SELF-SUSTAINED DUAL-MODE MECHANICAL FREQUENCY COMB SENSORS

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INTRODUCTION

Resonant frequency-shift detection has proven to be a highly-accurate method to detect perturbations in the environment with Q-fold passive signal amplification. The challenges associated with such scheme, are (1) sustaining oscillation by utilizing an energy restoring element that compensates for the losses in the mechanical resonator with minimal contribution to the overall noise, and (2) decoupling the frequency shift due to undesired environmental drifts from the frequency shift due to the sensed stimulus.

This work reports on a novel sensing scheme which addresses the two aforementioned challenges by utilizing integrated, self-sustained, high-Q, resonant-based frequency comb sensors that track the frequency spacing between the spectral lines as the "beat frequency" in order to increase the sensor sensitivity and cancel out the environmental drift effects on the sensor responsivity.

SENSING MECHANISM

Micromechanical resonators, in the most general definition, are passive components, which have to be integrated with an energy restoring element, *e.g.* electronic amplifiers, to sustain oscillation in a feedback-loop system. MEMS-circuits interface is particularly challenging as the size of the sensor shrinks. Scaling of the resonator is desirable to increase the sensor sensitivity to absorbed mass, justifying the constant efforts observed in shrinking of the size of the M/NEMS sensors. However this in turn yields larger motional impedances, rendering interface with electronic devices challenging. To address this challenge, instead of using electronic amplifiers as the energy restoring element, we utilize a single-tone pump with a frequency equal to the sum of the frequencies of two acoustic modes within the same resonator. This technique offers several advantages over the traditional MEMS-CMOS oscillator counterparts: (1) It obviates the need for electronic circuitry that suffer from shot noise [1], the associated challenges with MEMS-CMOS integration and thus improves the overall noise performance and (2) it offers a smaller footprint that takes advantage of piezoelectric-induced mode coupling between two (or more) resonance modes within the same acoustic cavity and a single-tone pump.

The latter challenge arises from the interfering effects of environmental changes on frequency detection. Various methods have been sought so far including utilizing multiple resonators with different sensitivities, or more efficiently, a dual-mode oscillator using two different resonance modes of the same oscillator, which yields two equations with two unknowns allowing for separation of the different effects [2]. Moreover, multi-mode frequency shift monitoring has been proposed for more accurate readout, as well as for inertial mass spectroscopy [3].

Implementation of dual-mode oscillators is challenging, due to complicated electronics to design two different loops to excite two resonance modes simultaneously. This work reports on a novel sensing technique based on efficient simultaneous excitation of two resonance modes using a single-tone pump. We recently experimentally demonstrated the generation and tuning of phononic frequency combs in a fully-integrated standalone piezoelectric platform [4]. In this work, we report on feasibility of application of such frequency combs for high-precision sensing that tracks the "frequency spacing" between the phase-coherent spectral lines; as the analogue of "beat frequency" in dual-mode oscillators, to increase the frequency shift sensitivity within the same resonant device. The pump frequency which is detuned from (f_{m1} +f_{m2}), where f_{m1} and f_{m2} are the two mechanical modes, induces an idler and signal mode at frequencies close to f_{m1} and f_{m2}.
Frequency mixing between the idler (signal) mode and f_{m1} (f_{m2}) creates Δf_1 (Δf_2) that are proportional to the detuning of the pump from f_{m1}+f_{m2} [5]. Such scheme can significantly reduce the electronics required for multipliers and mixers used in dual-mode oscillators to track "beat frequency".
It must be noted that any two mechanical modes can be chosen to generate the frequency comb based on non-degenerate parametric pumping. The threshold power for comb generation can be reduced by designing high Q-resonant modes with high coupling rates. Furthermore, by utilizing two modes with different sensitivities, one can decrease the beat frequency through their linear combination. Figure 1 shows the proposed sensing scheme, the two modes undergo different frequency shifts as the stiffness of the membrane is modulated by DC voltage (from -0.1 V to 0.1V with 0.1 V steps). The shift in the mechanical modes cause a shift in the detuned frequency and thus a change in the frequency spacing.

Another advantage of the proposed technique is the phase-coherence of the spectral lines. It has been shown that the generated side-bands have a defined phase relationship with respect to the pump phase [6]. In practical NEMS resonators, in often cases, the frequency shift detection is in fact not limited by the resonator Q, but instead bound to some anomalous temperature-dependent frequency/phase fluctuations [7]. Oscillator circuits traditionally have phase freedom, while their amplitude are limited by a limiting amplifier or a nonlinearities in the system. Using a phase coherent detection mechanism along with two-mode compensation techniques would yield higher phase stability as compared to traditional amplitude-saturated oscillator circuits.

EXPERIMENTAL RESULTS

Figure 2 shows the SEM image of the fabricated AlN-on-Si circular membrane, denoting the measurement setup for frequency comb generation. *Figure 3 (a,b)* show the driven resonance modes of the two acoustic resonance modes at different input power levels, demonstrating the duffing nonlinearity. The governing harmonic oscillator equations that include the two coupled modes are:

$$\ddot{x}_1 + {\omega_1}^2 x_1 + (^2/_{Q_1})\dot{x}_1 + (\gamma_{12}/m_1)x_1{x_2}^2 + (\alpha_1/m_1){x_1}^3 = (F/m_1)x_2 \mathrm{Cos}\,\omega_p t$$

$$\ddot{x}_2 + {\omega_2}^2 x_2 + (^2/_{Q_2})\dot{x}_1 + (\gamma_{21}/m_2)x_2{x_1}^2 + (\alpha_2/m_2){x_2}^3 = (F/m_2)x_1 \mathrm{Cos}\,\omega_p t$$

where $x_{1,2}$ are the mode displacements, $Q_{1,2}$ are the Q factors, $m_{1,2}$ are the effective masses, $\alpha_{1,2}$ are the duffing nonlinearity coefficients for mode 1 and 2 respectively, and γ_{12} denotes the dispersive coupling between mode 1 and 2. ω_p is the pump frequency and F is the amplitude of the pump.

Figure 4 shows the mechanical frequency comb spectrum, showing a shift in the $f_{spacing}$ when DC voltage shifts the two mechanical modes with different coefficients.

CONCLUSION

This work reports the first demonstration of fully-integrated self-sustained micromechanical frequency combs as highly-sensitive dual-mode sensors that can be optimized to cancel out environmental drifts with enhanced beat frequency, while taking advantage of simplified design and unprecedented footprint of only 30 μm×30 μm.

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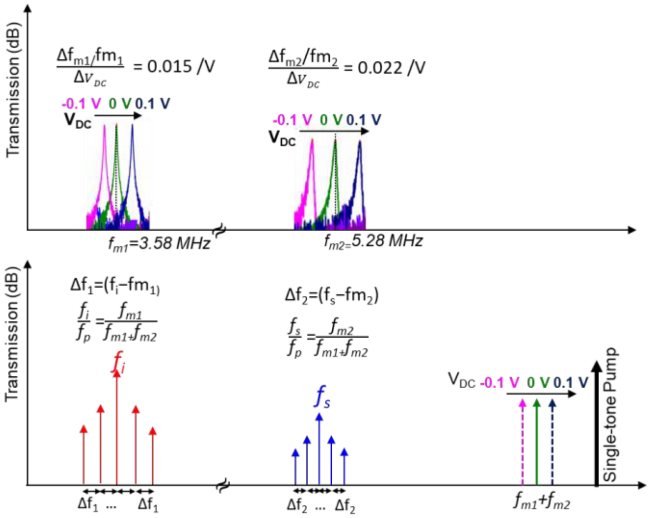


Figure 1: (Top) Resonant frequency shift of the driven modes. The resonant frequency shifts due to a change in the effective mass or stiffness. The DC voltage changes the stiffness of the membrane with different sensitivities at mode 1 and 2. The DC voltage is varied from -0.1 V to 0.1 V in 0.1 V steps and sensitivities of 0.015/V and 0.022 /V are observed for the two resonance modes. (Bottom) Pumping at the blue-side band above a certain threshold (20dBm in this work at 8.78 MHz) causes generation of frequency combs close to the two mechanical modes. As the DC voltage changes the stress, the detuning frequency between the pump and the sum of the two mechanical modes change, thus shifting the frequency spacing between the spectral lines.

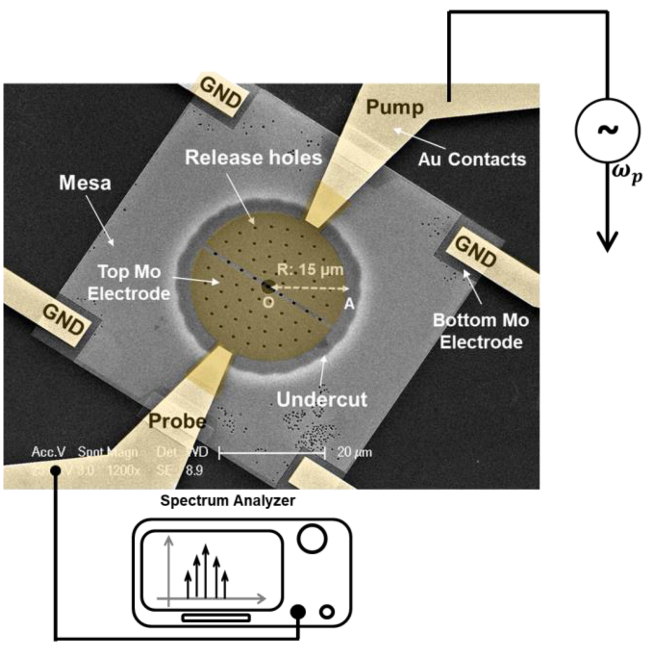
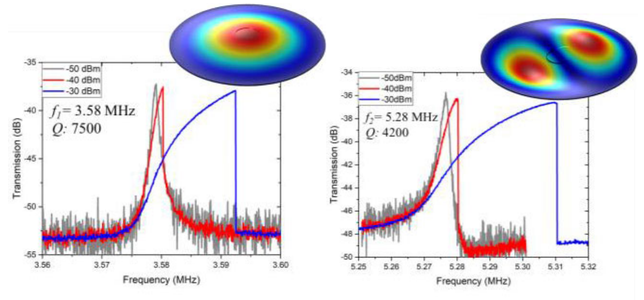


Figure 2. Scanning Electron Micrograph of fabricated AlN-on-Si piezoelectric frequency comb. The radius is 15 µm, and the pump and probe measurement setup are demonstrated.



(a) (b)

Figure 3: Driven resonance (a) mode 1 and (b) mode 2, along with the displacement mode shape at three different input power levels.

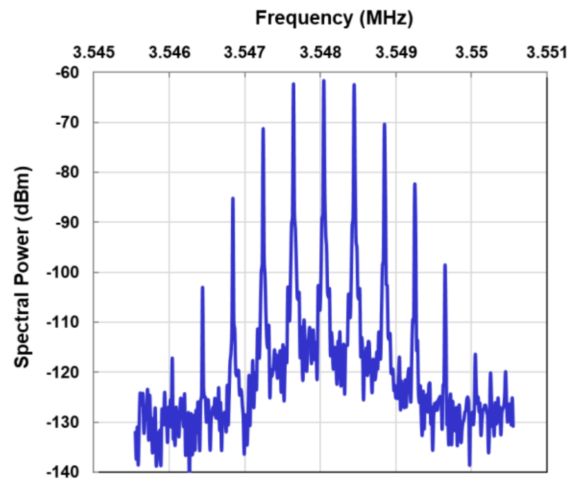


Figure 4: Mechanical resonant-based frequency comb generation, centered at the idler frequency with spacing determined by the detuning of the pump from the sum of mechanical modes.

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