A 1.5GHz CMOS/FBAR Frequency Reference with ±10ppm Temperature Stability

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***Abstract*—A temperature compensated 1.5GHz FBAR-based frequency reference implemented in a 0.35μm CMOS process is presented. The ultra-small form factor and low power dissipation of a temperature compensated FBAR oscillator presents a promising alternative for replacement of quartz crystal frequency references. The measured frequency post-compensation drift over a 0-100°C temperature range is <20ppm. The measured phase noise is -125dBc/Hz at 100 kHz offset from carrier. The overall system power consumption is 960μW.**

I. Introduction

Even a cursory glance at different existing electronic applications highlights the need for a clock source in every system. Quartz-tuned oscillators are the industry standard for portable clock applications. Owing to their very high frequency accuracy, low frequency drift with temperature and low noise, quartz oscillators dominate the commercial market for clock applications. But while the density of electronics has grown exponentially as predicted by Moore's law, the physical size of the quartz crystal has not scaled accordingly. Shown in Fig. 1 is a wireless sensing node module, and it is apparent that the physical size of quartz crystal has become comparable to integrated electronics. For miniaturized wireless systems, there is need for a quartz alternative that has a small form factor while providing integration possibilities with commercial CMOS processes.

This work presents a temperature compensated 1.5GHz Film Bulk Acoustic wave Resonator (FBAR)-based frequency reference with 20ppm frequency drift over 0-100°C. Other quartz alternatives are briefly discussed in section II. Section III provides design considerations for a temperature compensated FBAR/CMOS frequency reference, followed by the measurement results for our FBAR-based frequency reference in section IV.

II. Quartz Alternatives: Design Challenges and Choices

One of the biggest challenges for any quartz alternative is frequency drift over temperature. The operating frequency range for quartz oscillator varies from a few kHz to tens of MHz, while exhibiting better than 50ppm frequency drift over temperature without any electrical compensation. For high precision applications like cellular systems (with <10ppm specifications), the quartz oscillators are also temperature compensated. However, there are also applications like (USB, S-ATA) which can tolerate as much as a 300ppm frequency drift

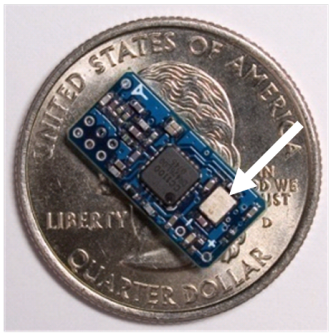

Fig. 1. Wireless sensor node

over a given temperature range. Presently, there are mainly two commercially available quartz alternative technologies that target electronic systems with relaxed specifications:

1) All-CMOS LC Oscillators: This alternative uses LC tuned oscillator in silicon CMOS process operating at high frequency, which is then divided down below 100MHz for clock applications [1]. Electrical compensation is used for canceling PVT variations of the LC oscillator.
2) Silicon MEMS Oscillators: This alternative uses a module comprising a silicon MEMS oscillator operating at low frequency (generally in the kHz range) and a fractional phase locked loop (PLL) to multiply and obtain a programmable clock in the MHz range.

While both of the above-mentioned quartz alternatives provide miniaturized options, they still do not meet requirements of low power wireless systems like Bluetooth, WiFi etc. This work explores another quartz alternative possibility: utilizing an FBAR-tuned oscillator for frequency reference generation. Native FBAR oscillators have demonstrated superior power/phase-noise performance compared to integrated CMOS LC oscillators [2] [3]. However, they show approximately -30ppm/°C temperature dependency. Mechanically-compensated FBAR oscillators have shown immense improvement in reducing the frequency drift over temperature (approx. 100ppm across 100°C), while still maintaining good power/phase-noise characteristics [4]. Without any electrical compensation, these FBAR oscillators provide comparable performance to other two alternatives for use as a clock in electronic systems with relaxed specifications. As explained

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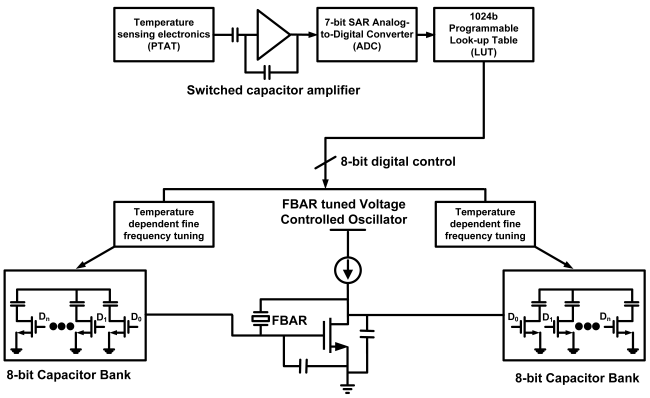

Fig. 2. FBAR-based Frequency Reference

in the following section, we further electrically compensate our FBAR-tuned CMOS oscillator to minimize frequency drift over temperature.

III. FBAR/CMOS Frequency Reference

The block-level diagram of a FBAR-based frequency reference is shown in Fig. 2. Similar to frequency stabilization efforts that are commonly used for quartz crystal references [5], we can address temperature instability using an on-chip real time temperature calibration of FBAR-tuned oscillator. The on-chip temperature calibration using a discrete switched capacitor array is performed as a three step process:

1) Sensing and amplifying temperature variations: This is accomplished by a combination of PTAT temperature sensor and a precision switched capacitor amplifier.
2) Digitizing temperature variations: A 7-bit low power successive approximation register (SAR) ADC digitizes the output of an on-chip switched-capacitor absolute temperature sensor. This digitized temperature reading addresses an integrated programmable 1024b look-up table (LUT).
3) Fine frequency tuning using a lookup table (LUT): A pre-stored temperature compensation profile is stored in an on-chip SRAM. The ADC addresses the LUT as the temperature changes, resulting in an appropriate frequency correction capacitor setting. The contents of the LUT controls an 8-bit binary weighted capacitor array with an LSB step size of 0.7ppm, allowing completely self-contained temperature compensation.

A. Sub-mW FBAR oscillator design

The Pierce oscillator topology is known for its frequency stability. The capacitor loading for the resonator in Pierce topology is grounded on one side, making the design simple and less susceptible to bias current variations. This work demonstrates an FBAR-tuned pierce oscillator at 1.5GHz carrier frequency, with 8-bit capacitor switch bank for fine frequency temperature calibration. It is important to maintain monotonicity of capacitor trimming bank, used for frequency

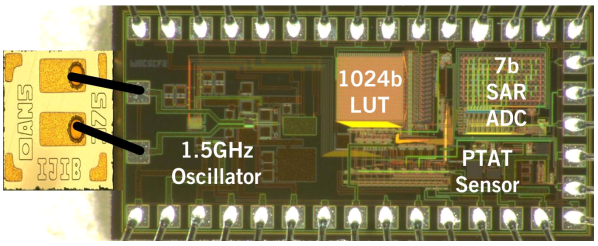

Fig. 3. Chip micrograph of FBAR/CMOS frequency reference

variation cancellation over temperature. The frequency sensitivity to capacitor change for FBAR-tuned oscillator is given by (1), providing a roughly linear frequency variation for small values of capacitor pulling.

$$\frac{\delta f_{osc}}{\delta C_T} = f_{series}\frac{-C_x}{2C_T^2} \quad (1)$$

In order to achieve good linearity for frequency tuning, this design uses discrete switching of minimum size MOS capacitors for unit capacitor to obtain sub-ppm frequency accuracy. The total tuning range using a 8-bit capacitor bank is 200ppm.

B. Temperature readout circuitry

The temperature readout circuitry consists of an analog PTAT sensor, a switched capacitor analog amplifier, and a 7-bit SAR ADC. The design of the temperature sensor is based on switching ratioed current through a single diode [6]. This approach eliminates area matching constraints for the temperature sensing diode, reducing noise in the temperature readout. As a continuous readout is not required, a switched capacitor amplifier is used to amplify analog readout voltage before sampling and digitizing with the ADC. A SAR ADC architecture is chosen for its ultra-low power operation capability. The temperature readout circuitry, as well as 1024 bit LUT uses a 20kHz system clock. This clock can be derived from the free-running FBAR-tuned oscillator.

IV. Performance

The system was implemented in a 0.35µm CMOS process with die size of 0.79mmx1.72mm. The FBAR is wirebonded with CMOS chip, and the micrograph of assembled system is shown Fig. 3. The measurement setup for this prototype is shown in Fig. 4, and it can be classified in two modes. In the Calibration mode (Fig. 4(a)), the temperature profile of the free-running FBAR oscillator is measured. Using this information, software processing in MATLAB generates a complementary calibration code for real-time temperature correction. After the calibration code is programmed into on-chip 1024b LUT, the measurement is run in Free-running mode (Fig. 4(b)).

Fig. 5 shows the measured output of the FBAR oscillator for three different samples, with compensation ON and compensation OFF. When the compensation circuitry is turned off, a frequency drift of approximately 100ppm is measured over

TABLE I
PERFORMANCE SUMMARY OF FBAR/CMOS FREQUENCY REFERENCE

Parameter	
Operating Frequency	1.5GHz
Silicon Die Area	0.79mmx1.72mm
Temperature range	0-100$^{\circ}C$
Frequency drift (ppm) vs Temperature	20 (Compensation ON), 100 (Compensated OFF)
Power Consumption (μW)	
Oscillator	950
PTAT+ADC+LUT	10
Phase noise (dBc/Hz) @10kHz offset	-125

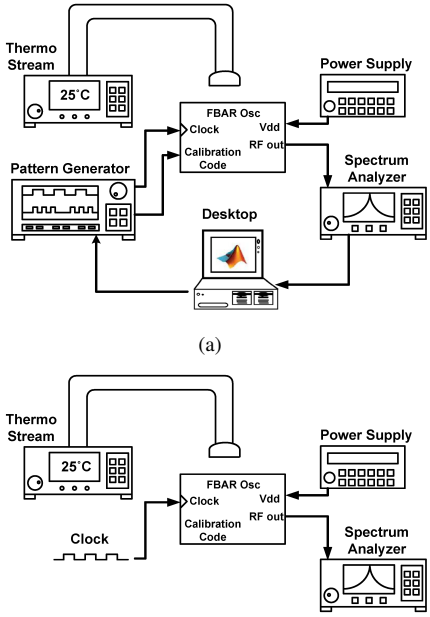

Fig. 4. Measurement setup in (a) Calibration mode, (b) Free-running mode.

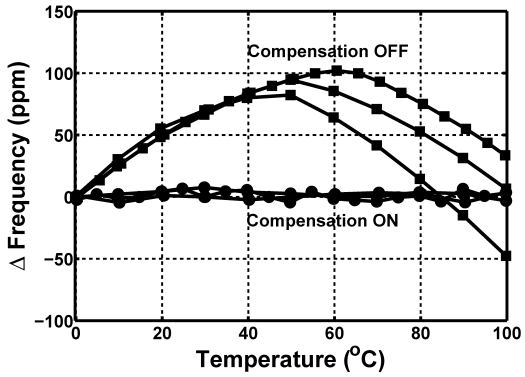

Fig. 5. Frequency drift over temperature for three samples with compensation OFF (▪), compensation ON (●)

a 100$^{\circ}C$ temperature range. The frequency drift is reduced to <20ppm post-compensation without any averaging in the measurement. In a separate setup, the data points were collected continuously for a transient temperature ramp and the frequency error remains below 20ppm post-compensation. The frequency error can be further reduced to less than 10ppm by averaging the temperature readout in the digital domain. The performance summary for the FBAR/CMOS frequency reference is tabulated in Table. I. The FBAR oscillator consumes 950μW and has a measured phase noise of -125dBc at a 100kHz offset. The ultra-low power on-chip temperature calibration circuitry consumes less than 10μW.

V. CONCLUSION

Mechanically-compensated FBAR-tuned oscillators show potential for quartz replacement in applications requiring <100ppm frequency drift over temperature. Further electrical compensation is needed for a quartz-free miniaturized FBAR frequency reference for wireless applications needing <20ppm. This work demonstrates a 1.5GHz FBAR/CMOS low power frequency reference with low-temperature sensitivity for wireless applications. Divided frequencies in the range of 10-150MHz can be used for quartz replacement in miniaturized electronic systems.

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