A 220dB FOM, 1.9GHz oscillator using a phase noise reduction technique for high-Q oscillators

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***Abstract* — We present a technique to reduce the close-in phase noise of high-Q (FBAR/MEMS/crystal) oscillators. The proposed technique suppresses the up-conversion of 1/f noise via AM-PM conversion by the addition of a non-linear capacitor to the tank. The proposed AM-PM suppression technique has no additional power penalty and incurs a minimal area penalty. Measurements from multiple dies of a 1.9GHZ FBAR oscillator show ≥3.5dB reduction in close-in phase noise using the proposed technique. The FBAR oscillator achieves a measured phase noise of -88dBc/Hz @ 1kHz, -116dBc/Hz @10kHz, -146dBc/Hz @ 1MHz offsets. The oscillator with the proposed technique achieves a Figure of Merit (FOM) of 220dB, which is 5.5dB better than the FBAR oscillator with lowest close-in phase noise reported to date [1].**

***Index Terms* — Oscillators,Phase Noise,MEMS,FBAR.**

I. Introduction

Wafer scale high-Q MEMS resonators are becoming attractive alternatives to quartz owing to their small size, low cost and integration potential[2]. Thermal stability of MEMS based references has also improved to sub-ppm levels in the recent past[3].

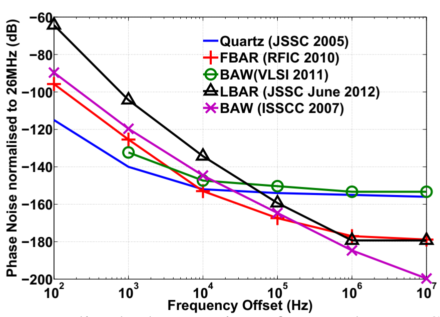

Fig. 1. Normalized phase noise of several MEMS oscillators compared to Quartz oscillator

Close-in phase noise is an important performance metric for a reference oscillator as it dominates the in-band phase noise of a frequency synthesizer in a radio. Fig.1 compares published MEMS oscillators[4][1][5][6][7] with quartz oscillator showing that MEMS oscillators perform poorly compared to quartz oscillators in terms of close-in phase noise. To successfully replace quartz references with MEMS references in all applications, advancements in close-in phase noise reduction techniques are needed.

Existing studies on close-in phase noise focus on ring oscillators and LC Oscillators [8] [9]. While Groszkowski's effect is the dominant source of close-in phase noise in LC oscillators [8], it is not the dominant mechanism in high-Q oscillators (we discuss this further in section II). Thus, the existing phase noise reduction techniques do not directly apply to high Q MEMS oscillators. In this paper we use an FBAR oscillator to study the close-in phase noise mechanisms of a high Q oscillator and accomplish the following.

- We show that AM-PM (amplitude modulation to phase modulation) arising from non-linear device parasitics is the dominant mechanism of close-in phase noise generation in an FBAR oscillator.
- We demonstrate that by making the oscillation frequency independent of bias current (at the operating point of the oscillator), one can suppress AM-PM conversion and reduce close-in phase noise.
- We accomplish the required AM-PM suppression by connecting a non-linear compensation capacitor across the tank.
- Measurements from a fabricated 1.9 GHz FBAR oscillator show a 4 dB reduction in close-in phase noise with no power penalty using the proposed AM-PM suppression technique.

The proposed AM-PM suppression technique is demonstrated using an FBAR oscillator but applicable to any oscillator employing a high - Q resonator.
The paper is organized as follows. Section II describes the proposed AM-PM suppression technique. Section III describes the circuit implementation and Section IV gives the experimental results and compares our oscillator with previously published FBAR oscillators.

II. Proposed AM-PM suppression technique

We use the Pierce oscillator topology shown in Fig. 2 as a test vehicle for the proposed technique. One can model the oscillator as shown in Figure 2b, where the active circuitry is replaced by a capacitor and negative resistance connected across the FBAR.

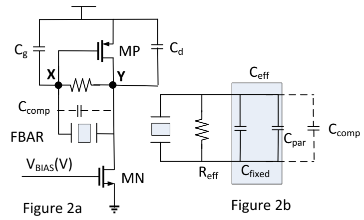

Fig. 2. Pierce oscillator and circuit model

A. AM-PM conversion

Large voltage swings at node X and Y in Fig.2, which are desirable for low far-out phase noise, cause transistors MP and MN to span multiple operating regions.The large voltage swings across the nonlinear gate and drain parasitic capacitances result in a very nonlinear C_{eff}. Any $\frac{1}{f}$ noise in the bias current of the oscillator modulates the oscillation amplitude (AM) and hence modulates C_{eff} generating phase noise. We can estimate the phase noise due to this well known AM-PM mechanism using the following formula [8].

$$L_{AM-PM}(\omega_m) = \frac{1}{2}\left|\frac{\partial\omega}{\partial I_{bias}}\right|^2 \frac{S_I(\omega_m)}{\omega_m{}^2} \tag{1}$$

where S_I is the PSD of the noise in the bias current, ω_m is offset at which phase noise is measured, ω is the oscillation frequency and I_{bias} is the oscillator bias current. Figure.3 compares the total simulated phase noise of the oscillator with the phase noise estimated from eq.(1). We see that AM-PM conversion dominates phase noise at low frequency offsets. This mechanism is similar to the varactor non-linearity discussed in [10] except the non-linearity arises from device parasitics and not from explicitly added varactors.

In contrast to FBAR oscillators, the dominant close-in phase noise mechanism in LC oscillators is the incremental Groskowzski's effect [8]. Phase noise due to incremental Groskowzski's effect is derived in [8] as

$$L_{Groszkowski}(\omega_m) \propto \frac{1}{Q^4}$$

FBAR/MEMS/Quartz resonators have more than two orders of magnitude higher Q compared to on-chip LC tanks. Hence, phase noise due to Groskowzski's effect is heavily suppressed in high-Q oscillators.

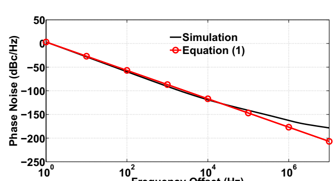

Fig. 3. Simulated phase noise compared to equation (1)

B. AM-PM suppression technique

From equation(1), we see that $\frac{\partial\omega}{\partial I_{bias}}$ is the gain with which flicker noise gets up converted to phase noise. To suppress this AM-PM up-conversion, the designer should strive to reduce $\frac{\partial\omega}{\partial I_{bias}}$, i.e make the oscillation frequency independent of bias current around the operating point of the oscillator. For an FBAR oscillator, we can write

$$\frac{\partial\omega}{\partial I_{bias}} = \frac{\partial\omega}{\partial C_{eff}}\frac{\partial C_{eff}}{\partial I_{bias}} \tag{2}$$

The term $\frac{\partial\omega}{\partial C_{eff}}$ is constrained primarily by the resonator and is typically not a degree of freedom for the circuit designer. But the term $\frac{\partial C_{eff}}{\partial I_{bias}}$ can be manipulated by the designer to reduce $\frac{\partial\omega}{\partial I_{bias}}$.

C_{eff} is made of the explicitly added MIM capacitors C_d and C_g and parastic capacitors of MP and MN, C_{par} . As C_{par} is usually more bias-dependent than C_d and C_g, we can write

$$\frac{\partial C_{eff}}{\partial I_{bias}} \approx \frac{\partial C_{par}}{\partial I_{bias}} \tag{3}$$

Typically, C_{par} is defined by the width and length of MP and MN, which are chosen with other considerations (power consumption,far-off phase noise, oscillator swing etc) in mind. So the designer does not have any degree of freedom to reduce $\frac{\partial C_{eff}}{\partial I_{bias}}$. To provide the required additional degree of freedom to the designer, we add a compensation capacitor C_{comp}.

$$C'_{eff} = C_{eff} + C_{comp} \tag{4}$$

If we choose

$$\frac{\partial C_{comp}}{\partial I_{bias}} = -\frac{\partial C_{par}}{\partial I_{bias}} \tag{5}$$

we can write

$$\frac{\partial C'_{eff}}{\partial I_{bias}} = \frac{\partial C_{par}}{\partial I_{bias}} + \frac{\partial C_{comp}}{\partial I_{bias}} \approx 0 \implies \frac{\partial\omega}{\partial I_{bias}} \approx 0 \tag{6}$$

By choosing an appropriate non-linear compensation capacitor C_{comp} the designer can desensitize the oscillation frequency with respect to the bias current, thereby suppressing AM-PM conversion. In our design, we choose a C_{comp} made up of zero-VT NMOS transistors shown in Figure.4. C_{comp} decreases with increasing oscillation amplitude, cancelling the increase in C_{par}. We size the NMOS transistors in Fig.4 to satisfy eq.(5).

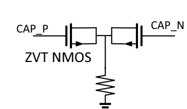

Fig. 4. Non Linear Compensation capacitor

Fig. 5 plots simulated C_{eff} (Compensation OFF), C'_{eff} (Compensation ON) and the compensation

capacitance,C_{comp} as a function of bias current. In Fig. 5 the mean value of the capacitances are subtracted out to bring out the compensation more clearly. We see that the slope of C'_{eff} is much smaller than that of C_{eff}. With a reduced $\frac{\partial C'_{eff}}{\partial I_{bias}}$ we see a suppression in the simulated close-in phase noise. Fig.6 shows the achieved close-in phase noise suppression in simulation.

It should be noted that the proposed scheme is complementary to flicker noise reduction in the bias circuits. Referring to eq.(1), the proposed scheme reduces $\frac{\partial \omega}{\partial I_{bias}}$, while one can independently reduce the bias noise S_I.

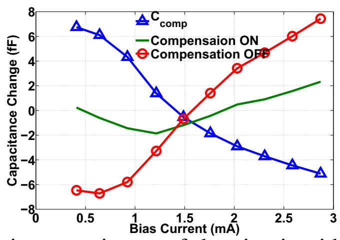

Fig. 5. Effective capacitance of the circuit with compensation

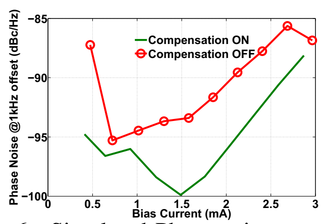

Fig. 6. Simulated Phase noise suppression

III. Circuit Implementation

To experimentally verify our AM-PM suppression technique, we fabricated the test circuit shown in Fig.7. MP1 and MN1 form a Pierce oscillator. The compensation capacitor is made of two zero VT NMOS sized $\frac{27\mu m}{0.42\mu m}$. The mean value of C_{comp} is 60 fF. A digital control D_{comp} selects either C_{comp} or C_{MIM}, a linear 60fF MIM capacitor to be connected across the FBAR. This enables us to turn the compensation ON and OFF, without affecting the total tank capacitance and other oscillator parameters.

A digitally programmable bias circuit controlled by D_{BIAS} biases MN1, providing an experimental knob to vary the current through the oscillator. The oscillator core occupies an area of $250\mu m$ x $100\mu m$. The oscillator nominally operates at a V_{dd} of 1.2V and consumes a bias current of 1.3mA.

IV. Experimental Results

The oscillator circuit was fabricated in 0.13 μm IBM CMOS 8RF process. The CMOS oscillator is wire bonded to an 1.9GHz FBAR from Avago Technologies. Fig. 8 shows the board assembly of the CMOS oscillator and FBAR.

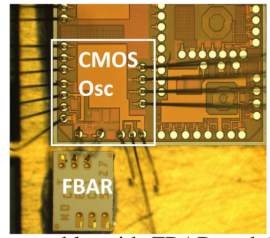

Fig. 8. Board assembly with FBAR and CMOS oscillator

To experimentally verify whether the proposed compensation reduces the term $\frac{\partial \omega}{\partial I_{bias}}$, we measure the oscillation frequency across bias currents, with and without the compensation. Fig.9 shows that the oscillation frequency becomes 2.7X less sensitive to the bias current, when the compensation is turned on.

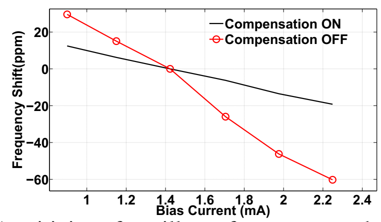

Fig. 9. Sensitivity of oscillator frequency to the bias current

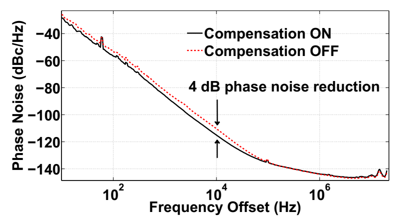

Fig. 10. Measured phase noise suppression using proposed technique

Fig. 10 shows the measured phase noise with and without the AM-PM suppression. Turning the compensation on reduces the close-in phase noise by 4 dB while retaining the far-off phase noise at the same value. We measured the phase noise performance of the oscillator on 4 different dies. We consistently observed a $\geq$ 3.5dB reduction in phase noise in all 4 dies using the proposed technique.

While a 2.7X reduction in $\frac{\partial \omega}{\partial I_{bias}}$ must correspond to 8dB reduction in phase noise, we measure only a 4 dB reduction. This indicates that the presence of phase noise from another mechanism at 7dB lower than the dominant AM-PM mechanism. This mechanism becomes the next dominant source of phase noise once the AM-PM upconversion is suppressed by 8 dB. Further experimental work is required to identify and address this mechanism.

Figure 11 shows the screen shot of the measured phase noise of the oscillator at a Vdd of 1.2 V and bias current of 1.3mA. With the compensation turned on, we achieve a phase noise of -88 dBc/Hz at 1kHz, -116.3 dBc/Hz at 10 kHz and a noise floor of -146 dBc/Hz.

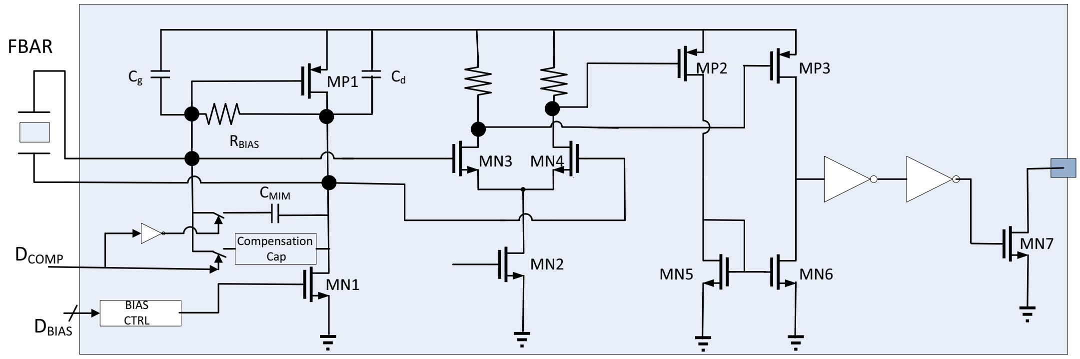

Fig. 7. Fabricated Oscillator Circuit

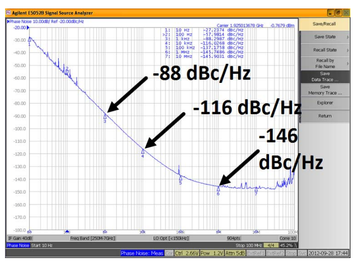

Fig. 11. Measured phase noise of the oscillator

In Table.I we compare the proposed oscillator with other previously published FBAR oscillators[11][12][13][1][7]. The Figure Of Merit (FOM) is computed at 10kHz offset as this study focused on close-in-phase noise. We see that the proposed technique enables the oscillator to achieve an FOM of 220dB, which is 5.5 dB better than the FBAR oscillator with the lowest close-in phase noise reported to date [1]. The oscillator in [11] achieves a 2 dB better FOM than this oscillator. However [11] achieves this FOM by drastically trading off phase noise for an ultra low power consumption, while this work achieves a comparable FOM by improving the phase noise using the AM-PM suppression technique.

TABLE I
PERFORMANCE COMPARISON

Ref	f_{osc} GHz	Power mW	PN 1kHz dBc/Hz	PN 10kHz dBc/Hz	FOM 10kHz dB
This Work	**1.925**	**1.6**	**-88.3**	**-116.0**	**219.6**
[13]	1.9	0.3	-75	-100	210.8
[1]	0.6	5.6	-96	-126	214
[11]	2.0	0.025	-76	-100	222
[12]	1.9	0.089	NA	-98	214
[7]	2.0	12	-70	-100	195.8

V. CONCLUSION

This work experimentally confirms that the dominant source of close-in phase noise in high-Q FBAR oscillators is the AM-PM up-conversion arising from non-linear device parasitics. A non-linear compensation capacitor added across the tank improves phase noise by ≥ 3.5 dB. The proposed compensation technique enables the 1.9 GHz FBAR oscillator to achieve a phase noise of -88dBc/Hz at 1kHz and an FOM of 220 dB.

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