Improving a Trapped-Ion Quantum Computer with a Cryogenic Sapphire Oscillator

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***Summary*—We report an 8.7-second qubit coherence time in a ytterbium ion ($^{171}Yb^{+}$) using a microwave synthesis system derived from an ultra-low phase noise cryogenic sapphire oscillator (CSO). Our measurement provides evidence that the phase noise of a local oscillator that serves as the master clock plays a significant role in the operation fidelities of a trapped-ion quantum information processor.**

I. Introduction

Individual qubits encoded in the hyperfine ground state of trapped ions benefit from excellent environmental isolation [1-3], providing an attractive platform for numerous applications in quantum technology. However, the coherence of these qubits is not solely limited by the atomic properties but also by the phase noise of the reference local oscillator. Frequency upconversion by a factor of N from a reference at 10 MHz to several GHz leads to the multiplicative phase noise of 20 $\log_{10}(N)$ dB, which can reduce the coherence and quantum gate fidelities. Here, we describe an agile microwave synthesis system derived from an ultra-low phase noise cryogenic sapphire oscillator [4] to generate a 12.64 GHz signal to serve as the master clock for a Yb^{+} hyperfine qubit confined in a Paul trap.

II. Methods/Results

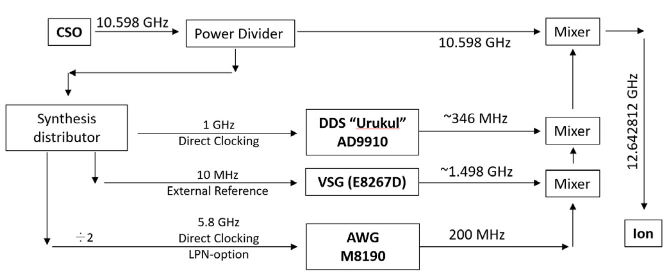

Figure 1. The schematic of a custom-assembled CSO-backed microwave synthesis system to manipulate Yb^{+} hyperfine qubit at 12.6 GHz.

Our system, shown in Fig. 1, provides an ultra-low phase noise microwave signal with a high level of flexibility to implement agile dynamical modulation. The CSO is housed in a closed-cycled cryogenic cooler maintained at 5.3 K. The native CSO frequency is 10.598 GHz. To generate a 12.64 GHz signal to drive qubit transition in Yb^{+} ion, we synthesize and mix four tones as follows. First, the native CSO signal is divided into two with one signal injected into a "synthesis distributor" (SD) to produce ultra-low phase-noise signals at 10 MHz, 1 GHz, and 11.6 GHz through a series of phase-lock loops and frequency conversions [5]. Second, we downconvert an SD-generated 11.6 GHz signal to 5.8 GHz and use this signal to directly provide the clocking signal through a low phase noise option of a Keysight M8190 arbitrary waveform generator (AWG). We fix the AWG output frequency at 200 MHz. Third, we use the SD-generated 1 GHz signal to provide the clocking signal for a direct digital synthesizer (DDS) (ARTIQ Sinara "urukul") based on the Analog Device AD9910 chip; we disable the phase-lock loop typically used to generate a desired clocking signal with an input reference signal at a low frequency. The nominal output frequency of the DDS is approximately 346 MHz. Fourth, a 10 MHz signal generated by SD is used to provide an external frequency reference for a Keysight E8267D vector signal generator (VSG). The VSG produces a 1.498 GHz signal. Finally, we mix these three signals with a native non-adjustable CSO signal to produce a 12.6 GHz signal.

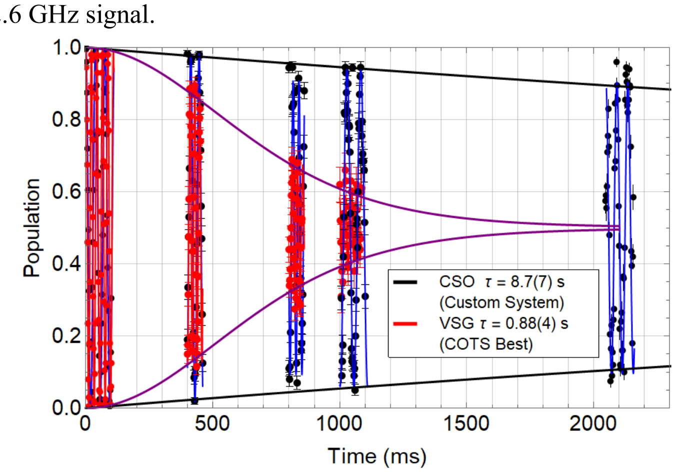

Figure 2. Population oscillations measured in Ramsey experiments (no echo pulses) with (i) a CSO synthesis system and (ii) a VSG externally referenced to a 10 MHz signal produced by an SRS FS725 Rb standard. In both cases, we deliberately detune the microwave frequencies from qubit resonance to expose coherent oscillations as a function of the Ramsey wait time. The black curve is a fit to determine the coherence time of 8.7(7) seconds when driven with a CSO synthesis system. The purple curve is determined by a no-free-parameter analytical solution [6] with the VSG's phase noise shown in Figure 3.

We benchmark the Yb^+ qubit coherence time with the CSO-derived synthesis system against a VSG referenced to rubidium (Rb) frequency standard at 10 MHz. Figure 2 shows the observed population as a function of the variable wait time in a Ramsey sequence. We determine the Yb^+ coherence time when driven by a CSO synthesis system to be 8.7(7) seconds, a 10-fold improvement compared to an Rb-referenced VSG system. We analyze the decay of the Ramsey contrast of the VSG-driven system using a transfer function approach that connects the oscillator's phase noise, shown in Fig. 3 to qubit's dephasing [6]. We find good agreement between analytically predicted behavior and experimental measurement (purple curve in Fig. 2).

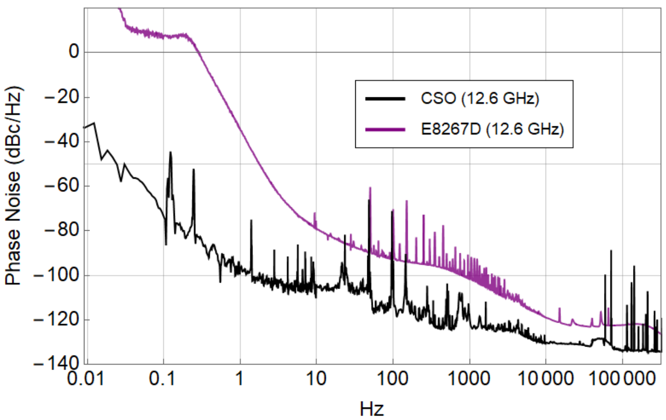

Figure 3. Single-sideband (SSB) phase noise of 12.6 GHz signals derived from (i) a CSO-backed microwave synthesis system and (ii) a vector signal generator (manufacturer: Keysight, model: E8267D) referenced to a rubidium frequency standard (SRS FS725).

III. Conclusions

Our result provides concrete evidence that the phase noise of a local oscillator plays a direct and significant role in the coherence time of a trapped-ion qubit. Furthermore, using a custom-assembled CSO-driven microwave synthesis system, we improved the coherence time of a Yb^+ hyperfine qubit to 8.7(7) seconds.

References

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