A Self-Sustained Phononic Comb MEMS Oscillator with Loop Phase Tuning

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***Summary*—This work investigates a self-sustained phononic comb Micro-Electro-Mechanical Systems (MEMS) oscillator with comb control by using loop phase tuning. The formation of the phononic combs in this work is carried out through a self-oscillation (closed-loop) at the nonlinear state of a piezoelectric flexure mode resonator without any external parametric pumping. We experimentally confirm the tunability of the phononic combs by adjusting the loop phase (θ_T) of the Phase Lock Loop (PLL) in the lock-in amplifier at various oscillation points. The first two eigenmodes of the fully clamped thin-film resonator are adopted to demonstrate the proposed mechanism. Each of the eigenmodes is successfully sustained for oscillation by the use of the lock-in amplifier, thus featuring different phononic comb states. The achievement in this work could be further extended to frequency comb-based sensor technologies.**

Keywords*—*Phononic frequency combs, nonlinear MEMS.

I. Introduction

Frequency combs are a special phenomenon that contains a group of equidistant tones in the spectrum. This particular spectrum behavior was first observed in the field of photonics, which has become the ruler of light frequencies [1]. Mode-locked lasers and micro-optical ring resonators are the two main mechanisms used to generate optical frequency combs. Photonic combs have been utilized in a variety of applications, such as timing references, astronomy, and LiDAR systems [2][3][4]. In addition to the frequency comb in photonics, researchers have also turned their attention to phononic systems, which exhibit similar wave propagation behavior.

The generation of the phononic frequency combs is mostly based on the nonlinear behavior of the Micro-Electro-Mechanical Systems (MEMS) resonator. Several previous works have demonstrated the generation of phononic combs using piezoelectric and capacitive transduction MEMS resonators. [5] firstly demonstrated the generation of phononic combs based on intrinsic three-wave mixing (i.e., 2:1 internal resonance) with a piezoelectric resonator. The internal resonance phenomenon has led to the transfer of energy from the in-plane mode to the out-of-plane mode at a lower resonant frequency. Similarly, [6] demonstrated comb generation based on 1:3 internal resonance with two individual clamped-clamped beam resonators coupled by electrostatic force. [7] demonstrated the formation of phononic frequency combs using non-degenerate parametric pumping with a piezoelectric flexure mode resonator. In addition to the experimental results, analytical analysis of phononic comb generation has also been developed recently. [8] demonstrated a quasi-periodic solution for 1:2 internal resonance with a capacitive backbone resonator.

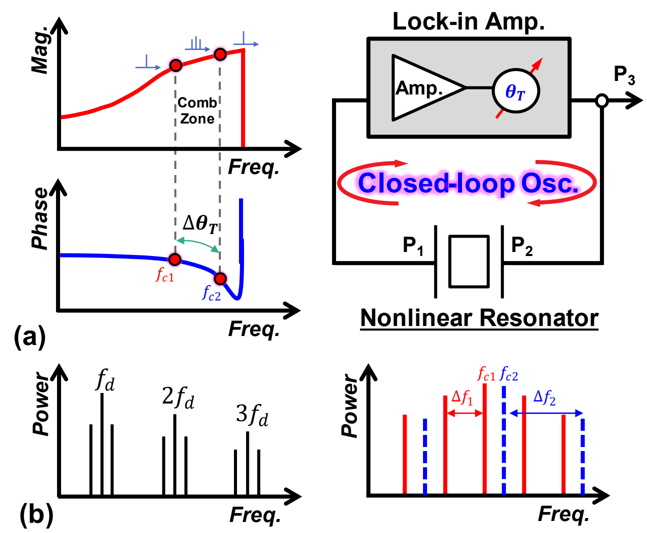

Figure 1: (a) Schematic of the proposed phononic comb oscillator with loop phase tuning. (b) Output frequency spectrum of the phononic comb oscillator. The phononic combs exist not only at the driving frequency (f_d) but also observable at the higher harmonic regimes.

In addition to reporting the physical phenomena, several works have demonstrated the usage of phononic combs in sensor and oscillator applications [9][10]. However, most of the previous works on phononic comb generation operate under open-loop driven conditions. Open-loop driven operation has one main drawback: the comb generation is out of control. That is, it cannot accommodate changes in the surrounding environment. This restricts the utilization of MEMS-based phononic combs in other applications. Therefore, this work demonstrates a phononic comb piezoelectric MEMS oscillator with loop phase tuning for controlling comb generation.

Fig. 1 shows the comprehensive view of the proposed concept in this work. The piezoelectric MEMS device operates as an oscillator system with the help of a lock-in amplifier under its nonlinear states. Later, the control of different comb generation states is realized by adjusting the loop phase in the lock-in amplifier, which enables the control of comb generation. The formation and control of the phononic combs have been demonstrated in the first two eigenmodes with the same operational mechanism in this work. A "comb zone" in the frequency spectrum could be roughly specified based on the measurement results. Besides the spectrum close to the oscillation frequency, a wideband spectrum has also been explored in this work for both cases, respectively.

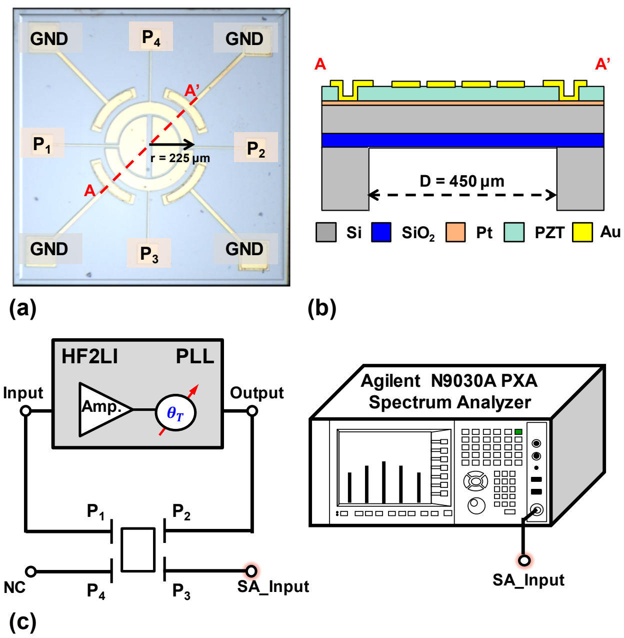

Figure 2: (a)(b) Optical image and the thickness configuration of the piezoelectric flexure mode resonator used in this work. (c) Measurement setup for the phononic comb oscillator.

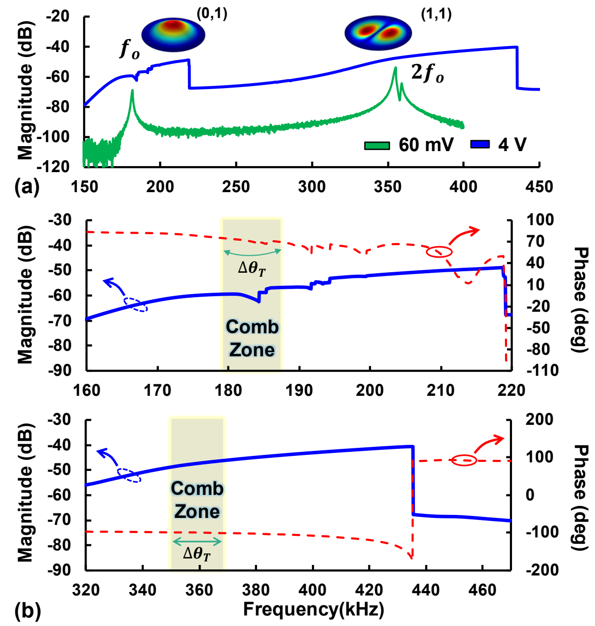

Figure 3: (a) Open-loop measurement result of the linear and nonlinear responses with different driving voltage. (b) Zoom-in of the open-loop measurement responses for two targeted eigenmodes. The comb zone has also been specified in the figure.

II. Methods

The phononic comb generation in this work is based on a piezoelectric flexure mode resonator which is initially used for ultrasonic range finding applications [11]. The device used in this work is designed based on the thin-film piezoelectric-on-substrate (TPoS) fabrication platform to enable the actuation of the flexure mode with a vertically applied electric field. PZT thin film has been chosen as the piezoelectric material in this work for its high electromechanical coupling factor. Four separated top electrodes are designed to serve the purpose of driving and sensing, with an unpatterned bottom electrode for electric potential grounding. Additionally, a multiple port design can eliminate the large static capacitance resulting from the high dielectric constant of thin-film PZT, which leads to better signal to feedthrough ratio.

Fig. 2(a) shows the optical image of the device used in this work. The resonator is designed with a fully clamped boundary condition and a radius of 225 µm. The resonator is fabricated using a thin-film piezoelectric-on-substrate (TPoS) platform, as shown in Fig. 2(b). The thickness configuration consists of a 1-µm PZT thin film sandwiched between the top gold electrode and the bottom titanium electrode. Fig. 2(c) shows the measurement setup of the phononic frequency comb oscillator. The main oscillation loop is performed by two center electrodes (i.e., P_1 and P_2) with a lock-in amplifier (Zurich HF2LI) to sustain the oscillation and loop phase tuning. Later, the side electrode (i.e., P_3) is connected to the spectrum analyzer (Agilent N9030A) for observing the output spectrum.

The characterization of the phononic frequency comb oscillator can be separated into two parts. First, a two-port (i.e., P1 and P2) open-loop measurement is performed to specify the linear and non-linear responses of the device. Later, a closed-loop measurement is carried out using the lock-in amplifier.

III. Results and Discussion

Fig. 3(a) shows the linear and nonlinear responses of the device with driving voltages of 60 mV and 4V, respectively. Both the first and second eigenmodes show a significant Duffing effect in the nonlinear states. Fig. 3(b) shows a zoom-in of the nonlinear responses for both modes. The "comb zone" indicates the frequency range where the phononic comb occurs in the output spectrum.

Fig. 4 shows the output spectra as the device oscillates at its first eigenmode (i.e., (1,0) mode) under different conditions. The result indicates that by increasing the phase shift, different states of frequency combs can be observed. From Fig. 4(a) to Fig. 4(b), the interval between the combs decreases from 9.5 kHz to 7.52 kHz. The triangular-envelope spectrum from Fig. 4(c) reveals that the oscillator system is operated under more chaotic conditions [7]. Later, Fig. 4(d) shows a similar response to Fig. 4(a), indicating that the oscillator is leaving the comb zone. Fig. 4(e) further presents the wideband response when $\Delta\theta_T = 2°$, with the frequency combs not only existing at the driving frequency but also in higher harmonic regimes. From the wideband spectrum, it can also be observed that the energy transfers from the first eigenmode to the second eigenmode (i.e., (1,1) mode). The eigenfrequency of the (1,1) mode is almost twice that of the (1,0) mode, indicating that the trigger mechanism of phononic comb generation is based on 1:2 internal resonance.

Fig. 5 shows the output spectra as the device oscillates at its second eigenmode (i.e., (1,1) mode). The response is similar to that of the first mode operation. The number of combs increases/decreases as the oscillation frequency enters/leaves the comb zone. The spacing between each comb varies from 34 kHz to 17 kHz, proving the tunability of the proposed

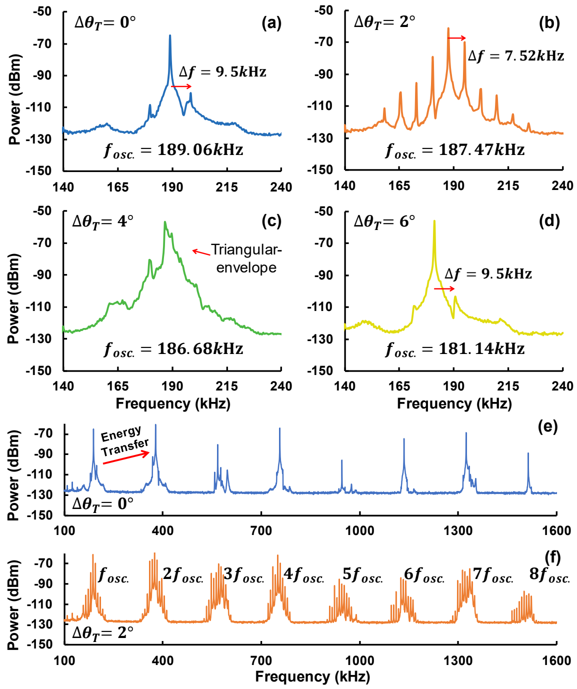

Figure 4: (a), (b), (c), and (d) show the frequency spectra of the first eigenmode with oscillation at different $\Delta\theta\theta_{TT}$. (e) and (f) show the wideband spectrum with energy transfer and the phononic comb also been generated in higher harmonics.

mechanism. The internal resonance phenomenon has also been observed in the measured wideband spectrum, where the energy transfers to other eigenmodes, as shown in Fig. 5 (g) and (h).

Previous work from our group has demonstrated the internal resonance phenomenon using the same design [12]. However, the phononic comb has not been observed due to the driving voltage not reaching the threshold for phononic comb generation. In this work, the driving voltage is increased to surpass the threshold and is controlled by adjusting the phase loop. We believe that through the theoretical analysis of phononic comb generation with this device, other tuning mechanisms could be introduced into this system to further control the formation of the phononic comb [13][14].

IV. Conclusions

This work experimentally reports a self-sustained phononic comb oscillator system with loop phase tuning based on a 4-port piezoelectric MEMS resonator. The results show that different states of comb conditions have been successfully manipulated by shifting the loop phase of the lock-in amplifier. Meanwhile, the comb zone has also been verified. The proposed concept is successfully demonstrated with the first two eigenmodes of the drum-head resonator. This work brings a new concept for the phononic comb generation and control in the piezoelectric oscillator system which could extend the technique to sensor and oscillator technologies.

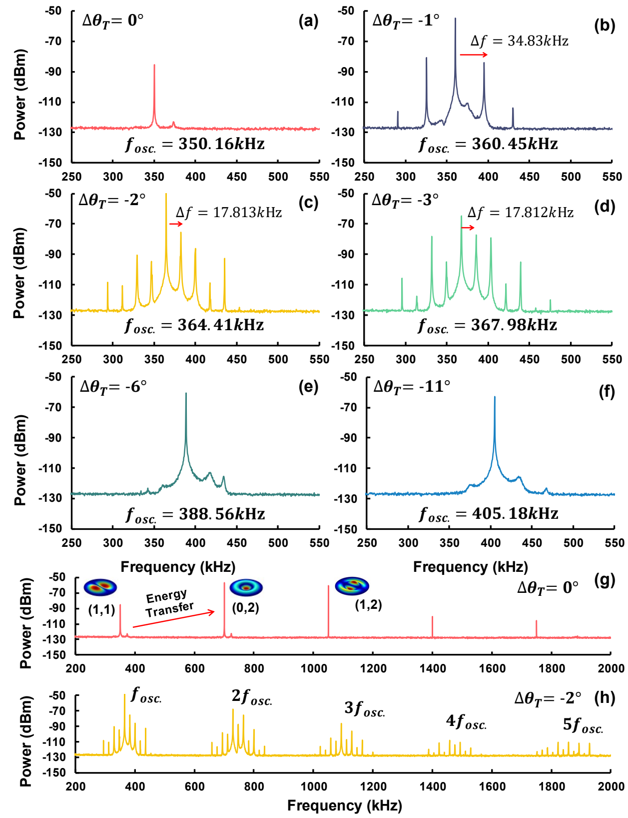

Figure 5: (a), (b), (c), (d), (e), and (f) show the frequency spectra of second eigenmode with oscillation at different $\Delta\theta\theta_{TT}$. (g) and (h) show the wideband spectrum with energy transfer and the phononic comb also been generated in higher harmonics.

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