Switch-less Dual-frequency Reconfigurable CMOS Oscillator using One Single Piezoelectric AlN MEMS Resonator with Co-existing S0 and S1 Lamb-wave Modes

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ABSTRACT

For the first time, this work demonstrates a switch-less dual-frequency (472-MHz and 1.94-GHz) reconfigurable CMOS oscillator using a single piezoelectric AlN MEMS resonator with co-existing S0 and S1 Lamb-wave modes of vibration. High performances (high $Q$ and $k^2$ for a resonator and low phase noise for an oscillator) have been achieved for both the resonator and oscillator in terms of dual-mode operation. Especially, the 1.94-GHz operation has the best phase noise performance when compared with all previously reported CMOS oscillators that work at a similar frequency.

INTRODUCTION

The need for efficient RF spectrum utilization such as in cognitive radios as well as multi-band/multi-mode wireless communications has greatly increased the demand for high-performance multi-frequency reconfigurable oscillators. In the past, either physical switches or higher-order coupled on-chip LC resonant tanks had been used to demonstrate multi-frequency reconfigurable oscillators.

For the switch-based technique [1-3], the presence of a physical switch comes with substantial parasitic resistance and capacitance, which unavoidably loads the resonator quality factor ($Q$) and lowers the closed-loop gain at high frequencies, therefore degrading oscillator phase noise and causing higher power consumption in the circuit. For multi-frequency oscillators based on high-order coupled on-chip LC resonant tanks, the much lower $Q$ of on-chip passives (especially inductors) compared with MEMS resonators generally results in much poorer phase noise performance [4-5] and use of significant chip area.

In this work, a novel tunable-supply circuit design is combined with a dual-mode high-$Q$ AlN MEMS resonator to realize switch-less reconfiguration of a two-frequency oscillator, as illustrated in Fig. 1. By properly patterning the top and bottom electrodes on a c-axis oriented piezoelectric AlN thin-film plate [6-8], co-existing dual-mode resonant operation has been achieved in a single MEMS structure with high performance. Based on this dual-mode AlN resonator, a tunable-supply CMOS circuit design has been proposed and experimentally demonstrated for switch-less reconfiguration of a dual-frequency oscillator (Fig. 1). The measured phase noise of the 472-MHz output is $-82$ dBc/Hz at 1-kHz offset frequency with a floor of $-160$ dBc/Hz. The phase noise of the 1.94-GHz response is measured to be $-71$ dBc/Hz at 1-kHz offset and $-155$ dBc/Hz for the floor. The performances at both frequencies are on par or superior to other state-of-the-art CMOS oscillators based on a single-frequency mechanical resonator. In particular, the 1.94-GHz operation exhibits the best phase noise performance when compared with earlier reported CMOS oscillators that work at a similar frequency [9-12].

DUAL-MODE ALN MEMS RESONATOR

One possible way to realize switch-less reconfiguration of a multi-frequency oscillator is to make use of the variable gain of the tunable-supply circuit [13] combined with a bank of multi-frequency AlN MEMS resonators, as illustrated in Fig. 2 (a). However, because of the lack of a switch, all the transducer capacitances (e.g., $C_{0}$ to $C_{0n}$) that form the array are seen as a capacitive load by the operating resonator (e.g., $C_{0}$) and therefore degrade its effective electromechanical coupling ($k^2$). Instead, if a single AlN MEMS resonator is designed with multiple resonant modes, only one transducer capacitance ($C_{0}$) is used and shared by all the motional branches (each associated with a different frequency of operation), so that the intrinsic $k^2$ of the desired resonant mode is preserved, as shown in Fig. 2 (b). The AlN MEMS contour-mode resonator (CMR) technology [6-7] relies on interdigitated electrodes to excite a mode of vibration and it can be properly designed so that multi-mode resonances can be demonstrated in a single structure. The design challenge consists in properly configuring the layout of the bottom and top electrodes of the AlN CMR so that more than one resonant mode can be excited and detected by the same group of electrodes.
Fig. 2: Circuit schematics showing (a) a multi-frequency AlN MEMS resonator bank and (b) a single resonator with multi-frequency modes of operation.

Fig. 3: (a) Cross-sectional schematic of the dual-mode AlN MEMS resonator and the simulated displacement profiles (using COMSOL FEM software) of the (b) S0 and (c) S1 Lamb-wave modes. In this case, the zoomed-in view of 3 fingers (n=3) is shown.

For example, by patterning only the top Pt thin film layer into signal-ground (+ and − in Fig. 3) alternating electrodes and leaving the bottom Pt thin film layer as a single floating electrode, both the S0 and S1 Lamb wave modes [14] can be excited in this AlN MEMS plate. For the S0 mode, which has generally been referred to as contour mode [6-7], the MEMS plate vibrates in plane (laterally) with a wavelength of 2W, and each finger of width W moves out of phase with respect to the one next to it. Electric charge is generated with alternating polarity through the direct piezoelectric effect and collected by the top electrodes. In the case of the S1 mode, each finger of the resonator vibrates in the thickness direction (primarily vertical displacement, as shown in Fig. 3) with a wavelength of 2T and also out of phase with respect to its neighbor. Therefore, the generated charge on the top surface of the piezoelectric AlN plate has an alternating polarity and can therefore be collected by the properly patterned top electrodes. The floating bottom Pt electrode is introduced primarily to enhance the effective electromechanical coupling by confining the electric field in the thickness direction.

Fig. 4. Measured admittance plot and its MBVD equivalent circuit model (shown in bottom left of Fig. 1) fitting for the 472-MHz S0 Lamb-wave mode of the dual-mode AlN MEMS resonator.

Fig. 5. Measured admittance plot and its MBVD equivalent circuit model (shown in bottom left of Fig. 1) fitting for the 1.94-GHz S1 Lamb-wave mode of the dual-mode AlN MEMS resonator.

For this dual-mode resonator to be applied in a switchless reconfigurable oscillator, specific design constraints have to be considered. As has been derived in [7, 13, 15], the critical resonator parameters that set the circuit gain requirements in an oscillator are the operating frequency, $\omega_0$, the motional resistance, $R_M$, (which depends directly on quality factor $Q$ and electromechanical coupling $k^2$):

$$V_{s1} \sim g_m \sim \omega_0^2 \cdot R_M \sim \frac{\omega}{Q \cdot k^2}$$  \hspace{1cm} (1)

Eq. (1) does not include the transducer capacitance, $C_0$, as a control parameter to independently set the gain at the two frequencies since it is the same for both resonant modes. In addition, since $k^2$ is mainly dependent on the material properties and mode of vibration and $Q$ is very difficult to predict a priori, the operating frequency becomes the only parameter that can be properly engineered so that the circuit requires largely different levels of gain in order to lock into each of the two resonant modes.
The $S1$ mode is a thickness mode that mainly relies on the $d_{33}$ piezoelectric coefficient, and has, according to simulations, a $k^2_{Q}$ that is approximately 2X that of the $S0$ mode, which relies on $d_{31}$. We have also experimentally found out that the $Q$ of the lower frequency $S0$ mode is roughly 2-3 times that of the $S1$ mode. In this case, because the $Qk^2_{Q}$ product is similar for the two modes, a relatively large frequency difference between the two resonances is required for separating the two regions of operation with respect to the control values of $V_{S1}$ of the oscillator, as described by Eq. (1). Therefore, in this work, the thin film thickness ($T = 1.2 \mu m$) is used to obtain a high frequency at 1.94 GHz, whereas the lateral dimension width ($W = 8 \mu m$) is designed to set the lower frequency resonance at 472 MHz. The other lateral dimensions, the resonator length $L = 150 \mu m$, and the number of fingers, $n = 7$, are set in such a way to effectively control the resonator impedance (and motional resistance) and the lateral aspect ratio (for $Q$ optimization).

According to these design guidelines, a dual-mode AlN MEMS resonator has been fabricated and tested so that co-existing $S0$ and $S1$ Lamb wave modes could be excited with high performance ($Q_s = 1800$ and $k^2_{Q} = 1.04\%$ for the $S0$ mode at 472 MHz; $Q_s = 600$ and $k^2_{Q} = 2.27\%$ for the $S1$ mode at 1.94 GHz). The measured admittance curves are plotted in Figs. 4 and 5. Fitting to the MBVD model [16] was performed to extract the equivalent circuit parameters for oscillator design.

It is also possible to realize two different frequency lateral modes in a single resonator so that both frequencies can be set by layout. Nevertheless, the same design guidelines outlined here apply to this other case as long as different $Q$ and $k^2_{Q}$ are properly taken into account.

**SWITCH-LESS RECONFIGURATION**

The reconfiguration and dual-frequency operation of the oscillator are attained by properly adjusting the supply voltage ($V_{S1}$ in Fig. 1). Oscillation occurs when the circuit loop gain is larger than 0 dB. The loop gain can be tuned by varying the local supply voltage ($V_{S1}$), as simulated and shown in Fig. 6. The two oscillation regions for the two different vibration modes are also marked in Fig. 6 and show that there is an overlap between these two regions. Therefore, this reconfiguration also depends on the initial value of the supply voltage ($V_{S1}$).

This switch-less reconfiguration mechanism was verified experimentally. When the supply voltage ($V_{S1}$) is gradually increased from 0 V, the oscillator starts oscillation at a voltage of 1.6 V with an output frequency of 472 MHz. The 472-MHz operation state continues until the supply voltage is changed from 4.6 to 4.7 V. After this point the oscillator locks into the 1.94-GHz mode of the AlN MEMS resonator. On the other hand, if the supply voltage is initially set at 5 V, the circuit oscillates only at 1.94 GHz. The 1.94-GHz operation continues until the supply voltage is reduced from 3.2 to 3.1 V, at which the oscillator commutes to the 472-MHz operation.

This behavior is similar to what was predicted via the simulation as shown in Fig. 6. In this way, the tunable supply technique is used to select the operating frequency. Once the frequency selection is performed and the oscillator is locked into a specific state, the supply voltage can be varied within the range of the overlapping region (3.2 to 4.6 V) to optimize the phase noise and power consumption of the selected mode of operation (Tables I and II).

**OSCILLATOR PERFORMANCE**

The tunable oscillator circuit design was implemented in the ON Semiconductor 0.5-µm CMOS process, while the dual-mode AlN MEMS resonator was fabricated in a 3-mask microfabrication process [17]. The MEMS resonator is wire-bonded to the CMOS circuit, and both dies are mounted on a custom-designed PCB for output signal characterization. An Agilent E5052B signal source analyzer has been used for measuring the phase noise, while an Agilent DSO80804A ultra-high-speed oscilloscope for time-domain monitoring.

![Fig. 6. Simulated loop gain of the oscillator circuit for locking into the S0 and S1 Lamb-wave modes, respectively. In the overlapping region, the operating frequency depends on the initial condition.](image)

![Fig. 7. Measured phase noise performances for the two frequencies of operation of the switch-less oscillator.](image)
Table I. Experimental Results for Operation at 472 MHz

<table>
<thead>
<tr>
<th>$V_{in}$ [V]</th>
<th>1.6</th>
<th>1.7</th>
<th>2.2</th>
<th>2.6</th>
<th>3.0</th>
<th>3.4</th>
<th>3.8</th>
<th>4.2</th>
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<td>Phase Noise @ 1 kHz [dBc/Hz]</td>
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<td>-73</td>
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<tr>
<td>Phase Noise Floor [dBc/Hz]</td>
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<td>-160</td>
<td>-159</td>
<td>-156</td>
<td>-154</td>
<td>-152</td>
<td>-150</td>
<td>-148</td>
<td>-146</td>
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<tr>
<td>Output Power [dBm]</td>
<td>-7.3</td>
<td>-6.5</td>
<td>-7.5</td>
<td>-7.5</td>
<td>-9.6</td>
<td>-11.5</td>
<td>-13.4</td>
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Table II. Experimental Results for Operation at 1.94 GHz

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<th>$V_{in}$ [V]</th>
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<td>-70</td>
<td>-70</td>
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<td>-69</td>
<td>-160</td>
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<td>Output Power [dBm]</td>
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<td>-17.1</td>
<td>-16.5</td>
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Table III. Phase Noise Comparison to Prior Art

<table>
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<tr>
<th>Reference</th>
<th>$f_o$ [GHz]</th>
<th>$p_o$ [dBm]</th>
<th>Phase Noise @ 1 MHz [dBc/Hz]</th>
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<td>This work 2010</td>
<td>1.9</td>
<td>-1</td>
<td>-153</td>
<td>Dual-Mode AlN MEMS 0.5-µm CMOS</td>
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<td>K. B. Östman, JSSC 2006 [9]</td>
<td>2.1</td>
<td>-3</td>
<td>-144</td>
<td>Above-IC FBAR BAW 0.25-µm SiGe BiCMOS</td>
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<td>S. S. Rai, JSSC 2008 [10]</td>
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<td>P. Vincent, JSSC 2008 [11]</td>
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<td>M. Straayer, ISSCC 2002 [12]</td>
<td>1.7</td>
<td>-3</td>
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CONCLUSION

A switch-less reconfigurable dual-frequency (472-MHz and 1.94-GHz) CMOS oscillator has been demonstrated based on a single piezoelectric AlN MEMS resonator with co-existing $S_0$ and $S_1$ Lamb-wave modes of vibration. By properly patterning the top and bottom electrodes on a $c$-axis oriented piezoelectric AlN thin-film plate, co-existing dual-mode resonant operation has been achieved in a single MEMS structure with high performance: $Q_s = 1800$ and $k_v^2 = 1.04\%$ for the $S_0$ Lamb-wave mode at 472 MHz; $Q_s = 600$ and $k_v^2 = 2.27\%$ for the $S_1$ resonant mode at 1.94 GHz. A tunable-supply oscillator circuit design has been proposed and experimentally demonstrated for switch-less frequency reconfiguration. This switch-less solution results in low phase noise for both frequencies of operation and reduces the switching time during state transition.

ACKNOWLEDGMENT

This work was supported by the DARPA S&T grant.

REFERENCES