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HBAR-Based 3.6 GHz Oscillator with Low Power Consumption and Low Phase Noise

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***Abstract*—We have designed and built 2 oscillators at 1.2 and 3.6 GHz based on high-overtone bulk acoustic resonators (HBARs) for application in chip-scale atomic clocks (CSACs). The measured phase noise of the 3.6 GHz oscillator is −67 dBc/Hz at 300 Hz offset and −100 dBc/Hz at 10 kHz offset. The Allan deviation of the free-running oscillator is 1.5 × 10^{-9} at one second integration time and the power consumption is 3.2 mW. The low phase noise allows the oscillator to be locked to a CSAC physics package without significantly degrading the clock performance.**

I. Introduction

An atomic clock provides an extremely stable periodic signal that is based on a narrow electromagnetic transition in an atom. Often, microwave transitions of alkali atoms, typically rubidium and cesium, are used. The goal is to provide frequency or timing information that is stable over long averaging times. To date, the smallest commercially available atomic clocks occupy approximately 100 cm^3 of space and consume approximately 5 W of power. The combination of coherent population trapping (CPT) and microelectromechanical systems (MEMS) fabrication technology has led to the recent development of chip-scale atomic clocks [1], which are expected to achieve the stability of commercially available atomic clocks with a small fraction of the size and power consumption. Applications include improvements in secure digital communications and jam-resistant global positioning system receivers [2], [3]. Passive atomic frequency references typically include a physics package, a local oscillator (LO), and control electronics [4]–[6]. The signal generated by the local oscillator is sent to the physics package, which provides an output that depends on the difference between the LO frequency and the natural resonant frequency of the atoms. Control electronics lock the LO frequency to the atomic resonance, resulting in improved long-term frequency stability. The short-term frequency stability of the working atomic clock depends at some level on the stability of the unlocked LO. Thus, the local oscillator must run with excellent short-term frequency stability at a frequency equal to the atomic transition frequency or, in the case of CPT clocks, a subharmonic (typically the first subharmonic at 3.417 GHz or 4.596 GHz for ^{87}Rb or ^{133}Cs, respectively).

The frequency stability of an oscillator can be characterized by its single-sideband phase noise, $L\{f_m\}$. Leeson's equation [7] shows that low phase noise operation can be achieved by increasing the loaded quality factor Q_{load} of the resonator. The formula that describes the single-sideband phase noise is

$$L\{f_m\} = 10\log\left[\left\{1+\frac{f_o^2}{\left(2f_m Q_{\text{load}}\right)^2}\right\}\left\{1+\frac{f_c}{f_m}\right\}\frac{FkT}{2P_s\left(1-Q_{\text{load}}/Q_0\right)}\right], \tag{1}$$

where P_s is the circulating signal power level; f_0 is the nominal oscillation frequency; f_c is the offset corner frequency at which flicker noise begins to dominate; f_m is the offset frequency; Q_0 is the unloaded quality factor of the resonator; F is the_amplifier noise factor; and $kT = 4.1 \times 10^{-21}$ J at 300 K. According to Leeson's model, a higher resonator quality factor (Q) or circulating power level improves the phase noise and, therefore, the short-term stability of the oscillator.

To date, local oscillators designed for CSAC have used either ceramic coaxial resonators [8] or film bulk acoustic resonators (FBAR) [9], due to the small size and relatively high Q of these resonators. Table I summarizes the recent achievements from these groups.

The coaxial ceramic resonators and thin film bulk acoustic resonators have loaded Q factors that are typically between 100 and 500 at frequencies between 3 GHz and 5 GHz. These modest values can lead to unsatisfactory short-term frequency stabilities. Thus, resonators with higher Q have been sought for CSAC local oscillators.

At frequencies of several gigahertz, high-overtone bulk acoustic resonators (HBAR) currently give the highest Q factors [10] among small devices suitable for use in chip-scale atomic clocks. In this letter, HBAR-based oscillators with Pierce and Colpitts topologies are described. The Colpitts oscillator is based on a 1.2-GHz HBAR with an unloaded Q of 25 200.[1] The resonator's Q is calculated

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[1] The loaded Q of the overall oscillator is not this high; better coupling of the resonator to the rest of the oscillator circuit will give better phase noise that is more consistent with such a high Q.

TABLE I. Recently Developed Local Oscillators for Chip Scale Atomic Clock (CSAC).

Reference	Resonator used in Oscillator	Allan deviation (free running oscillator)	Allan deviation (locked oscillator)	Phase noise of oscillator (at 300 Hz offset)	DC power consumption of oscillator
[8]	Coaxial ceramic resonator at 3.4 GHz	3.8×10^{-8}	2.4×10^{-10}	−55 dBc/Hz	2 to 3 mW
[9]	Film Bulk Acoustic Resonator at 4.6 GHz	6.5×10^{-9}	N/A	−53 dBc/Hz	7.6 mW

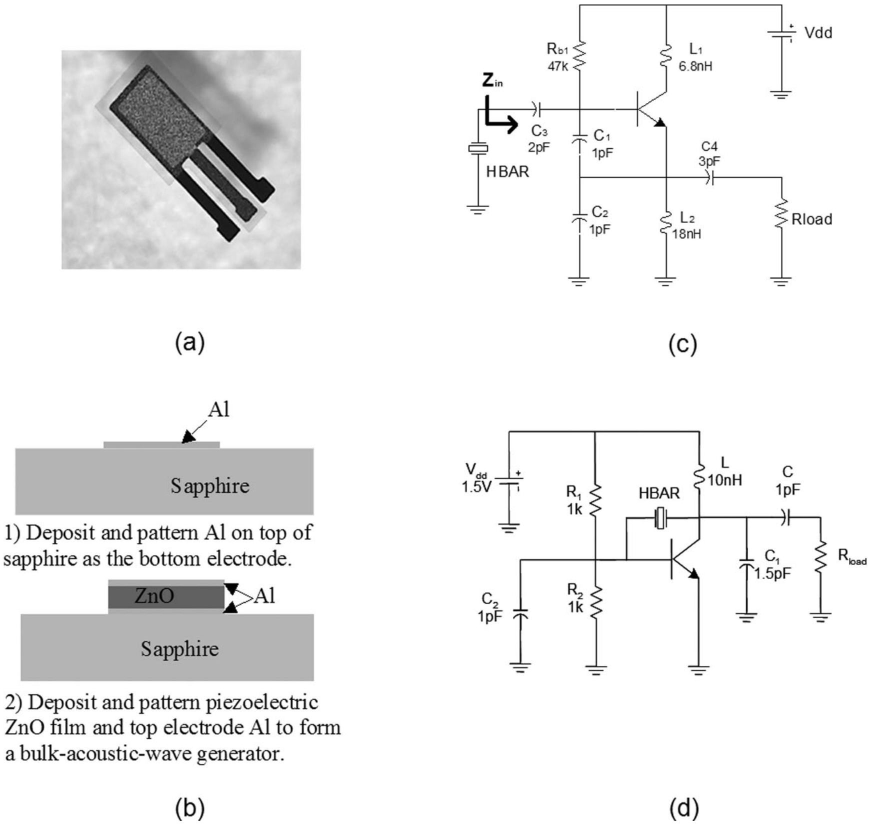


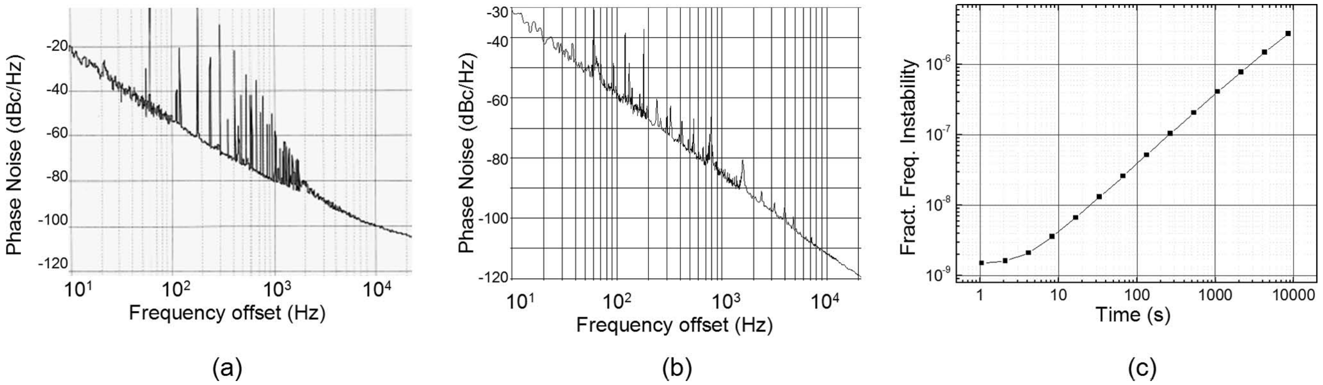
Fig. 1. (a) Photo of a fabricated HBAR; (b) fabrication process for the HBAR; (c) circuit schematics of the 1.2-GHz Colpitts oscillator; and (d) circuit schematic of the 3.6-GHz Pierce oscillator.

by $Q = (f/2)(d\Phi_z/df)$, where f and Φ_z are the frequency and the phase of the HBAR impedance, respectively. This oscillator consumes only 8 mW of dc power, and the measured phase noise is −73 dBc/Hz at 300 Hz offset. The Pierce oscillator is based on a 3.6-GHz HBAR with an unloaded Q of 19 000. This oscillator consumes only 3.2 mW and the measured phase noise is −67 dBc/Hz at 300 Hz offset. For the latter oscillator, the measured Allan deviation under free-running conditions is 1.5×10^{-9} at one second of integration time.

II. Device and Circuit Design

Figs. 1(c) and (d) illustrate the top-view photo and fabrication process of the HBAR, which is typically built on a crystalline substrate that is a few hundred micrometers thick with a submicrometer thick piezoelectric film layer covering an area approximately 100 × 100 μm. The piezoelectric film generates acoustic waves propagating into the substrate. The Q is dominated by the acoustic property of the thick substrate, with most of the acoustic energy being stored in the substrate. An HBAR made on a sapphire crystal often has a Q greater than 15 000 up to 5 GHz. The HBARs fabricated for the oscillators reported here have structures of 0.10 μm Al/0.88 μm ZnO/0.10 μm Al/400 μm sapphire (for 3.6-GHz HBAR) and 0.10 μm Al/2.2 μm ZnO/0.10 μm Al/400 μm sapphire (for 1.2-GHz HBAR), and are measured to have a Q of 25 200 and 19 000 at 1.2 GHz and 3.6 GHz, respectively. The temperature coefficient of the resonant frequency is measured on a hot chuck to be −28.5 ppm/°C for both HBARs.

Figs. 1(b) and (c) show the schematics of the Colpitts and Pierce oscillators using silicon bipolar junction transistors (BJT) that typically present better flicker noise characteristics than FETs. A copper-coated printed-cir-



(a) (b) (c)

Fig. 2. Phase noise measurement data of (a) the 3.67-GHz Pierce oscillator and (b) the 1.2-GHz Colpitts oscillator. (c) Allan deviation of the free-running 3.67-GHz oscillator that consumes only about 3 mW.

cuit board (PCB) is patterned by photolithography, and is etched to form a circuit board for an HBAR-based oscillator.

III. Measurement Results

The phase noise and Allan deviation of each free-running oscillator were measured with a TSC 5120A phase noise test set (Timing Solutions, San Jose, CA)[2], after the signal is down-converted to the required frequency range of the test set, which is between 1 MHz to 30 MHz. The reference frequency comes from a frequency synthesizer that is externally referenced to a hydrogen maser. Figs. 2(a) and (b) show the measured phase noise data for the 3.67-GHz Pierce oscillator and the 1.2-GHz Colpitts oscillator, demonstrating outstanding close-in performance between offsets of 10 Hz and 100 kHz. The noise spikes have negligible impact on the Allan deviation and are due mostly to 60 Hz power and harmonics, and other noise sources in the lab. The measured phase noise of the 3.67-GHz oscillator is −67 dBc/Hz and −100 dBc/Hz at 300 Hz and 10 kHz offsets, respectively, while the device consumes only 3.2 mW with output power of −15.37 dBm. The 1.2-GHz oscillator has phase noise of −73 dBc/Hz and −112 dBc/Hz at 300 Hz and 10 kHz offset, respectively, with only 8 mW power consumption and output power of −8.83 dBm.

The Allan deviation of the free-running oscillator at integration times of less than one second is of high importance, as it largely determines the short-term stability of the atomic clock. The measured Allan deviation, in Fig. 2(c), shows that the HBAR-based oscillator at 3.6 GHz has an Allan deviation of 1.5×10^{-9} at one second, better than any reported near the CSAC frequency with the power consumption less than 5 mW.

To demonstrate that the HBAR-based oscillator stability was sufficient for application to atomic clocks, the oscillator was used as the local oscillator in a table-top atomic clock experiment based on coherent population trapping. This table-top experiment consisted of a vertical-cavity surface-emitting laser, an alkali vapor cell containing Rb and a buffer gas and a photodetector [11]. The injection current of the VCSEL was modulated with a signal synthesized from the HBAR oscillator output and the CPT resonance measured by the change in the laser power transmitted through the vapor cell was used to lock the oscillator frequency to the atomic transition.

Because the HBAR oscillator frequency could not be tuned to the first subharmonic of the atomic hyperfine frequency, the oscillator output was mixed with a second signal of approximately 200 MHz generated by a synthesizer. This moved the output frequency to near the atomic transition after the unwanted frequencies were filtered out. The HBAR oscillator could be successfully locked to the CPT resonance and the measured Allan deviation under these conditions was 1.5×10^{-10} at an integration time of one second.

IV. Summary

Oscillators based on high-overtone bulk acoustic resonators are shown to present outstanding performance at gigahertz frequencies. The resonators' extremely high Q produces the oscillators' ultra-low fractional frequency instability (Allan deviation) and very low phase noise. The Allan deviation of the 3.6 GHz free-running oscillator is 1.5×10^{-9} at 1 s, while the oscillator locked to a table-top physics package is stable to 1.5×10^{-10} at 1 s. These measurements, combined with the oscillators' small size and very low power consumption, show that an HBAR oscillator can be a useful alternative to existing oscillators for chip-scale atomic clocks.

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[2] The identification of this part is provided for technical clarity and does not imply endorsement by NIST. Other equipment may work as well or better.

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