A CMOS Molecular Clock Probing 231.061-GHz Rotational Line of OCS with sub-ppb Long-Term Stability and 66-mW DC Power

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Abstract

Recent progress of on-chip spectroscopic systems enables a new set of highly-stable frequency references (i.e. clocks) with low cost, power and volume. It is based on the rotational spectrum of gaseous molecules in sub-THz regime, a physical mechanism alternative to that in traditional atomic clocks. This scheme also enables fast start-up operation and robustness against mechanical vibration and external electromagnetic fields. This paper demonstrates the first chip-scale molecular clock in 65nm CMOS which probes the 231.061GHz spectral line of Carbonyl Sulfide (\(^{15}\text{O}^{32}\text{C}^{32}\text{S}\)). The clock consumes only 66mW DC power and has a measured Allan deviation of \(3.8 \times 10^{-10}\) with an averaging time of \(r=10^3\)s.

Introduction

Stable frequency references are critical for equipment used in navigation, communication and sensing. The widely adopted mechanical-resonance oscillators, such as crystal oscillator and MEMS oscillator, suffer from long-term frequency drifts due to external disturbances (vibration, temperature change, etc.) and aging. By optically probing the invariant electron transition of atoms, an atomic clock significantly improves the long-term stability. Chip-scale atomic clock (CSAC) further achieves clock miniaturization using coherent population trapping (CPT) [1, 2], but has exceedingly high cost and hence limited applications. Here, we show that sub-THz rotational spectral lines of gaseous molecules are a promising set of timebase for portable clocks. Compared to cesium (Cs) atomic clocks, our selected OCS molecular spectral line does not require the slow and power-consuming heaters for alkali evaporation, and is by nature less sensitive to external electromagnetic fields (e.g. Zeeman-shift coefficient is 98ppt/Gauss for OCS at 231.060983GHz and 150ppb/Gauss for Cs at 9.1926GHz). Thus, lower power, instantaneous start-up and better long-term stability are enabled. Its absolute linewidth \(100-1000\) larger than that in CSACs also leads to a high clock loop bandwidth of \(~100\) kHz, providing error corrections under rapid mechanical vibration. More importantly, this scheme, combined with recent progress in on-chip THz spectrometers [3], allows for clock implementation on low-cost silicon chips without any electro-optical assembly needed in atomic clocks. In this paper, we report the first molecular clock using a 65nm CMOS technology.

Architecture of Molecular Clock

The CMOS molecular clock is illustrated in Fig. 1. A rotational spectral line of OCS near \(f_0=231.060983\)GHz is chosen. The OCS gas with 5-Pascal pressure is held inside a WR4.3 waveguide gas cell, the length (L=140mm) of which is optimized for maximum spectroscopic signal-to-noise ratio (SNR) [4]. Fig. 1 also presents the measured spectral profile with a quality factor of \(Q=2.6 \times 10^2\). The Tx probing signal \((f_\text{c} \approx 231.061\)GHz) is FSK-modulated (modulation frequency \(f_\text{m} = 16\)kHz and frequency deviation \(\Delta f = 1\)MHz) and detected by a square-law detector in Rx. The intensity of two sidebands of the FSK signal is shaped by the absorption line profile, and any frequency offset \((f_\text{c} - f_0)\) leads to absorption imbalance and causes envelope fluctuation (at \(f_\text{m}\)) of the detector output. A feedback error voltage is then generated, which indicates the sign and magnitude of the frequency offset. After amplification and low-pass filtering, it is fed into a voltage-controlled crystal oscillator (VCXO) in the Tx to establish a dynamic frequency compensation for its 80-MHz output.

Probing Signal Generation and Detection on CMOS

Fig. 2 shows the Tx including a 224-242GHz fractional-N phase-locked loop (PLL). The sub-THz signal is extracted from a frequency quadrupler chain, which utilizes the nonlinearity of MOSFETs driven by a 57.8GHz harmonic oscillator. A 40-bit MASH 1-1-1 \(\Delta\Sigma\) modulator enables \(ppt\)-level frequency tuning resolution. The FSK modulation is performed by periodically changing the control word of the \(\Delta\Sigma\) modulator. The \(f_\text{m}\) and \(\Delta f\) of FSK are selectable with a resolution of 3-bit. Fig. 3 gives the schematic of the Rx. A NMOS transistor biased at sub-threshold is utilized as a square-law power detector. A low-noise folded-cascode op-amp further amplifies the baseband signal. Finally, the error signal is detected by an on-chip lock-in detector, which is referenced to \(f_0\). To couple the probing signal from/into the chips, a pair of custom-designed chip-to-waveguide transitions using quartz probes is implemented. The loop filter is off-chip for post-fabrication adjustments of loop parameters.

Measurement Results

The measured loss of the gas cell is 7.3dB (Fig. 5 (left)). Fig. 5 (right) presents the output spectrum (no FSK) of the Tx at 231.061GHz. The output power including the loss of chip-to-waveguide transition (~10dB) is -20.2dBm (Fig. 6). This power level avoids spectral broadening due to saturation [4]. The measured phase noise is -68.4dBc/Hz with a frequency offset of 1MHz. The measured noise equivalent power (NEP) of the Rx, including the transition loss, is 501pW/Hz\(^{0.5}\) at \(f_\text{m}=16\)kHz (Fig. 6). Fig. 7 shows the packaged CMOS molecular clock as well as the dispersion curve \((V_\text{error} \text{ versus } f_\text{c}-f_0)\) measured by the FSK signal (in an open loop) with a SNR of 53dB. The molecular clock is locked onto the zero-crossing point of the curve. Fig. 8 (left) presents the measured instantaneous frequencies of the closed-loop clock and the free-running VCXO over 4000s. The measured stability (quantified by Allan deviation [5]) reaches \(2.4 \times 10^{-8}\) for \(r=1\)s and \(3.8 \times 10^{-10}\) for \(r=10^3\)s. The suppression factor of VCXO frequency drift is \(\sim 10^5\) through the molecular-clock regulation, and is expected to be higher under large ambient-temperature change. Shown in Table I, the CMOS clock achieves high stability (comparable to that in [1]), faster response (thanks to the much larger absolute linewidth), start-up speed, and significantly simplified construction. Currently, the drift of our prototype is mainly due to the OCS gas leakage of the set up (0.1Pascal/hr), which can be improved with a hermetic package. This, along with improved chip-waveguide transition design with reduced
loss (i.e. ~10× higher SNR), will lead to a predicted stability below $10^{-11}$ ($\tau=10^3$ s) (Fig. 8). The chip consumes 66mW power and the waveguide gas cell has a volume of 5.6cm³.

References

![Fig. 1 System architecture of the molecular clock by probing the 231.061GHz OCS spectral line in a WR4.3 bended waveguide gas cell.](image1)

![Fig. 2 Schematic of the clock Tx with a 40-bit fractional-N PLL.](image2)

![Fig. 3. Schematic of the clock Rx with THz and lock-in detectors.](image3)

![Fig. 4. Photograph of wire-bonded CMOS Tx and Rx chips.](image4)

![Fig. 5. The measured S-parameters of the waveguide gas cell (left) and the output spectrum of Tx at $f_0=231.010$GHz (no FSK) (right).](image5)

![Fig. 6 The measured Tx output power at 224–242GHz (left) and the Rx noise equivalent power (NEP) at 231GHz (right).](image6)

![Fig. 7 Photograph of the packaged CMOS molecular clock (left) and the dispersion curve of the spectral line obtained by the chip (right).](image7)

![Fig. 8 Measured instantaneous frequency w/ and w/o locking (left) and the measured Allan deviation (right) using a Keysight 53230A counter.](image8)

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The power of the VCXO is not included.

2 The power of off-chip heater, laser, and other components is not included.