Phononic Frequency Combs For Engineering MEMS/NEMS Devices With Tunable Sensitivity

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***Abstract*—Over the past two decades, MEMS resonators have received considerable attention for physical, chemical and biological sensing applications. Typically, the operation of MEMS resonant sensors relies on the tracking of a resonance frequency using a feedback oscillator. The sensitivity of these sensors is limited by physical parametric variations, as in the Young's modulus, and noise in the oscillator circuit, such that improvement in the sensitivity can require significant effort in the design, fabrication, ovenization, and control of the resonator. In this paper, we experimentally demonstrate an alternative sensing approach based on a newly documented physical phenomenon, 'phononic frequency combs', where the sensitivity can be actively tuned by the drive conditions. In addition, the spectral response of frequency combs enables an 'N+1' fold enhancement in the sensitivity, with '2N+1' being the number of spectral lines associated with a frequency comb.**

Keywords—MEMS resonator; mechanical resonator; sensor; temperature sensor; nonlinear dynamics; phononic frequency comb.

I. Introduction

MEMS resonators have been actively explored for sensing applications by many research groups around the world [1-8]. Resonant sensing is traditionally made possible by tracking the resonance frequency of one of the modes of the MEMS structure with the help of an electronic feedback circuit. Parametric variations due to temperature fluctuations and noise in the oscillator circuit can limit the performance of these sensors. Solutions for mitigating these limits, including the use of material combinations that minimize parametric variations, ovenization, and improved circuit and control design are possible but require significant research effort to optimize their performance. In this paper, we present an alternative sensing approach that fundamentally relies on the nonlinear dynamics of MEMS resonators leading to the generation of phononic frequency combs. Phononic frequency combs correspond to a series of equidistant and phase-coherent frequencies [9-18]. These frequency combs can be generated when a resonant

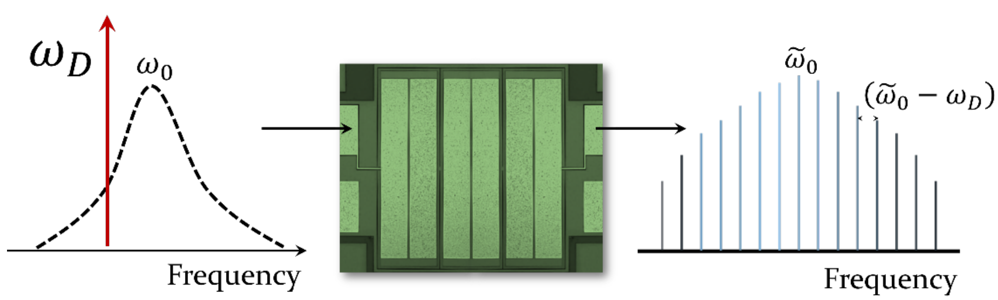

Figure 1: A strong off-resonance drive of the mechanical mode leads to an array of equidistant frequencies, referred to as a 'phononic frequency comb'. The equidistant frequency spacing of the frequency comb is set by the difference between drive frequency (ω_D) and the renormalized resonant frequency ($\widetilde{\omega}_0$) of the MEMS resonator.

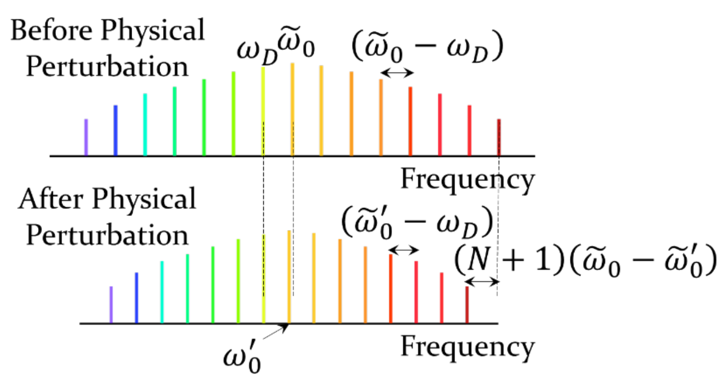

Figure 2: The shift of the frequency comb line $[\widetilde{\omega}_0 + N(\widetilde{\omega}_0 - \omega_D)]$ is 'N+1' times more sensitive than the fundamental comb line $[\widetilde{\omega}_0]$.

mode of a MEMS resonator is strongly driven off-resonance (Figure 1). The frequency spacing of such combs is governed by the difference between the drive frequency (ω_D) and the renormalized resonance frequency ($\tilde{\omega}_0$) of the MEMS resonator (Figure 1). Unlike the resonance frequency of MEMS resonators (ω_0), the renormalized resonance frequency can heavily depend on the drive conditions. We want to leverage this dependence for sensing applications. Also, since the shift of the renormalized resonance frequency is cumulatively accrued in the highest order frequency comb lines, an 'N+1' fold enhancement in the sensitivity can be obtained: $[\tilde{\omega}_0 + \mathrm{N}(\tilde{\omega}_0 - \omega_D)] - [\tilde{\omega}'_0 + \mathrm{N}(\tilde{\omega}'_0 - \omega_D)] = \left[\underbrace{(\mathrm{N}+1)} * (\tilde{\omega}_0 - \tilde{\omega}'_0)\right]$, as pictorially demonstrated in Figure 2.

II. Experimental Setup

For the demonstration of the phononic frequency comb-based sensing approach, a MEMS system containing three coupled free-free beam structures of dimensions $1100\ \mu m \times 350\ \mu m \times 11\ \mu m$ is considered (Figure 1). The mechanical coupler connecting the three beams has the dimensions $20\ \mu m \times 2\ \mu m \times 11\ \mu m$. The device consists of three material layers: $10\ \mu m$ thick Si, $0.5\ \mu m$ thick AlN and $1\ \mu m$ thick Al. The Al pad electrodes that are connected to Al patterns on the MEMS device allow for electrical interfacing, and the AlN film provides piezoelectric actuation in response to the electrical signal inputs. The synthesized electrical signal from an arbitrary waveform generator with the frequency set close to the resonance frequency is applied and the resulting response of the device is characterized using a spectrum analyzer. Additionally, a vector network analyzer is used to characterize the linear response of MEMS resonator. All frequency measurements have an uncertainty of +/- 8 Hz. The entire set of measurements presented here was conducted in a temperature-controlled oven.

III. Temperature Sensitivity of the Linear Dynamics for the MEMS Resonator

The open-loop response of the MEMS resonator is obtained at 0 dBm (Figure 3A). The peak frequency of ≈ 3.853 MHz is tracked using a manual peak detection algorithm at varying oven temperature and the scatter in the data is due to measurement repeatability and fit errors (Figure 3B). The temperature range of 70 ℃ to 90 ℃ was chosen arbitrarily. The temperature coefficient of frequency (TCF) for this specific device under test is calculated to be ≈ -4.67 Hz/MHz/℃ (ppm/℃).

IV. Temperature Sensitivity of Phononic Frequency Combs

For the excitation of phononic frequency combs, a single tone is fed into the MEMS resonator. The device is set at a temperature of 70 ℃ and the drive conditions corresponding to the existence of phononic combs is charted out in Figure 4. A representative spectral response of the phononic frequency comb is presented in Figure 5, with frequencies at $\tilde{\omega}_0 + \mathrm{N}(\tilde{\omega}_0 - \omega_D)$.

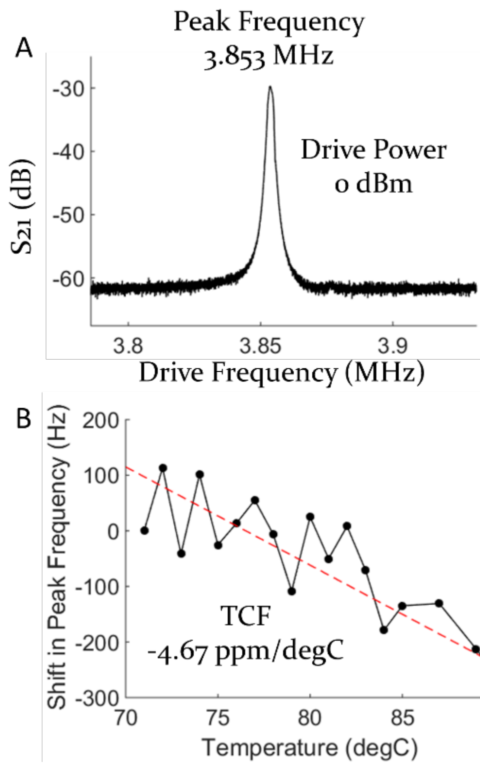

Figure 3: A: Linear response of the MEMS resonator, as recorded using the network analyzer; B: The shift in the peak frequency as the temperature is varied from 70 ℃ to 90 ℃. A linear fit to the experimental data is used to calculate the temperature coefficient of frequency (TCF).

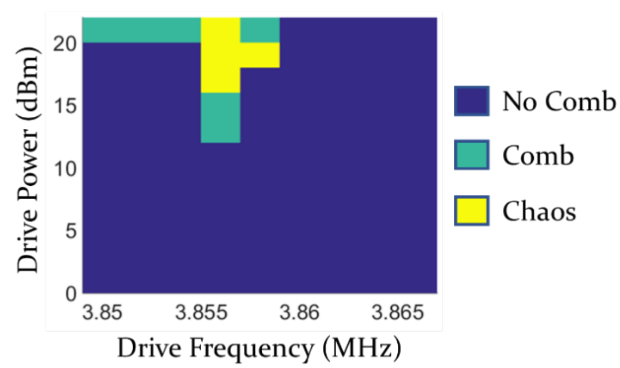

Figure 4: The drive parameter map indicating the existence of phononic frequency combs - 'green' colored region.

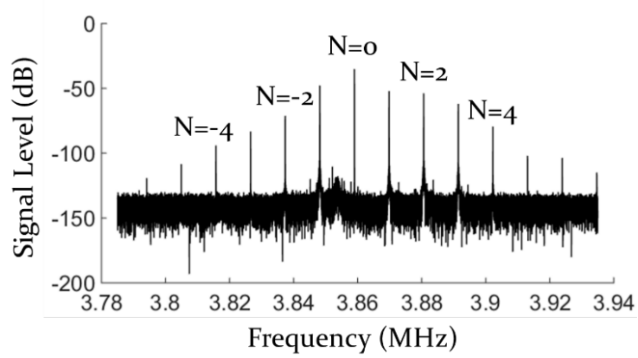

Figure 5: The spectrum of phononic frequency combs at the drive frequency 3.859 MHz and drive power 22 dBm.

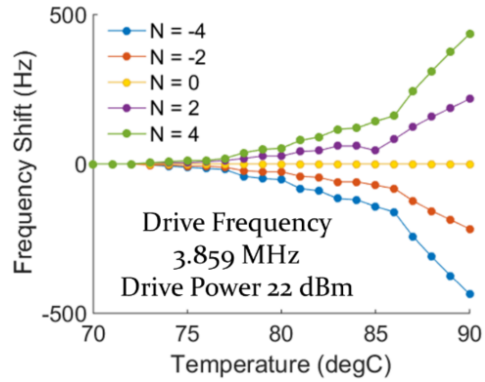

Figure 6: Temperature dependence of different lines, $\mathrm{N} = 0, \pm 2, \pm 4$, of the phononic frequency comb: $[\widetilde{\omega}_0 + \mathrm{N}(\widetilde{\omega}_0 - \omega_D)]$.

Figure 6 shows the temperature dependence of different comb lines of the phononic frequency comb. The higher order comb lines of $\mathrm{N} = \pm 4$ demonstrate greater shifts in frequency than those associated with the nearer lines $\mathrm{N} = \pm 2$. While the frequency comb in this experiment contains a sparser number of comb lines (Figure 5), it is desirable to engineer a broadband comb spectrum to achieve greater sensitivity by tracking the highest order line in the comb using narrowband electrical filtering. From Figure 6, we can see that there is a greater temperature gradient in the range of 85 ℃ to 90 ℃. Hence, for greater temperature sensitivity, it is desirable to operate the device in this band of temperatures, which can be practically implemented using *in situ* microheaters.

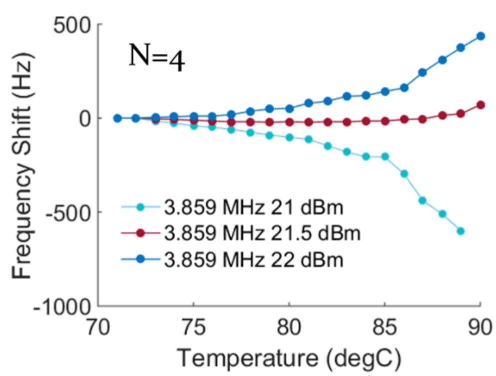

Figure 7: Temperature dependence of the 4th line of the phononic frequency comb $[\widetilde{\omega}_0 + \mathrm{N}(\widetilde{\omega}_0 - \omega_D)]$ at varying drive conditions.

While it is desirable to track the higher order comb line to achieve greater sensitivity (Figure 6), Figure 7 shows that even a slight increase in the drive power from 21 dBm to 22 dBm can reverse the nature of the temperature dependence, with the drive power of 21.5 dBm leading to temperature-insensitive frequency comb lines. Hence, without the need for sophisticated materials, fabrication, and ovenization, the temperature sensitivity can be actively tuned by the drive conditions. In comparison to Figure 3B, the frequency shift over the temperature range of 70 ℃ to 90 ℃ has increased by a factor of 5/3, which in turn can be improved by rigorous computational and experimental studies of the dynamics of phononic frequency combs.

V. SUMMARY

This paper demonstrates that the temperature sensitivity of MEMS resonators can be tuned using a newly documented physical mechanism: phononic frequency combs. The highest order line in the frequency combs offers 'N+1' fold enhancement in the sensitivity, with '$2\mathrm{N}+1$' being the number of comb lines. The sensitivity of these comb lines can be further tuned by the drive power and drive frequency. While we chose temperature as the physical variable to prove the concept of frequency comb-based sensing, the technique can be readily used for other sensing applications including particle detection. The concept of frequency comb-sensing is also relevant to other established frequency comb sources including microresonator-based frequency combs [19-22]. By integrating such multiwavelength optical sources with phononic frequency combs through dynamic optomechanical interactions, the number of comb lines $(2\mathrm{N}+1)$ can be drastically enhanced to achieve a greater magnitude of '$\mathrm{N}+1$' fold enhancement in the sensitivity.

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