A PARAMETRIC FREQUENCY COMB GENERATOR IMPROVING BY 10X THE LIMIT-OF-DETECTION OF 120 MHZ ALSCN-BASED IR DETECTORS

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ABSTRACT

This article addresses the imperative of reducing the limit-of-detection (LoD) in sensing systems, focusing on micro- and nanoelectromechanical (MEM/NEM) resonant technologies. Typically, advancements on MEM/NEM offer high sensitivity and electromechanical performance, which is crucial for achieving quantum-limited LoD. However, when these devices are integrated in closed-loop oscillator, frequency fluctuations are introduced due to electrical noise, degrading the LoD. This work proposes a novel sensing system for Aluminum Scandium Nitride (AlScN) microacoustic resonant infrared (IR) detectors that addresses these challenges. Moreover, it enables self-sustained oscillation states without active components, while consuming minimal power (~10 mW) and limiting RF power dissipation (< 1 µW), thus shaping a new paradigm in sensing technology.

KEYWORDS

Parametric Frequency Comb Generation, IR detection, limit-of-detection, AlScN, Nonlinear Dynamics.

INTRODUCTION

Reducing the limit-of-detection (LoD) of sensing systems has been a key priority for a variety of applications. Progress in micro- and nanoelectromechanical (MEM/NEM) resonant technologies has provided key opportunities to improve the achievable LoD by offering high sensitivities and electromechanical performance [i.e., high quality factors (Q > 1000) and electromechanical coupling coefficients (k_t^2 > 0.1%)] even when MEM/NEM devices are formed by materials with nm-scale thicknesses. As a result, the most advanced MEM/NEM devices exhibit exceptionally low thermomechanical noise-driven frequency fluctuations, creating a pathway for a quantum-limited LoD when used as sensors.

Typically, resonant MEM/NEM devices are integrated in closed-loop oscillators to serve as reference frequency for read-out. However, the frequency fluctuations (Δf_n) due to electrical noise originated from the oscillators' active components dominates the MEM/NEM devices' thermomechanical noise. This tremendously degrades the achievable LoD. Yet, to date, there is no existing sensing scheme allowing to read-out the frequency of a resonant sensor placed into a self-sustained motion without using active components in a closed-loop.

In addition, the miniaturization of the most sensitive MEM/NEM devices pushes the power required to sustain their oscillation into the Watts range, shrinking significantly their field of use, introducing LoD-degradations due to the limited power handling that compact MEM/NEM devices naturally exhibit and increasing the thermomechanical noise limit.

In this Article, we address these challenges and present a new sensing system for Aluminum Scandium Nitride (AlScN) microacoustic resonant infrared (IR [1]) detectors that shapes a completely new paradigm. This system, namely a "Parametric Frequency Comb Generator (PFCG [2])" allows to generate self-sustained oscillation states set by the resonance frequency of a 120 MHz AlScN IR detector without requiring active components, while consuming ~10 mW and while limiting the RF power dissipated by the AlScN device to less than 1 µW.

PARAMETRIC FREQUENCY COMB GENERATOR

Our PFCG consists of an RF parametric oscillator (PO) coupled with the AlScN device. Unlike in conventional POs, where increasing the power of the input pump signal beyond a certain threshold (P_{th}) triggers a subharmonic oscillation phase-locked to the pump signal, when the PFCG is driven beyond threshold it enters a pre-synchronization regime. In this regime, the PFCG generates a frequency comb centered around half of the pump signal's frequency (f_{in}), with a line spacing set by the difference between the resonance frequency of the AlScN device and $f_{in}/2$.

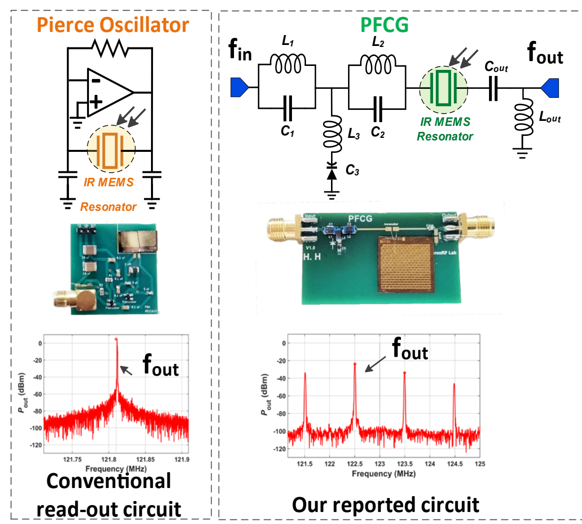

Figure 1: Schematic representation and board-picture of the Pierce oscillator and PFCG built in this work. The typical output spectrum for both circuits is also shown, demonstrating the CW/frequency-comb output for the Pierce Oscillator/PFCG circuit.

ALUMINUM SCANDIUM NITRIDE IR DETECTOR

The infrared (IR) detector utilizes piezoelectric ScAlN Contour-Mode Resonators (CMRs) integrated with plasmonic metamaterials, as illustrated in Figure 2.a. This system specifically employs metal-insulator-metal (MIM) plasmonic absorbers, which are favored for their lithographic tunability, and superior absorptive capacity compared to other IR absorbers [3]. The operational principle relies on the dynamic interaction between absorbed IR radiation and the piezoelectric resonator. When IR light impinges upon the surface of the MIM absorbers, it gets absorbers and efficiently converted into thermal energy, the consequent temperature increase induces a shift in the resonator's center frequency hence the output frequency of the oscillator.

The fabrication process of the devices includes eight main steps, as depicted in Figure 2.b. Initially, the bottom electrode is patterned with a 100 nm thick layer of platinum. Subsequently, a 350 nm layer of 30% doped ScAlN is deposited on top. The next step involves the evaporation and patterning of 100 nm of gold to form the top electrode. Following this step, 250 nm of aluminum nitride (AlN) is deposited to create the dielectric layer of the absorbers, and the vias are created through a process of wet etching. The subsequent step includes the patterning and etching of release pits, followed by, the patterning of 85 nm of gold using electron beam (e-beam) lithography to precisely define the absorption wavelength of the MIM absorbers. The process concludes with the release stage, which creates a suspended structure, a crucial step to reduce mechanical damping and maximize the quality factor of the resonators.

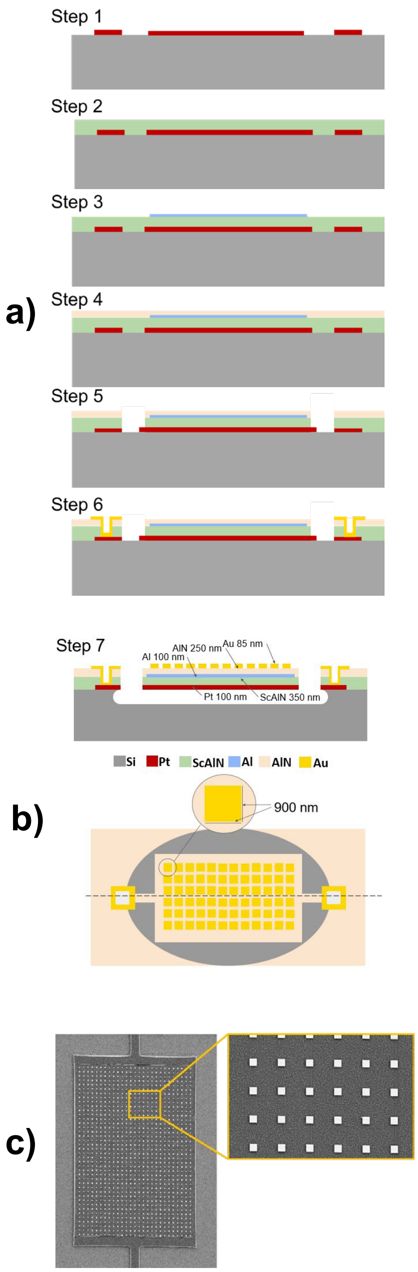

Figure 2: (a) Microfabrication process: 1) Sputtering and lift-off of Pt electrodes; 2) Sputtering of AlScN; 3) Patterning and sputtering of Al plate; 4) Sputtering of AlN; 5) AlN-dry etch to form the release pits; 6) Etching of the vias followed by gold deposition for pads; (b) Schematic of the cross-section of the released resonator; (c) Top view Scanned Electron Microscope image of the fabricated AlScN IR detector.

Following the fabrication, the devices were tested using a vector network analyzer (VNA) to assess their electromechanical performance. A remarkably high *Q* (Q_m ~ 1800) and the electromechanical coupling (k_t^2 ~ 2.66%) were extracted, illustrated in Figure 3. The temperature coefficient of frequency (TCF) was also determined by conducting repeated admittance measurements across a range of temperatures using a heated stage, resulting in an estimated value of approximately -40 ppm/C.

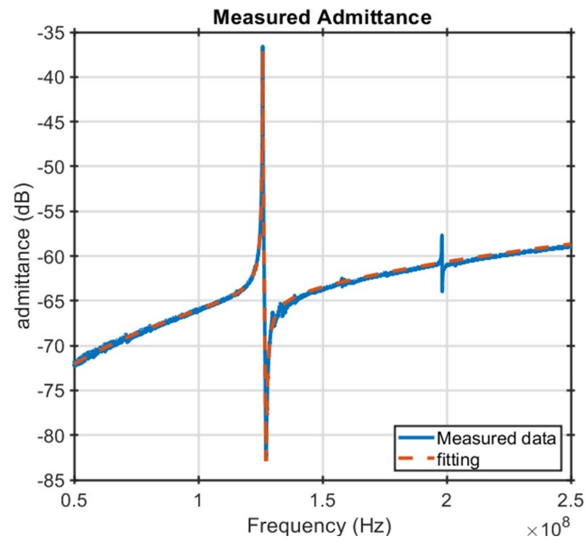

Figure 3: Admittance response of the measured resonant IR sensor and the corresponding mBVD fitting.

Additionally, a Fourier-transform infrared spectroscopy (FTIR) measurement was performed to evaluate the IR absorption efficiency of the devices. The results depicted in Figure 4, reveal that the devices demonstrate a high IR spectral absorption efficiency, achieving an absorption peak (η_peak) of approximately 63% near the targeted wavelength of the laser source, used in the final experiment.

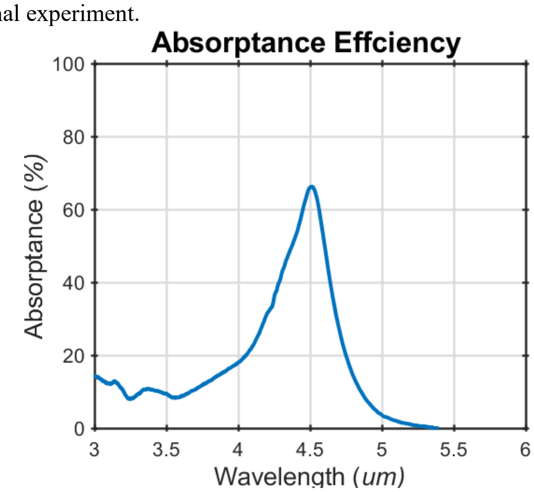

Figure 4: FTIR measurement of the fabricated device

EXPERIMENTAL RESULTS

To compare the performance of PFCGs with those of conventional read-out schemes, we assembled two read-out circuits on two separate printed-circuit-boards (Figure.1) by using two copies of the same AlScN IR detector (Figure.2). One circuit consists of a Pierce-oscillator using a bipolar junction transistor, while the other one consists of a PFCG using an off-the-shelf varactor as a nonlinear reactance. The PFCG's phase-noise at 100 Hz/1 kHz/10 kHz offsets from the strongest comb line's frequency (f_{out}) was measured (Figure.5) for varying pump power levels, proving the existence of a region of operation (including "Point A" and "Point B") with highly improved long-term stability with respect to the Pierce-oscillator (Figure.6).

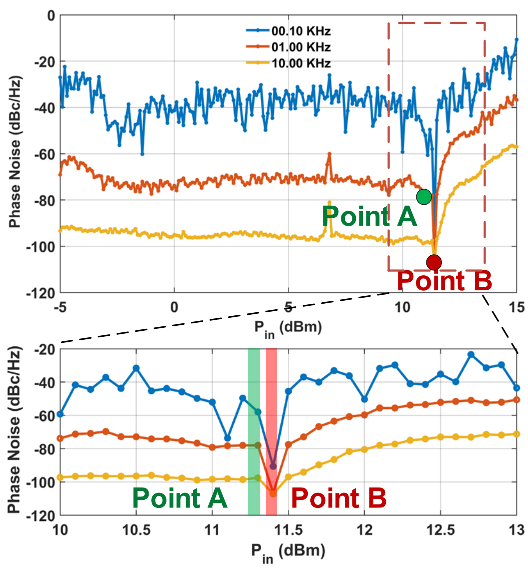

Figure 5: PFCG's measured phase noise levels at three different frequency offset (0.1, 1 and 10 kHz) when sweeping the PFCG's input power at 246 MHz. We identify two operating points ("A" and "B"). Point "B" shows the best phase-noise, at the price of being more sensitive to random amplitude variations in the input power levels. Point "A" leads to worst performance than Point "B" but shows full immunity to stochastic fluctuations in the pump power drive.

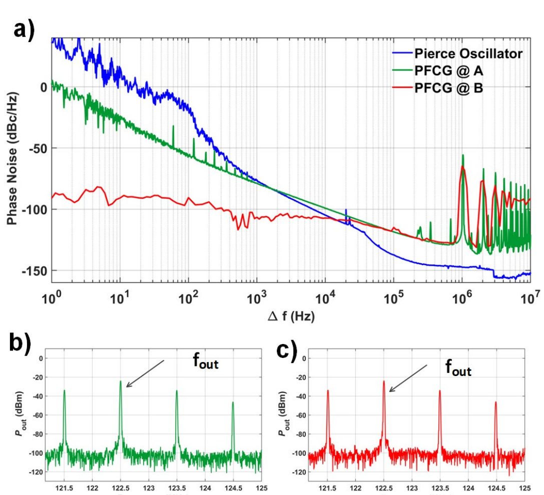

Figure 6: Measured phase noise for the Pierce oscillator (in blue) and for the PFCG when operating at point A/point B (in green/red). The PFCG's input power power is 14 mW while the output power of the strongest tone is 10 μW. The DC power consumption of the loop oscillator is 100 mW while the output power is 0.4 mW.

We characterized the sensitivity of both assembled circuits to IR by using an ON/OFF modulation of a 4.53 μm laser source (Figure.7). During this study we configured the PFCG to operate at Point A. From these measurements, we extracted an average sensitivity to IR [$S=\Delta f/f_{out}$, being Δf the IR-induced frequency shift of f_{out} for both circuits (Figure.8)]. From the extracted S-values and phase-noise performance of both circuits, we computed the LoD as $S/\sigma_v(\tau)$, where σ_v is the Allan deviation (i.e. $\Delta f_n/f_{out}$) at different integration times (τ) attained from Figure.9. Excitingly, our PFCG shows an up-to-10x improvement in the best achievable LoD with respect to the Pierce-oscillator and a minimum Noise Equivalent Power of 36 pW/$\sqrt{Hz}$ at 0.1 msec, while consuming (~15 mW) nearly one-fold less power and while limiting the RF power absorbed by the resonator to less than 360 nW. Even higher performance are expected from the PFCG when it operates at Point B, which we plan to experimentally demonstrate by the start of the workshop.

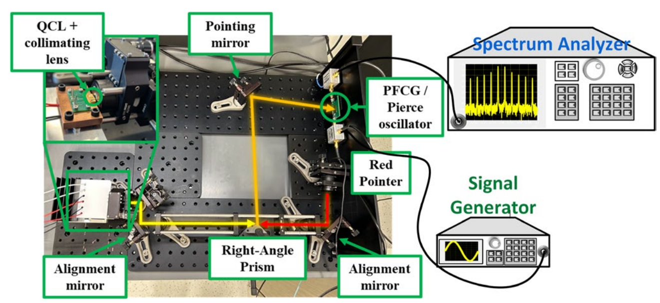

Figure 7: Experimental setup used to detect IR-induced frequency shifts for both PFCG and Pierce oscillator. A collimated QCL and a red pointer are first aligned along the same optical axis, then combined through a right-angle reflective prism, and finally pointed together towards the IR AlScN detector. We measure the IR-induced frequency shift by connecting the read-out circuit to a spectrum analyzer.

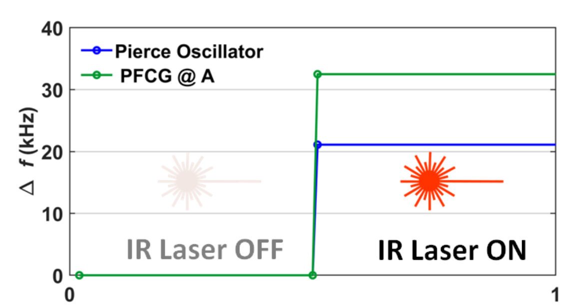

Figure 8: Measured frequency shift for both our PFCG and Pierce oscillator when switching the IR laser from OFF to ON. In the ON state the IR power absorbed by the resonator is estimated to be 10.7 μW. Evidently, the PFCG shows a higher sensitivity than the Pierce oscillator.

CONCLUSIONS

In this paper, we presented a novel sensing scheme that relies on the frequency read-out of AlScN IR detectors through a parametric frequency comb generator. The parametric frequency comb generator operates fully without requiring any active components with power consumption ~10 mW. Our system shows an improvement of up to 10× compared to the best achievable LoD of a conventional Pierce-oscillator and shows a minimum Noise Equivalent Power of 36 pW/$\sqrt{Hz}$ at 0.1 msec. Overall, the findings presented here contribute to the advancement of sensing technology, offering a promising solution for enhancing detection sensitivity and efficiency.

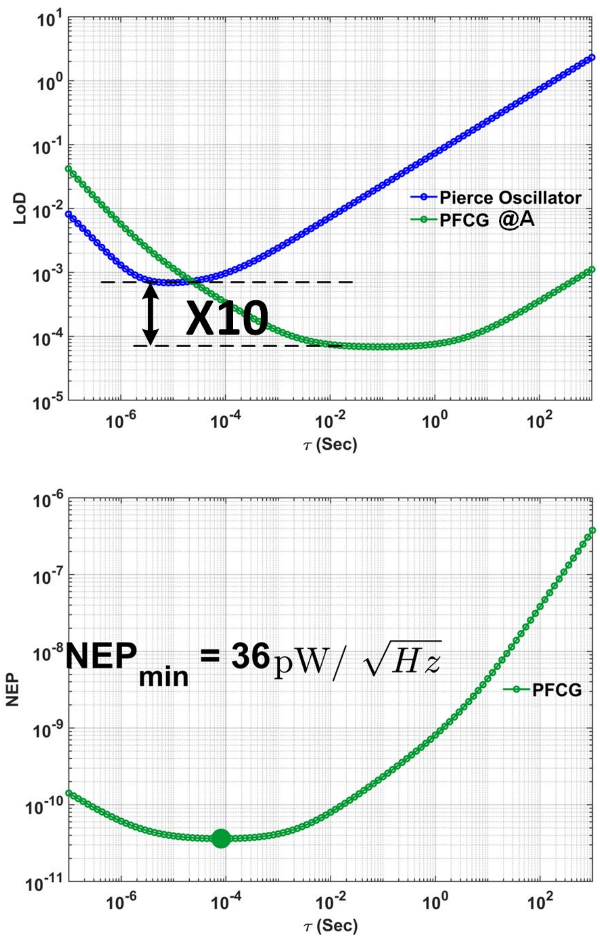

Figure 9: Measured LoD for both the PFCG operating at point "A" and the Pierce loop oscillator. The PFCG shows a one-fold improvement in the best achievable LoD, and two orders of magnitude improvements at key integration times for IR cameras with 10-to-1000 Hz refresh rates (like those used for aerial thermography, surveillance, etc.).

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