TEMPERATURE COMPENSATED IBAR REFERENCE OSCILLATORS

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ABSTRACT

This work presents a two-chip automatically temperature-compensated micromechanical IBAR reference oscillator with a temperature drift of 39ppm over 100°C. Temperature compensation is provided by a parabolic V_P correction scheme and provides 10X improvement over previously reported results. Tunable 6MHz, 10MHz, and 20MHz resonators were characterized with 2000–4500ppm tuning and Q up to 119000. Motional impedances as low as 218Ω were extracted from measurement data with V_P=18V. The interface IC for temperature compensation and oscillation consumes only 1.9mW. Measurements also show that temperature compensation of a 10MHz resonator with 65nm gaps is possible with less than 5V.

1. INTRODUCTION

Frequency references are ubiquitous in electronics. In high performance applications, quartz crystal units have historically been the solution since they provide high quality factor, temperature stability, and excellent aging characteristics. However, their large size is an impediment to system integration. Micromechanical resonators, especially those fabricated from bulk materials such as single crystal silicon (SCS), have strong potential as a solution for package-level integrated frequency references. The attractiveness lies in their small size, high Q, and potential for excellent reliability. In spite of this, improved frequency stability from these resonators remains desirable.

Various schemes have been demonstrated to compensate for the typically -25 to -30ppm/ºC temperature drift of silicon resonators [1-4]. Electrostatic temperature compensation (TC) with polarization voltage (V_P) correction (Fig. 1) was first presented at MEMS'05 [1], and 380ppm drift was reported for a linearly compensated 4MHz oscillator [2].

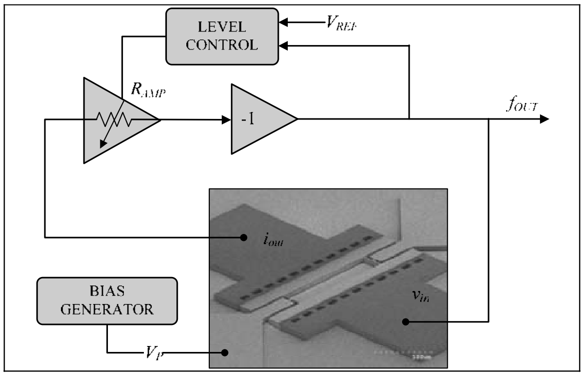

Figure 1: A MEMS-based oscillator with temperature compensation

Other demonstrated TC schemes include geometric stress compensation [3] and resistive heating [4]. However, tuning by V_P correction is more attractive because no additional structural features are necessary and does not require heating of the resonator. In this work, an improved V_P correction method and associated circuitry is presented along with high Q resonators that enable oscillation and temperature compensation with low polarization voltages.

2. TEMPERATURE COMPENSATION

The temperature drift of the resonator is a result of the change in stiffness with temperature and thermal expansion and can be expressed by:

$$\frac{df}{f_0} \propto dT. \tag{1}$$

The fractional electrostatic tuning of a parallel plate resonator is proportional to V_P^2:

$$\frac{df}{f_0} = \frac{\varepsilon A_e}{k_n d^3} dV_P^{\,2} \tag{2}$$

where A_e is the electrode area, k_n is the dynamic stiffness, and d is the gap. Thus for TC, it is necessary that the tuning voltage V_P follows

$$V_P^{\,2} \approx A - B\cdot\left(T - T_0\right) \tag{3}$$

in which A and B are determined by resonator characteristics. The block diagram for this TC scheme is shown in Fig. 2.

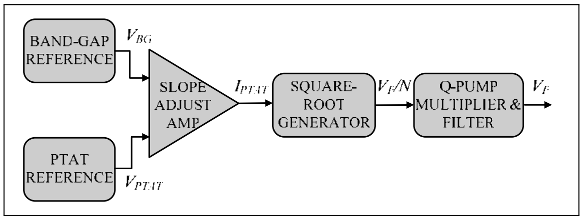

Figure 2: Parabolic temperature compensation circuit (Bias generator)

3. IBAR DESIGN, FABRICATION, AND CHARACTERIZATION

A high-Q electrically-tunable resonator is needed for low phase noise temperature-compensated reference oscillators. The I-shaped bulk acoustic resonator (IBAR) is an extensional mode resonator with an enlarged flexural electrode (Fig. 3) for greater electrostatic tunability and reduced motional impedance [2]. Thus, the IBAR is unique in combining high Q with the tunability of flexural resonators, which is ideal for this application. By placing multiple sections adjacently, the motional impedance and power handling can be improved.

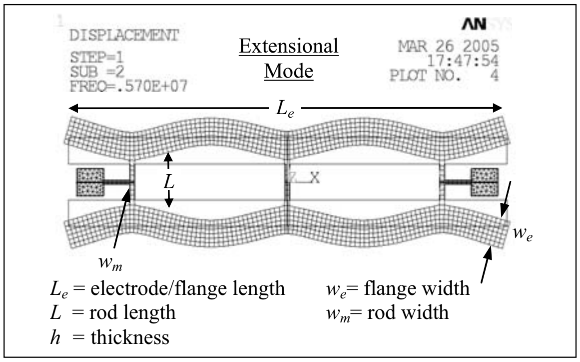

Figure 3: Mode shape and design parameters for a three-section I-shaped bulk acoustic resonator (IBAR or I^3)

IBARs with center frequencies of 6MHz, 10MHz, and 20MHz were fabricated on a low-resistivity substrate using the HARPSS-on-SOI process [5]. The entire resonator body is defined by DRIE trenches in the SCS device layer. See Fig. 4. Sacrifical LPCVD oxide is then deposited in the trenches. LPCVD polysilicon is deposited next in the trenches to form the electrodes, which are subsequently connected to polysilicon pads that rest directly on SCS. The resonators are released in a HF solution to remove the sacrificial oxide and buried oxide beneath the resonator. The resulting structure is suspended (through connections to the anchors), and can have narrow and high aspect-ratio vertical capacitive air gaps to enable good tunability (2).

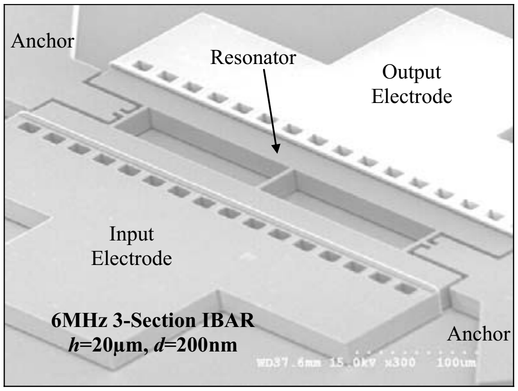

Figure 4: SEM of a 20µm thick HARPSS-on-SOI 6MHz 3-section IBAR (I^3), d=200nm

The resonators were wire-bonded on a PCB and characterized through direct connection to an Agilent 4395A network analyzer. The highest measured Q was 119000 in high vacuum (~1µTorr). See Fig. 5. Distinct peaks with approximately 40dB signal to noise ratios could be measured with polarization voltages as low as 1V. The measured impedance of the 6MHz resonator when V_P=18V is 655Ω, of which 437Ω is contributed by the resistive loading of the resonator body, electrodes, and electrical terminations. The extracted motional impedance is therefore only 218Ω (Fig. 6). Q is loaded to a third of $Q_{unloaded}$ due to the resistive loading of the silicon substrate and polysilicon electrodes.

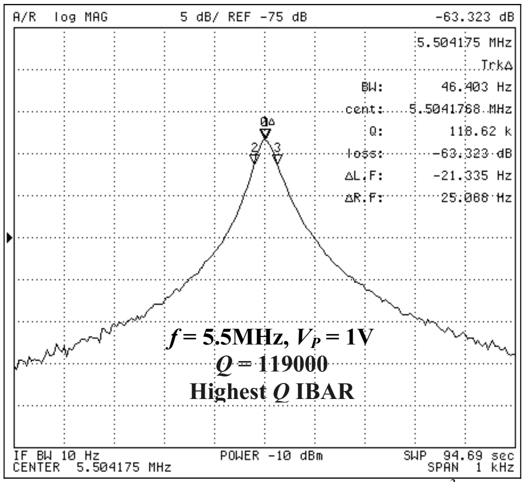

Figure 5: Measured Q of 119000 from the 6MHz I^3 resonator at 1µTorr (V_P=1V)

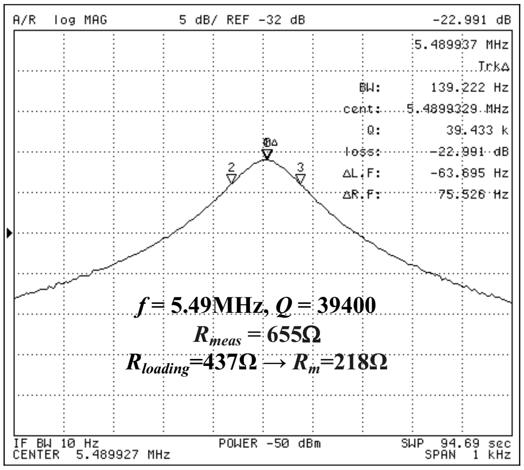

Figure 6: Lowest measured impedance of 655Ω (R_m=218Ω) from the 6MHz I^3 (V_P=18V)

The fractional tuning characteristic (2) and measured impedance of the 6MHz IBAR are shown in Fig. 7. In varying V_P from 1V to 18V, the center frequency shifted by 2580ppm, which corresponds to an *ETC* of -8.9ppm/V^2. Motional impedances when V_P is 3V and above are sufficiently low to sustain oscillations with a low power trans-impedance amplifier.

As resonator frequency increases, the tunability generally decreases. To compensate for this, 10MHz and 20MHz IBARs were implemented in 10µm thick SOI with 65nm gaps (Fig. 8). A 10MHz IBAR offers 2800ppm of tuning over a V_P range of only 2-4V (Fig. 9). This obviates the need for charge pumps for temperature compensation, thus potentially reducing oscillator power consumption. A 20MHz IBAR is also tunable to the extent of 4500ppm with V_P<15V (Fig. 10), thus enabling TC with lower voltages at higher frequencies. The measurement data in Fig. 9 and Fig. 10 were collected in low vacuum (1Torr) and therefore quality factors are reduced.

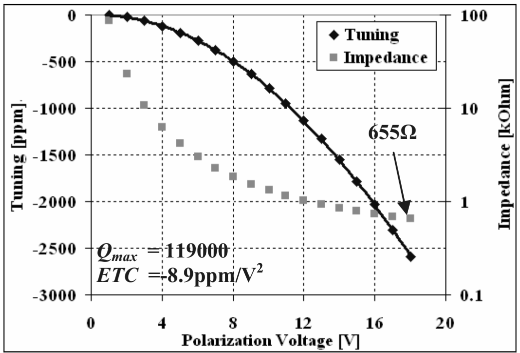

Figure 7: Impedance and tuning of the 6MHz I^3 resonator with 200nm gaps

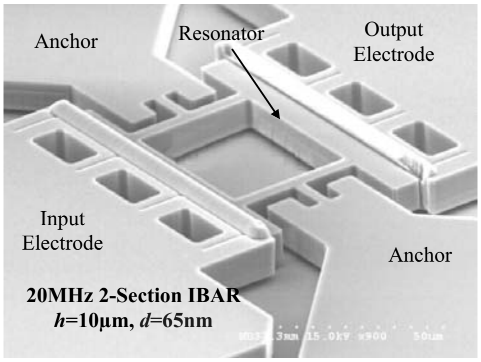

Figure 8: SEM of a 20MHz 10µm thick 65nm gap IBAR

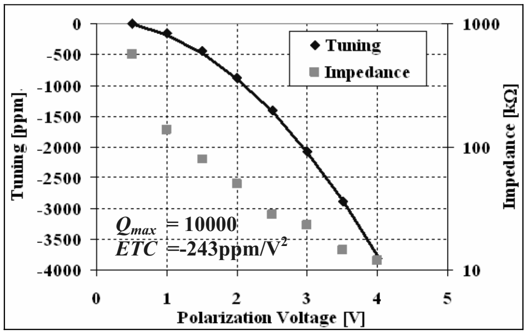

Figure 9: Impedance and tuning of a 10MHz IBAR with 65nm gaps at 1Torr

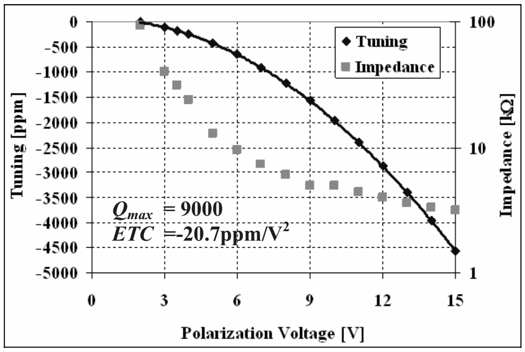

Figure 10: Impedance and tuning of a 20MHz IBAR with 65nm gaps at 1Torr

4. INTERFACE IC DESIGN

The interface IC consists of a trans-impedance amplifier to sustain oscillations and an automatic level control (ALC) circuit to control power input to the resonator (Fig. 1). Level control is accomplished by detecting the amplitude of oscillations, comparing it to a reference voltage, and using the difference to control the gain of a feedback MOS resistor [2]. The reference voltage used for comparison is dependent on the power handling of the resonator.

The temperature compensation circuit (Fig. 2), comprises of band-gap and PTAT voltage generators that feed low-power scaling and difference amplifiers. The coefficients A and B of (2) are adjustable using different gain-setting resistors in the amplifiers to accommodate tuning characteristics of different resonators.

Since the V_P tuning characteristic is approximately parabolic, a square-root generator is required for accurate temperature compensation. This function is provided by the simple square-law relation between the drain current and the V_{GS} of a MOS transistor biased above V_T. The last stage of the difference amplifier is designed to be a transconductance stage that feeds a PTAT current I_{PTAT} into a square-rooting circuit. The square-rooting circuit generates a voltage proportional to the square-root of the current thus providing the required temperature coefficient.

A charge pump voltage multiplier steps up the generated voltage to a maximum of 25V. A Dickson type charge pump was preferred in this implementation to obviate the need for high voltage transistors. The change in the temperature slope arising from the charge pump diodes is also accounted for while choosing the gain-setting resistors for the PTAT amplifier.

5. OSCILLATOR CHARACTERIZATION

To characterize the performance of IBAR oscillators, a two-section 6MHz IBAR (similar to the resonator in Fig. 4) was interfaced with the IC. The 6MHz oscillator exhibited a temperature variation of only 39ppm over 100ºC with parabolic TC (Fig. 11) – an improvement of 72X over the uncompensated drift (Table 1). This is also an improvement of 8.5X over the linear compensation circuit reported earlier [1, 2]. Measurements below room temperature were avoided due to problems with vapor condensation on the unpackaged resonators. It is estimated that the curvature of the band-gap and the PTAT generators account for almost 25ppm in error and can be minimized with curvature correction techniques. The remaining error is a result of the non-linearity in the square-root generator, the TC mismatch in the charge pump diodes, and inaccuracies in setting A and B.

The phase noise of the oscillator (Fig. 12) was measured with an Agilent E5500 phase noise analyzer. The resonator was biased at 5V for this experiment to minimize Q-loading. At 100Hz offset, the phase noise is a mere -90dBc/Hz, largely a result of the exceptionally high quality factor. The far-from-carrier phase noise of the oscillator with ALC was -135dBc/Hz and is limited by the power handling limit of the resonator.

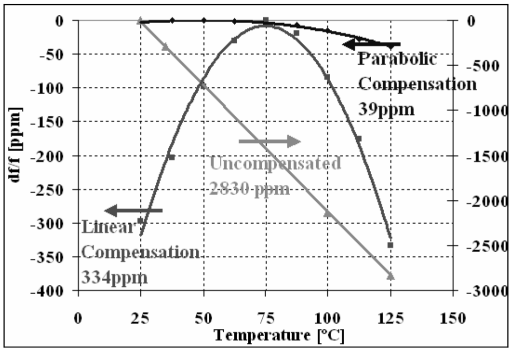

Figure 11: Temperature dependence of the 6MHz I^2 resonator. Stability improved 72X with parabolic TC

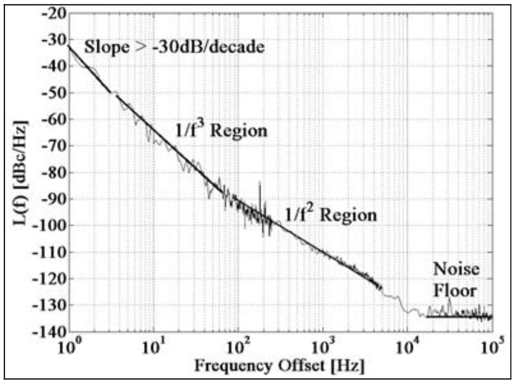

Figure 12: Phase noise of the 6MHz IBAR oscillator. PN far from carrier is -135dBc/Hz.

Table 1: 6MHz IBAR Oscillator Specifications

Resonator Specifications	
Open loop quality factor	
1V bias	112000
10V bias	54000
Tuning coefficient	-7.34ppm/V^2
Circuit Specifications	
Amplifier GBW product	175MHz
Charge pump clock	1MHz
Ripple filter -3dB freq.	1kHz
Total power consumption	
w/ linear compensation	1.8mW
w/ parabolic compensation	**1.9mW**
Die area (for either IC)	2.25mm^2
Oscillator Specifications	
Freq. stability over 100ºC	
Uncompensated	2830ppm
w/ linear compensation	334ppm
w/ parabolic compensation	**39ppm**
Phase Noise performance	
10Hz offset	-66dBc/Hz
1kHz offset	-112dBc/Hz
Phase noise floor	-135dBc/Hz

The interface circuit was fabricated in a 2P3M 0.6µm CMOS process and the die picture is shown in Fig. 13. The power consumption for sustaining oscillations and temperature compensation was only 1.9mW.

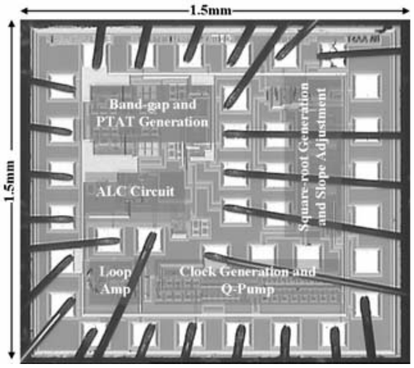

Figure 13: Die picture of the interface IC with ALC loop amplifier and parabolic temperature compensation circuitry

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6. CONCLUSIONS

The work demonstrated an electronically temperature compensated 6MHz IBAR oscillator. A technique for improving temperature stability over prior art was identified and implemented using standard CMOS electronics. The *Q* and the tuning of the resonator have been maximized for optimal phase noise and temperature compensation. Temperature stability of 39ppm over 100°C was achieved for a 6MHz oscillator. Proposed techniques for extending the frequency range and further reduction in power consumption have been described. Also, the limiting factors for temperature stability with V_P correction have been identified.

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