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Near-Carrier Phase Noise Suppression at Turnover Temperature in a Thin-Film Piezoelectric-on-Silicon Oscillator

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***Abstract*— In this paper, the near-carrier enhancement of phase-noise (PN) at turnover temperature (T_{to}) in a quasi-thickness-Lamé (QTL) mode thin-film piezoelectric-on-silicon (TPoS) oscillator is reported for the first time. QTL-TPoS resonators fabricated on degenerately-doped n-type silicon offer a T_{to} greater than 80°C and are suitable for implementation of highly-stable ovenized oscillators. In this work, a ∼123MHz QTL-TPoS resonator is heated up to T_{to} (∼90°C) by injecting current through the silicon body of the resonator. It is experimentally observed that at turnover temperature, the phase-noise slope close to the carrier frequency ($\Delta f < 100Hz$) decreases substantially in contrast to the expected trends. A ∼10dB improvement in phase noise at 10Hz offset and a ∼25dB improvement at 1Hz offset is recorded when the oscillator is operating at T_{to} compared to room temperature. [2020-0206]**

***Index Terms*— Turnover temperature, phase noise, temperature fluctuation, thickness-Lamé mode.**

I. Introduction

STABLE timing devices lie at the heart of most digital circuits and communications systems. Such oscillators are often required to demonstrate extreme frequency accuracy as well as excellent temperature stability (ppm levels or better). Oven-controlled resonators are widely used to compensate for the temperature dependence of frequency in resonators for applications where extreme temperature stability is essential [1], [2]. In recent years, micro-electro-mechanical resonators have offered a new window of opportunity to achieve low power consumption in micro-oven-controlled oscillators as an alternative to the legacy quartz-based OCXO due to their small size, and silicon-based fabrication process [2]. The minimum requirement for enabling a highly stable oven-controlled oscillator is a resonator that exhibits a local zero temperature coefficient of frequency (i.e. turnover temperature) outside the nominal operating temperature range of the device.

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Several solutions have been proposed to enable such turnover points in silicon-based resonators [3], [4]. Our group recently reported a new family of TPOS resonators, which operate based on the excitation of quasi thickness-Lamé modes with reasonably high Q and high turnover temperature without the need for extremely high doping concentrations or any additional embedded silicon oxide layer [5].

Despite the outstanding progress made in development of MEMS-based oscillators, the phase noise performance of MEMS-based oscillators, does not match those typically offered by quartz oscillators. Specifically, this disparity is more noticeable in the close-to-carrier noise region. In communication systems with narrow channel spacing, close-to-carrier phase noise is particularly important and constrains the allowable channel spacing [6]. It is postulated that when the resonator size scales down to the nanometer range, there are fundamental thermomechanical mechanisms that dominate the noise performance of the oscillators assembled based on such resonators [7]. In this work, we examine whether thermally-induced fluctuations of frequency could also be responsible for relatively poor near-carrier performance of oscillators assembled based on micro-scale resonators. In particular, we investigate the effect of operation at turnover temperature on the near-carrier phase noise of quasi thickness-Lamé mode oscillators and postulate that the observed improved performance could be a result of the reduced thermally-induced fluctuation of frequency.

II. Phase Noise: Background and Theory

Phase noise and frequency variations are closely related to each other, and the term phase noise could be used to describe random frequency fluctuations of a signal. Several models have been proposed to predict the phase-noise behavior of oscillators [8], [9]. The Leeson model is one such model developed to estimate the behavior of phase noise in an electrical oscillator [8]. From this linear model, the phase noise of an oscillator can be defined as:

$$L(\Delta f) = 10\log\{\frac{2FKT}{P_{sig}}[1 + (\frac{f_0}{2Q\Delta f})^2(1 + \frac{\Delta f_{1/f3}}{|\Delta f|})]\} \quad (1)$$

where Δf is the offset frequency, f_0 is the oscillation frequency, $\Delta f_{1/f3}$ is the corner frequency for the flicker noise, k_B is the Boltzman constant, T is the temperature, F is noise factor of the amplifier, and P_{sig} is the power of carrier signal.

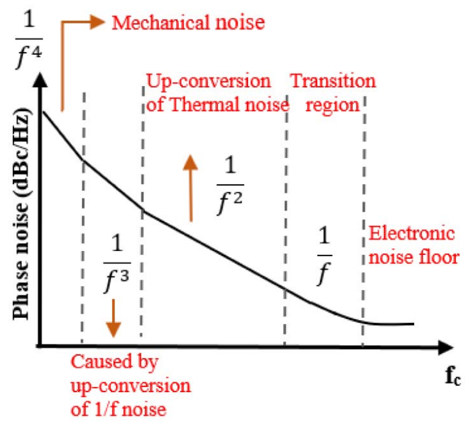

Fig. 1. The phase-noise spectrum of a typical feedback oscillator.

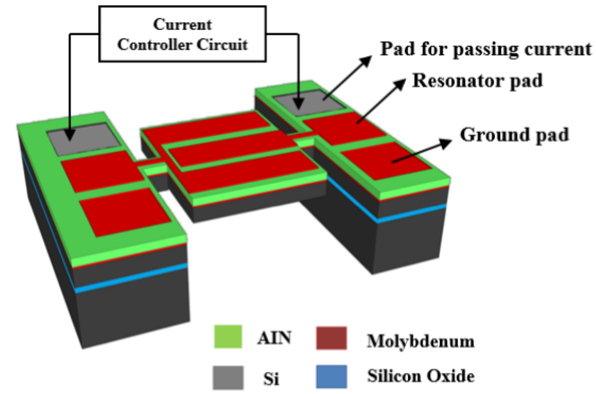

Fig. 2. The schematic of the quasi thickness-Lamé TPoS (QTL-TPoS) resonator highlighting the pads for injection of a DC current through silicon body to efficiently heat the resonator.

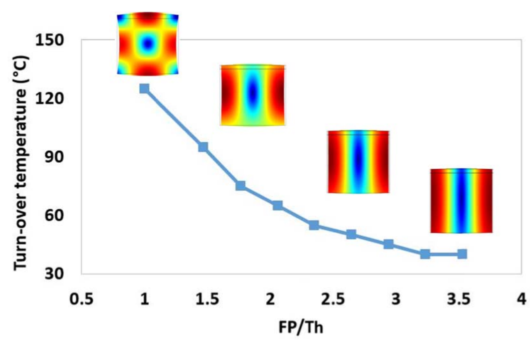

Fig. 3. The simulated turnover temperature of a QTL TPoS resonator as a function of finger pitch to stack thickness ratio [5].

Since MEMS oscillators contain both electrical and mechanical components, both noise sources should be considered to allow for a comprehensive study of phase noise. Different regions in the phase noise plot of a general oscillator are depicted in Fig. 1 [10]. Possible sources for the typical slope of phase noise in each region are also highlighted in this figure. It should be mentioned that all of these different regions will not necessarily be observed in all oscillators. The first region closest to the carrier is the $1/(f^4)$ region which is typically attributed to the random frequency fluctuations of the resonant tank. In micromechanical oscillators, this region has been attributed to adsorption–desorption noise [11], Brownie noise [11], [12], defect motion or temperature fluctuation of a resonator [7], [13]. The temperature-induced fluctuations of frequency is assumed to dominate the close-to-career noise as the resonator dimensions scale down to nanoscale [7], [13]. However, the theoretical limits of temperature fluctuations resulted from the theory developed in such work won't predict the levels of noise typically measured in microscale resonators, including those presented in this work (this will be shown later in section IV).

In the present work, we propose investigating the near-carrier phase noise of a micro-scale oscillator at varying temperatures, from room temperature to the turnover temperature and beyond. A correlation between the phase noise and the effective temperature coefficient of frequency (TCF), if observed, would suggest that the effect of thermally-induced frequency fluctuations is significant in mechanical resonators even at the micro-scale.

With this objective in mind, the characterization of the resonator and oscillator design is briefly discussed first. Then, the effect of resonator's temperature on near-carrier phase noise is recorded and it is shown that, in fact the phase noise at turnover temperature reaches a minimum. Similar suppression of phase noise at the turnover temperature has been reported by other groups [14].

III. Resonator Characterization and Oscillator Design

The device utilized in this work is a quasi thickness-Lamé mode thin-film piezoelectric-on-silicon resonator [5] fabricated on a 16 um degenerately n-type doped [100] SOI substrate. The piezoelectric film is a 1μm $Sc_{0.2}Al_{0.8}$ N layer sandwiched between two 100 nm Molybdenum layers (provided by Advanced Modular Systems Inc.) overlaid on the silicon device layer (Fig. 2). The resonator finger pitch (FP), which is the distance between two adjacent top electrodes, is relatively close to the thickness (t) of these resonators, and consequently, the pure lateral-extensional mode would transition to a QTL mode with the advantage of increased turnover temperature [5].

As shown in Fig. 3, the turnover temperature in QTL resonators could be designed between the turnover temperature of a pure lateral extensional mode and a pure thickness-Lamé mode.

The scanning electron micrograph (SEM) of the QTL-TPoS resonator used in this work is presented in Fig. 4 for which $FP = 25\mu$m.

In the silicon contact area (marked in Figure 4), all the top stack layers are etched down to the silicon device layer to facilitate injection of a DC current through the silicon body of the resonator to control the resonator temperature. A 20 nm AlN seed layer under the bottom metal provides for the electrical isolation of the AC and DC signals in the resonator. The frequency response of the QTL TPoS resonator and the simulated resonance mode shape are shown in Fig 5. An unloaded Q of ~5 k is measured for this resonator at 123 MHz.

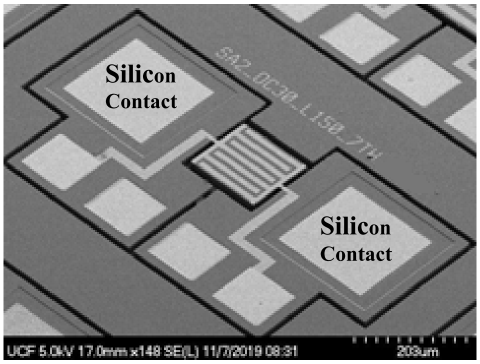

Fig. 4. The scanning electron micrograph of the QTL-TPoS resonator with isolated contact to silicon body for injecting current to heat up the resonator.

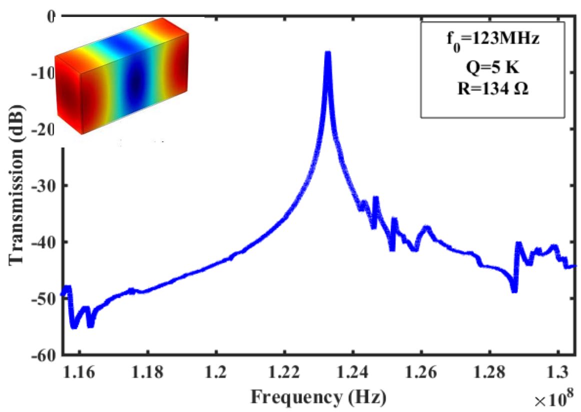

Fig. 5. Frequency response of the QTL-TPoS resonator and the stress-profile profile of the mode-shape.

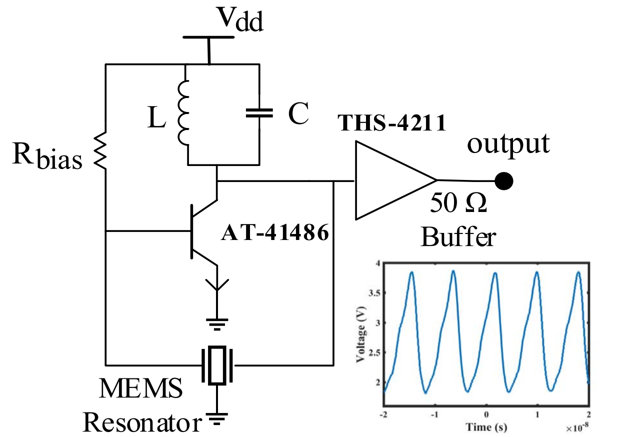

Fig. 6. Schematic of the oscillator circuit and the measured output waveform.

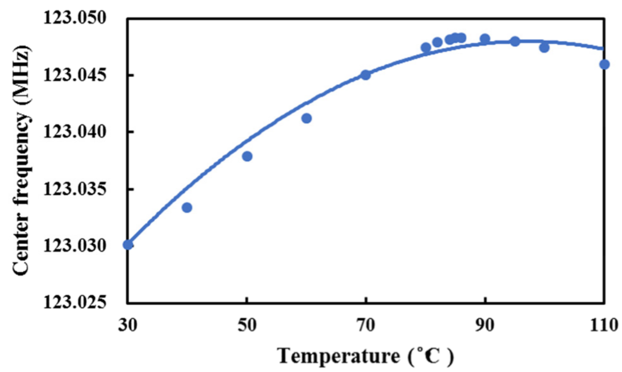

Fig. 7. The frequency vs. temperature plot exhibiting a turnover temperature at ∼90°C.

Due to the low motional impedance of this resonator (∼120Ω), a single high-frequency bipolar junction transistor (BJT) could provide sufficient gain as a sustaining amplifier in the oscillator feedback loop (Fig. 6). The BJT utilized here is AT-41486, an NPN bipolar transistor that offers excellent high-frequency performance in terms of gain and noise figure with the gain bandwidth product of 8 GHz. This transistor is biased at 2 V with a 2mA bias current. Such a single-transistor oscillator promotes lower circuit noise due to the reduced number of components.

In order to connect the oscillator to the 50 Ω termination of a phase noise analyzer, a buffer stage is required. Here, a THS4211 IC is utilized as the buffer which offers a wideband frequency operation. The measured oscillation frequency of the circuit is ∼123 MHz with a 1.5 V peak to peak amplitude (The waveform of the oscillator is shown in the inset of Fig. 6).

To characterize the frequency vs temperature behavior of the resonator, the resonator is placed in a vacuum chamber and the resonator is heated as the pressure is kept at 0.01 Torr. As seen in Fig. 7, the T_{to} is ∼90°C and the room temperature TCF is ∼10ppm/°C.

IV. Analysis of Results

As discussed in section II, thermally-induced frequency fluctuations are postulated to significantly impact the near-carrier phase noise of an oscillator as the dimensions of the mechanical resonator approaches the nanoscale regime. At such small scales, the thermal heat capacity of the resonator is reduced to a level that random transfer of heat energy in and out of the resonator will generate appreciable levels of temperature fluctuation in the resonator. Such temperature fluctuations in return affect the density and elastic modulus of the resonator which leads to a change in the resonance frequency [7], [13].

A simple equivalent electrical circuit that captures the thermal diffusion of a structure such as a resonator is shown in Fig. 8 (It is assumed that the resonator is in thermal equilibrium).

In this figure, the current source (P) models the noise source, which behaves as a white frequency noise. C and G represent the heat capacity and the thermal conductivity of the resonator. G is dependent on the dimension of the resonator and the suspension tethers and can be formulated to include both radiation and conduction for the systems in which the resonator is operating in vacuum [7]. However, it could be shown that for the resonator and the tether dimensions of our oscillator (shown in Table I) and considering the excellent thermal conductivity of silicon (1.5 watt/cm.K) the effect of radiation could be neglected.

Using the model in Fig. 8, the resulting voltage across C and G represent the temperature fluctuation ΔT and the differential equation describing the heat transfer of the

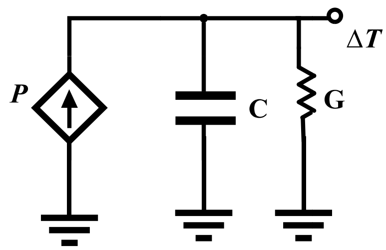

Fig. 8. Equivalent electrical circuit for the thermal diffusion of an resonator.

TABLE I
THE DIMENSION OF THE RESONATOR AND TETHERS

	Width	Length	Thickness
Resonator dimension	210 μm	171 μm	16 μm
Tether dimension	9 μm	8 μm	16 μm

resonator is written as:

$$C\frac{d(\Delta T)}{dt} + G\Delta T = P(t) \tag{2}$$

It could be shown that the spectral density of noise due to the temperature fluctuation resulted from solving this differential equation is [7]:

$$S_{\Delta T}(f) = \frac{4k_B T^2 B/G}{1 + 4\pi^2 f^2 C^2/G^2} \tag{3}$$

where $k_B = 1.38 \times 10^{-23}$ W$\cdot$ sec/K is the Boltzmann's constant and T is the resonator's temperature. The spectral density of temperature-induced fractional frequency noise is then calculated from:

$$S_y(f) = \alpha_t^2 S_{\Delta T}(f) \tag{4}$$

in which α_t denotes TCF of the resonator. Therefore, the thermally-induced root mean square (RMS) fluctuation of frequency is calculated from RMS of (4) multiplied by the center frequency, and finally the phase noise due to temperature fluctuation can be calculated as follows:

$$L(f)' = 0.5 * \frac{f_0^2}{f^2} S_y(f) \tag{5}$$

where f_0 is the carrier frequency and f is the offset frequency from the carrier.

It is clearly observed from this analysis that if the near-carrier noise of the oscillator is dominated by the temperature fluctuation of the resonator, the phase noise could be improved by reducing α_t and it should reach a minimum at turnover temperature where TCF is theoretically zero. Moreover, from (3), we can conclude that at higher offset frequencies, the nonzero heat capacitance acts as a filter and the amount of spectral density of temperature fluctuations would be small at higher frequency from the carrier. As a result, we expect the noise power spectral density due to the temperature fluctuations to reduce at higher offset frequencies from the carrier, and the other noise sources to dominate the behavior of phase noise.

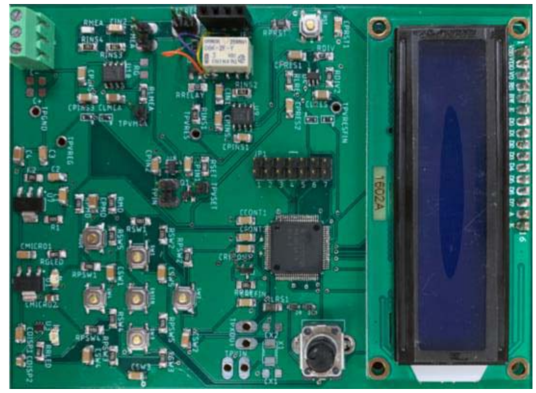

Fig. 9. The printed circuit board of a custom-made micro-controlled based temperature controlling circuit.

To investigate whether the resonator temperature fluctuations are significant in our oscillator, and to evaluate the accuracy of this presented model, we proceed to measure the phase noise at different temperatures.

After placing the oscillator in the vacuum chamber, the resonator is gradually heated while the pressure is kept constant. A current (I_{heater}) is passed through the resonator by a custom-designed current controller circuit shown in Fig. 9. This circuit is capable of monitoring the resonator temperature and automatically keeping the resonator temperature at the turnover temperature, but this feature of the circuit hasn't been utilized for this work.

Current (I_{heater}) is then passed through the resonator until the frequency is maximized (i.e. $T_{resonator} = T_{to}$). The variations of frequency versus I_{heater}. is shown in Fig. 10 and the turnover temperature appears to be reached for $I_{heater} = 80$mA.

Phase noise plots are then measured at different currents and the results for $I_{heater} =$ 0-80mA at 20mA intervals are overlapped in Fig. 11 while the near-carrier portion of the phase noise is highlighted. It is observed that the slope of phase noise is significantly reduced at offset frequency less than 100Hz which is in contrast to the typical phase noise behavior that demonstrate steeper slope at close-to-carrier offset. Overall, more than 8dB and 20dB enhancement are observed in phase noise at10 Hz and 1Hz respectively when the resonator is operating at around T_{to} relative to the room temperature operation.

In order to validate that the observed improvement of phase noise is not directly related to the rising temperature as opposed to correlating with the TCF, the phase noise was measured for currents above 80mA as well. The phase-noise values at 10Hz offset from the carries are plotted as a function of I_{heater} in Fig. 12. By examining the data, it can be concluded that close-to-carrier phase noise enhances by increasing the temperature up to T_{to}, and the phase noise deteriorates beyond that. Hence, it is concluded that the thermally-induced frequency fluctuations are not a negligible source of noise

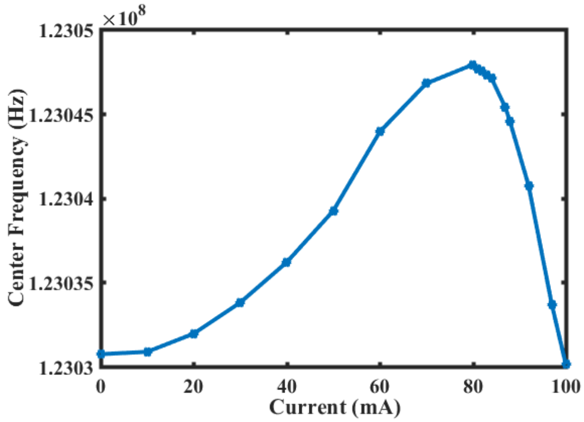

Fig. 10. The variation of center frequency versus the current injected through the silicon body of the resonator.

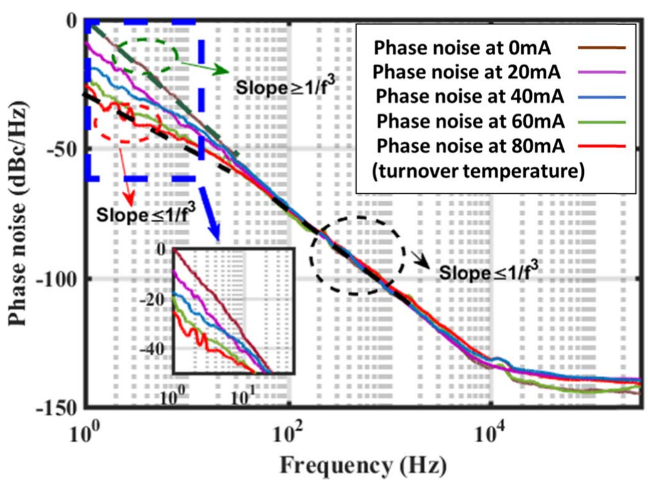

Fig. 11. The measured phase noise at different levels of injected current through the resonator.

for the oscillator in this region, as the effect of this noise source is measurably suppressed by operation at turnover temperature.

By extracting the near-carrier phase noise values at room temperature from Fig. 11 and substituting in (4) (Phase noise @ 1 Hz $= -0.1$ dBc/Hz), the equivalent RMS value of thermally-induced fluctuation of frequency can be estimated and is calculated to be $\sim$1 Hz @ 1Hz (note: α_t is $\sim$10 ppm at room temperature derived from Fig. 7).

To compare the thermally-induced fluctuations based on the measurements with the values predicted by the model presented in [7] and [13], the thermally-induced fluctuation of frequency is calculated using the resonator and the tether dimensions are calculated equations (3) and (4).

The comparison between the data extracted from the measurement and the theoretical prediction is shown in table 2 for 1 Hz and 10 Hz carrier offset at room temperature. As evident from this Table, there exist a large difference between the values extracted from the theoretical model and the hypothetical thermally-induced fluctuations extracted based on measured data. As a result, the theories presented before [7], [13], for predicting the effects of temperature fluctuations on phase noise appear to not capture the effect of thermally-induced noise accurately.

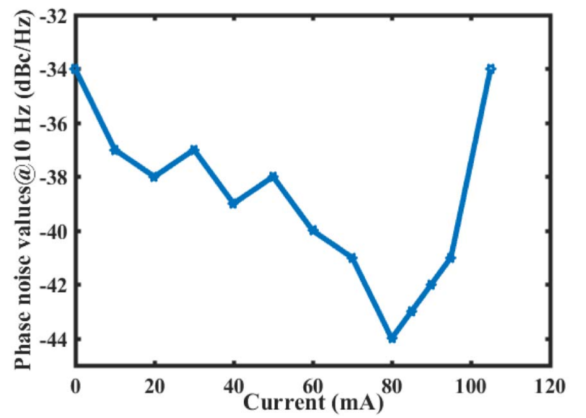

Fig. 12. Measured phase noise @10Hz carrier offset for different amount of current injected in the resonator.

TABLE II

THE COMPARISON OF THE THERMALLY-INDUCED FLUCTUATIONS BASED ON THE MEASURED DATA AND MODELS DESCRIBED IN [7]

	@1 Hz	@10 Hz
thermally-induced fluctuation calculated from measured data	≈1 Hz	≈0.4 Hz
thermally-induced fluctuation based on models in [7]	≈0.0045 Hz	≈0.0044 Hz

TABLE III

THE COMPARISON OF PHASE NOISE PERFORMANCE FOR A SELECTED GROUP OF MEMS-BASED OSCILLATOR REPORTED IN LITERATURE

MEMS-based oscillator	[15]	[16]	[17]	This work
Resonator type	Piezo (AlN)	Capacitive (polysilicon)	Piezo(AlN)-on-silica	Piezo(AlN) -on-Silicon
Center frequency (MHz)	204	61	4.9	123
Phase Noise[1] @1 Hz (dBc/Hz)	-49**	-46**	-43	-48
Phase Noise[1] @10 Hz (dBc/Hz)	-61	-57	-73	-68
Phase Noise[1] @1K Hz (dBc/Hz)	-103	-128	-131	-124
Phase Noise floor[1] (dBc/Hz)	-146	-139	-148	-163

[1]Normalized to 10 MHz.
** extrapolated data

Nevertheless, by examining the data, we can conclude that temperature fluctuation is appearing to be one of the dominant sources of noise at near-carrier offset frequencies. However, the exact mechanism through which this source affects the noise is not fully understood through the existing models.

Finally, to compare the phase noise results reported here with prior published results, the performance summary of several state-of-the-art MEMS-based oscillators are shown in Table 3. Since each oscillator in this list is designed for a different frequency, the phase noise values are normalized to 10 MHz for ease of comparison.

V. Conclusion

The near-carrier phase noise behavior of a 123MHz quasi-thickness-Lamé thin-film piezoelectric-on-silicon oscillator was studied for variable resonator temperature. It was observed that the close-to-carrier phase noise improves at turnover temperature, and specifically, the slope of phase noise plot decreased for the smaller offset frequencies which is in contrast to the expected trends predicting steeper slope. This observation suggests that the effect of temperature fluctuations in this region is significant. It is believed that the enhancement of the near-carrier phase noise is a result of minimal frequency variations at turnover temperature. However, it was illustrated that existing theories do not predict the significance of temperature fluctuations at near-carrier phase noise for micro-scale silicon resonators such as those studied here and further theoretical studies are warranted.

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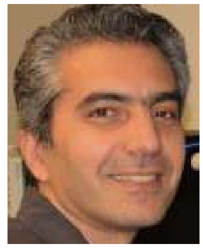

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