Development of cryogenic sapphire oscillators at HUST

Encai Zhong, J.-M. Le Floch, Hongli Liu, Ke Deng, Jie Zhang, Zehuang Lu
MOE Key Laboratory of Fundamental Physical Quantities Measurement & Hubei Key Laboratory of Gravitation and Quantum Physics, PGMF and School of Physics, Huazhong University of Science and Technology
Wuhan, China
zehuanglu@hust.edu.cn

***Abstract*—Ultra-low phase noise cryogenic sapphire oscillator (CSO) can be used for to cesium fountain clocks, radar and other precision measurement applications. We built two CSOs at Huazhong University of Science and Technology (HUST), which can generate 10.8 GHz high-stability microwave signal. Based on Leeson's model [1], we analyze the phase noise of these two CSOs and develop a suitable model for describing their phase noise performance. By measuring the beat note of the two CSOs we can evaluate their phase noise to be -90 dBc/Hz @ 1 Hz, and the fractional frequency instability is 5×10^{-15}@1 s. According to the phase noise model, we are currently limited by the noise of the detection system due to the limited sapphire Q factor.**

***Keywords*—Cryogenic sapphire oscillator, Phase noise model, Frequency instability.**

I. Introduction

Sapphire has ultra-low loss at cryogenic temperature, which corresponds to a very high Q factor. Based on this property, CSO can generate microwave signal with ultra-low phase noise [2-3]. We plan to use this ultra-stable microwave source as local oscillator for our cesium fountain clock HUST-CsF1 to reduce the Dick effect caused by the local oscillator noise [4]. This work would be performed in the near future by using a fiber link [5] to transmit the signal generated by the CSO to the fountain clock laboratory, as shown in Fig. 1. The transmitted microwave signal will replace the conventional OXCO as the local oscillator of the fountain clock.

II. Experimental Setup

A. Phase noise detection

In order to realize the frequency control of CSO, we adopt the Pound frequency discrimination scheme [6], which can also detect the phase noise of the carrier signal fed into the cryogenic resonator. As shown in Fig. 2, a voltage-controlled phase shifter (VCPn) is used as the generator of phase noise, and another phase shifter VCPm is used to generate 70 kHz phase modulation. The phase transfer function of the system can be measured by comparing the phase noise φ_n produced by VCPn and the error signal of the lock-in amplifier.

B. Control servo

The whole CSO system has three main noise contributions. They are the power fluctuation noise, temperature fluctuation noise from the resonator, and the phase noise introduced by the electronic components. A feedback servo is used to suppress these noises, as shown in Fig. 3.

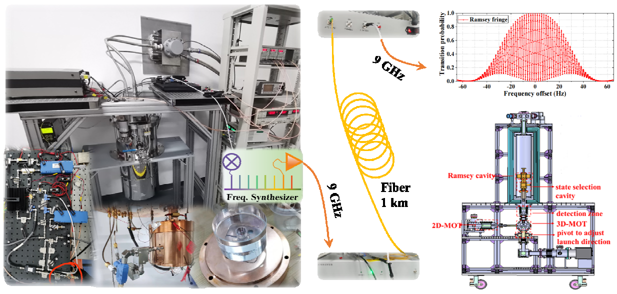

Fig. 1. Use of CSO as the local oscillator for cesium fountain clocks.

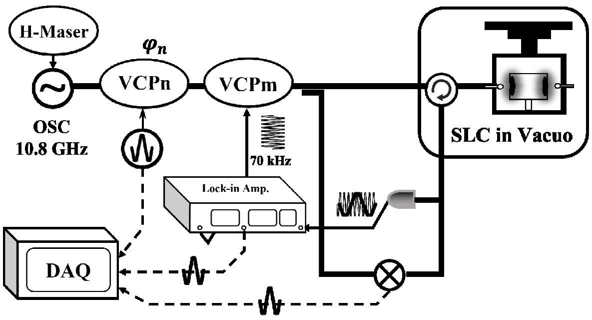

Fig. 2. Phase detection system based on Pound scheme. The temperature of the sapphire loaded cavity (SLC) is near liquid helium temperature at the sapphire resonator frequency temperature turning point (FTTP). A lock-in amplifier is used to demodulate the phase noise when the carrier is resonating with the SLC.

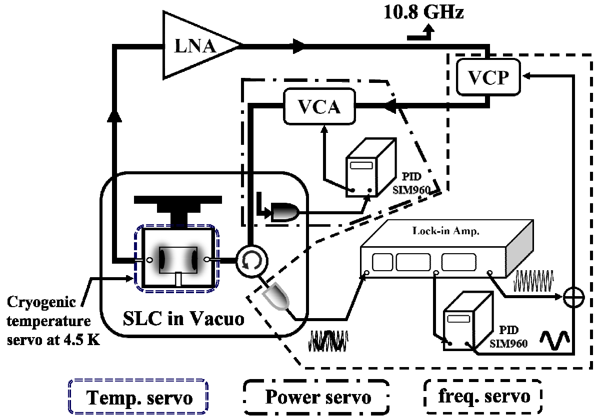

Fig. 3. The arrangement of the entire feedback system.

III. Phase Noise Model

In order to facilitate the analysis of the noise performance of the entire system, we develop a phase noise model, as shown in Fig. 4.

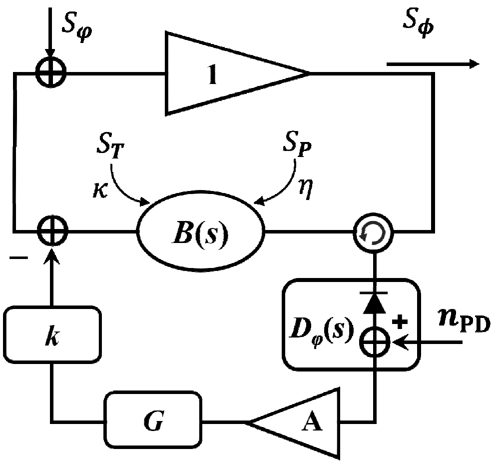

Fig. 4. The oscillator's phase noise model.

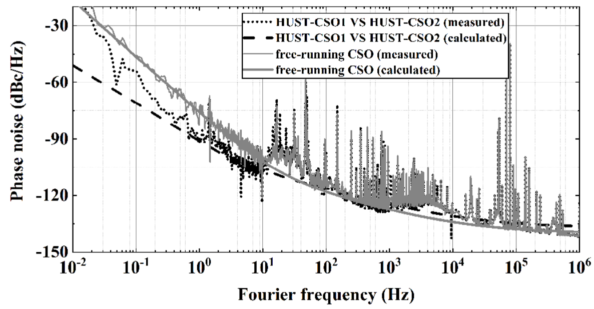

Fig. 5. The measured and calculated phase noise the CSOs when they are free-running or servo locked.

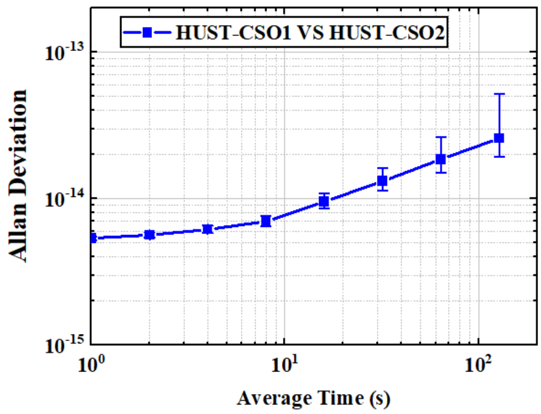

Fig. 6. Allan deviation of the fractional frequency stability of CSOs.

TABLE I. PARAMETERS OF TWO INDEPENDENT CSOS

Items	Expression	Value (Unit)	
		HUST-CSO1	**HUST-CSO2**
Gain of lock-in Amp.	A	46 (dB)	46 (dB)
Frequency discrimination coefficient	$D_v = D_\varphi / f$	11.8 (mV/Hz)	13.3 (mV/Hz)
Sensitivity of phase actuator	k	1.02 (rad/V)	0.63 (rad/V)
Resonant frequency	f_0	10.7885 (GHz)	10.8013 (GHz)
Loaded Q factor	Q_L	4.8E8	3.6E8
Coupling coefficient	β	0.43	0.60
Working temperature	T	4.4 (K)	5.9 (K)
The second derivative of the frequency-temperature fitting curve	κ	1E-9 (K^{-2})	1E-9 (K^{-2})
Power to frequency shift coefficient	η	-0.210 Hz/dB @-4 dBm	0.052 Hz/dB @-10 dBm

In this model, the phase noise S_φ of the amplifier directly contributes to the servo loop noise. The phase response $B(s)$ of SLC is measured using the scheme in Fig. 2. $D_\varphi(s)$ is the detection efficiency of the phase discrimination system, n_{PD} is the additional detector noise. After theoretical analysis, we can express the phase noise of the whole system, as shown in Fig. 4. A properly tuned PI, k and gain A can suppress the relevant noise contributions. For more details, we can refer to Tab. 1, where we recorded the experimental parameters of the two CSOs.

IV. Experimental Results

In order to verify our phase noise model, we carried out simulation and experiment. We take into account the phase noise of the low phase noise amplifier and the detection noise of the frequency discrimination system. Putting the measured noise data into the model, the phase noise of the CSO output signal can be calculated. As shown in Fig. 5, we calculate the contribution of each part of the noise while turning on and off the frequency servo.

We find that the phase noise performance of the free-running CSO and the servo locked CSO is consistent with the developed phase noise model, as shown in Fig. 5. At offset frequencies below 0.3 Hz, the phase noise performance deviates from the model because the fluctuations of temperature and power is not taken into account. The measured phase noise can reach − 90 dBc / Hz @ 1 Hz, as shown in Fig. 5.

We also measured the frequency stability of two CSOs. The beat note of two CSOs is measured by phase noise analyzer (Microsemi 5120A). A fractional frequency instability of 5×10^{-15} @ 1 s is obtained, as shown in Fig. 6. At the moment the phase noise and the fractional frequency instability of our CSOs are limited by the Q factors of the sapphires at around 10^8. It is expected that with a 10^9 level sapphire an instability level of 10^{-16} can be achieved.

Acknowledgment

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