Implementation

The FIM-FAM based bandpass filter system is demonstrated through a technique based on selective phase modulation sideband modification [4] (Fig. 1). The RF data is first modulated onto the optical carrier with a phase modulator, with the generated higher (lower) frequency sideband in-phase (out-of-phase) with the carrier. The modulated carrier is

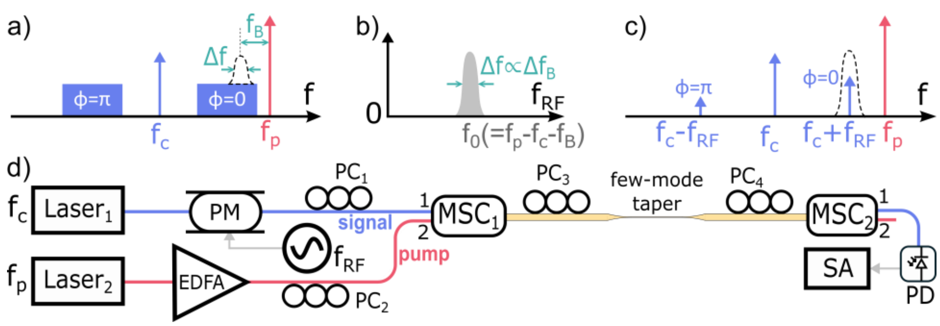

Figure 1: Design of the bandpass filtering system. a) The RF data is modulated onto the optical carrier (f_c), then part of the carrier sideband will be selectively amplified according to the FIM-FAM frequency f_B, by the Brillouin pump (f_p) with a 3-dB amplification bandwidth, Δf. b) The bandpass filtering response determined by the FIM-FAM process (linewidth Δf_B), with a central frequency f_0 and the bandwidth Δf proportional to Δf_B. c) A single-frequency RF signal (f_{RF}) sweeps through the frequency region to demonstrate the filter response. d) The experimental setup of the full filter system. EDFA, erbium-doped fiber amplifier; PM, phase modulator; PC, polarization controller; MSC, mode selective coupler; PD, photodetector; and SA, spectrum analyzer.

then coupled into the fundamental mode of the FIM-FAM active few-mode fiber taper through a mode-selective coupler. A distinct Brillouin pump is coupled with the other port of the same coupler into a single higher-order mode, and spectrally positioned such that the higher frequency carrier sideband coincides with the FIM-FAM Stokes response relative to the pump (Fig. 1a-b). The Brillouin pump then selectively amplifies the part of the sideband within the Lorentzian FIM-FAM linewidth, breaking the amplitude symmetry between the two out-of-phase carrier sidebands. Another mode selective coupler then removes the excess pump from the signal, and the two sidebands individually beat with the carrier with a relative π phase difference on the final detector. Non-perfect destructive interference only occurs for the RF signal corresponding to the FIM-FAM amplified optical sideband, creating a bandpass response with the passband positioned by the FIM-FAM process. To measure the filtering response, a tunable single-frequency RF source is applied to the phase modulator, and the RF power is measured from the detector output at the same frequencies. This frequency is continuously swept over a broadband to represent RF data (Fig. 1c-d).

3. Experimental Results

In prior narrowband FIM-FAM devices based on fiber tapers [9], the transmission of the higher-order optical mode was limited by the non-adiabaticity of the taper transition regions. Here, through an improved fabrication procedure to be described elsewhere, a fiber taper is developed with improved adiabaticity leading to an increase in the available pump power for FIM-FAM. The Brillouin pump in the TM_{01} higher-order mode is first positioned for a filter response centered at 13 GHz, yielding a measured 3-dB bandwidth of 275 kHz (Fig. 2a). The out-of-band rejection is 29 dB over 500 MHz, with small residual sidebands from undesired high-order optical modes that have not yet been fully suppressed. The instantaneous bandwidth can be increased beyond 500 MHz through mitigation of mode cross-coupling leading to residual pump in the detected signal. The central filter frequency is varied over the bandwidth of the currently implemented modulators and detectors, yielding a measured filter response from 7 to 19 GHz, with the 3-dB bandwidth varying negligibly around 273 kHz ($\pm$3 kHz in Fig. 2b), and the out-of-band rejection exceeding 25 dB over 500 MHz in all cases, without additional optimization. From the sub-MHz level demonstrated here, the filter bandwidth can be further reduced through improving the device homogeneity or through enhancing the stimulated interaction with increased pump powers or longer lengths of the FIM-FAM device.

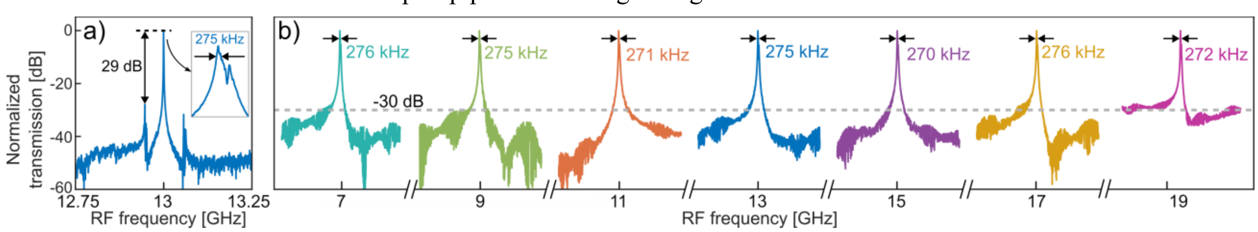

Figure 2: Ultranarrow filter measurements over >10GHz. a) The wideband RF response of the bandpass filter centered at 13 GHz, with a 3-dB bandwidth of 275 kHz and 29 dB out-of-band rejection over 500MHz, limited by undesirable high-order optical modes. b) The RF filtering response with the central frequency of the passband varying from 7 GHz to 19 GHz in 2 GHz intervals, each plotted over an 80MHz range. The 3-dB filter bandwidth is labeled on each plot.

In summary, a FIM-FAM based photonic bandpass filter platform is demonstrated using a few-mode fiber taper. Sub-MHz bandwidth (~270 kHz) is measured over a wide and continuously tunable range (7-19 GHz shown here) with large out-of-band rejection ratios (> 25 dB over 500 MHz in all cases measured). Photonic devices leveraging FIM-FAM are well suited for microwave and signal-processing applications requiring large frequency tailorability, wideband operation, and high spectral resolutions.

4. References

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