

## 10<sup>-15</sup> Frequency Stability Microwave Synthesizer for Atomic Fountain Frequency Standard

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**Abstract.** This paper presents the design and phase noise measurement of microwave frequency synthesizer for atomic fountain frequency standard. In this synthesizer, a voltage-controlled DRO is locked to 100MHz hydrogen maser signal through a divider chain. The required interrogation frequency 9192631770 Hz is generated by mixed with 7368230 Hz and 400 MHz signals. The experimental results show that the phase noise of interrogation signal at 9.192 GHz is -88dBc/Hz@ offset 1Hz. With such performances, the expected Dick effect contribution to atom fountain frequency standard is reported at a level of 1.0×10<sup>-15</sup> at 1 s integrating time, that is a factor 10 higher than quantum noise limit of atom frequency standard. The carrier spectral spur of microwave synthesizer signal impacted on atomic fountain frequency standard is also discussed.

### Introduction

Atomic fountain standard provides the most accurate realization of the SI second and define the accuracy of the widely used international atomic time (TAI)[1-2]. In the cesium atomic fountain standard, the microwave-atom interrogation process is periodic. The frequency of LO oscillator is compared to that of the atomic frequency during a part of duration of the whole operating period( $T_c$ ) only[3-5]. This effect, first presented by Dick[6-9], lead to the frequency noise of LO oscillator at multiples of  $T_c$  is down-converted to atom frequency standards. It is shown that frequency instability of atom clock will degrade.

The limitation of the short-term frequency stability for the cesium atomic fountain clock, which is locked LO, is related to the relative frequency fluctuation spectral density of the free running oscillator[8]:

$$\sigma_{y\text{lim}}^2(\tau) = \frac{1}{\tau} \sum_{m=1}^{\infty} \left( \frac{g_m^{c2}}{g_0^2} + \frac{g_m^{s2}}{g_0^2} \right) S_y^f(m/T_c). \quad (1)$$

Here  $\sigma_{y\text{lim}}^2(\tau)$  is a lower limit to frequency instability of the cesium atomic fountain clock.  $S_y^f(m/T_c)$  is side-band power spectral density of the relative frequency fluctuations at Fourier frequencies  $m/T_c$ , which the oscillator is free running. In addition,

$$\begin{pmatrix} g_m^s \\ g_m^c \end{pmatrix} = \frac{1}{T_c} \int_0^{T_c} g(t) \begin{pmatrix} \sin(2\pi mt/T_c) \\ \cos(2\pi mt/T_c) \end{pmatrix} dt,$$

$g_0 = \frac{1}{T_c} \int_0^{T_c} g(t) dt$ ,  $g(t)$  is the sensitivity function.

Hydrogen maser signal is an external reference to atomic fountain frequency standard, which exhibit phase noise of -95 dBc/Hz at 100MHz. The residual phase noise of microwave synthesizer should be much lower than that of hydrogen maser to achieve instability of  $10^{-15}$  for cesium atomic fountain standard.

### Design of Frequency Synthesizer

Figure 1 shows a block diagram of the microwave frequency synthesizer for cesium atomic fountain standard. The synthesizer produces a 9.192 GHz signal by a voltage-controlled dielectric resonant oscillator (VCDRO) locked to 100MHz hydrogen maser signal through a divider chain.

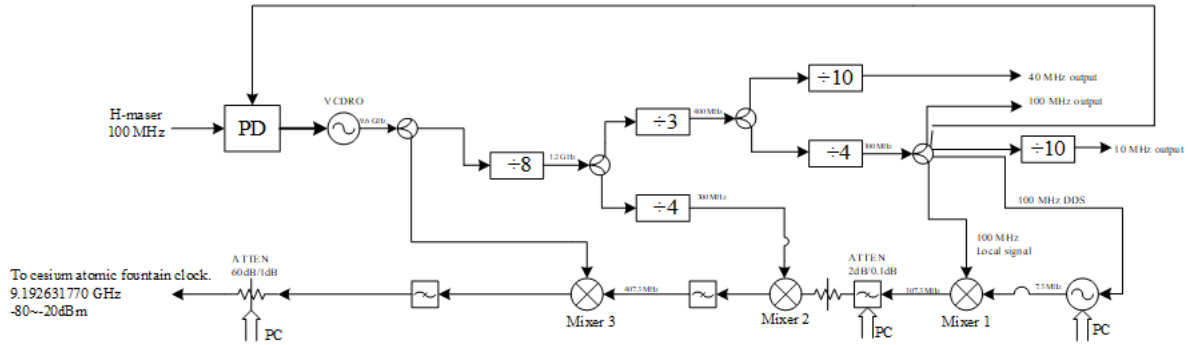


Figure 1. Block diagram of the frequency synthesizer.

The 9.6 GHz signal from VCDRO has two same signals via the power splitter. A 9.6 GHz signal is connected to the LO terminal of mixer 3. Another 9.6 GHz signal forms a 407.3 MHz signal, then that is linked with the RF terminal of the mixer 3. The 407.3 MHz signal is generated by mixing 300 MHz signal obtained by dividing by 8-divider and 4-divider with a 107.3MHz frequency signal. The 107.3MHz filter has better performance, especially the out-of-band suppression ratio. The 107.3 MHz output of the mixer 1 is synthesized using 100 MHz and 7.3 MHz produced that 100 MHz is up-converted. The 100 MHz signals are obtained using 9.6 GHz signal via 8-divider, 3-divider and 4-divider. Figure 2 shows measurement results for the phase noise of this 4-divider used inside the frequency synthesizer.

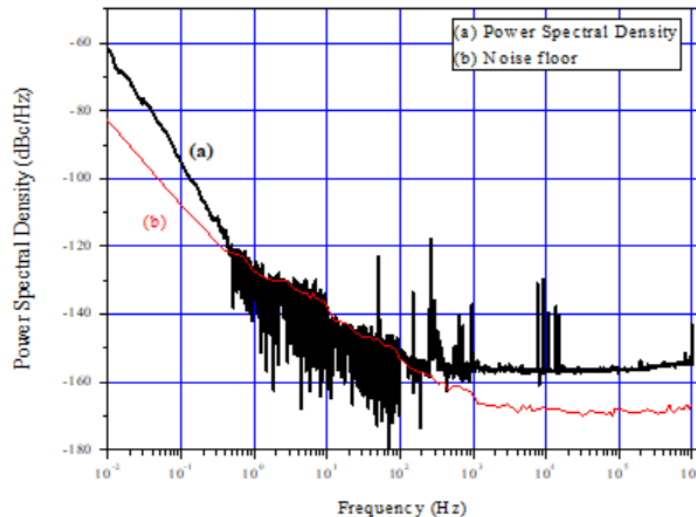


Figure 2. Power spectrum density curve of 4-divider. (a) frequency divider by 4. (b) TSC 5125A.

We can see from the figure clearly that the phase noise of the frequency divider is different from the phase noise of the system outside 0.2 Hz to 100 Hz. However, what we are concerned is that the phase noise around 1 Hz is not much different from the noise floor of the system.

Among 5-way 100MHz signals, the 100 MHz phase-detection signal is locked to an external reference through the phase detector(PD). 100MHz signal outputs 10MHz signal through a 10-divider,

and 100MHz local signal is used to generate 107.3MHz frequency signal. 100 MHz DDS outputs 7.3MHz signal by up-conversion. Another signal is divided to 40 MHz using 10-divider.

Frequency of 9.192 GHz signal from frequency synthesizer would be regulated by that of DDS via the computer with  $\mu\text{Hz}$  resolution. Alternatively, the DDS could be replaced by a commercial signal generator (Stanford Research DS345) that used 40 MHz signal as external reference source. A digital attenuator is used to adjust power of frequency synthesizer. In order to eliminate the leakage microwave, 300MHz signal could be connected to the microwave interference switch.

## Measurement

Figure 3 shows the frequency spectrum curve of the 9.192631770 GHz frequency signal. We do not find out that any spur occurs at about  $\pm 250$  Hz from the vicinity of the clock transition frequency, and the power drops by more than 70 dB. Hence, these spurs would lead to the frequency shifts less than  $2 \times 10^{-18}$  of cesium atomic fountain standards [10].

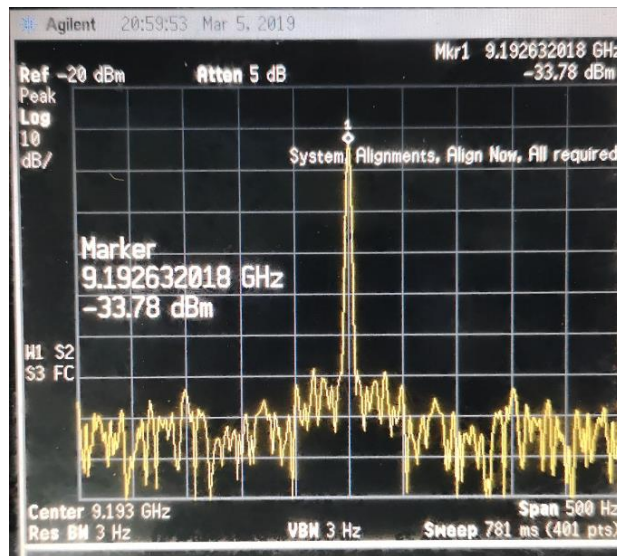


Figure 3. Frequency spectrum of the 9.192 GHz.

Two identical frequency synthesizers compare to each other directly for testing their residual phase noise. A commercial signal generator generates a 100MHz signal, which is used as a common frequency reference source. Two identical frequency synthesizers generate 9.192631770 GHz and 9.190631770 GHz frequency signals, respectively. Phase noise of 2 MHz signal which is produced by mixer DB0218LW2 represent that of microwave frequency synthesizer. Finally, it connects to the input end of phase noise and Allan deviation test set 5125A made in Symmetricom, the reference input of which is a 10MHz frequency signal from the Hydrogen maser.

The phase noise of 9.192GHz signal is shown in Figure 4. The frequency spectral density is fitted based on the power law spectrum model [11]. In the formula (2), this represents random walk FM( $f^{-2}$ ), flicker FM( $f^{-1}$ ), white FM( $f^0$ ), flicker PM( $f^1$ ) and white PM( $f^2$ ):

$$S_y(f) = \sum_{i=-2}^2 h_i f^i. \quad (2)$$

The fitting result in the range of 0.1 Hz to 12 Hz :

$$\begin{aligned} h_{-1} &= 9.1147 \times 10^{-31} \\ h_0 &= -8.1977 \times 10^{-30} \\ h_1 &= 2.72549 \times 10^{-29} \\ h_2 &= -6.07729 \times 10^{-31} \end{aligned}$$

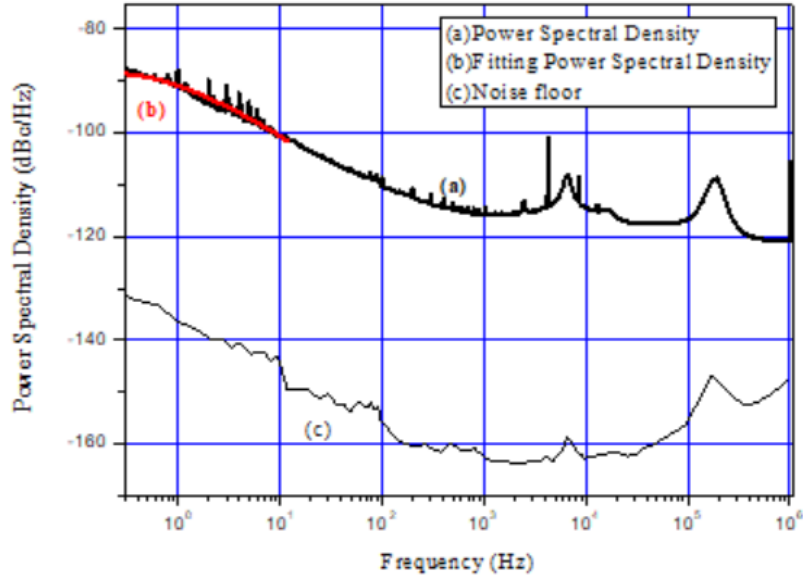


Figure 4. Spectrum density curve. (a) microwave frequency synthesizer. (b) fit curve of power spectral Density. (c) Noise floor.

In the low frequency, the limitation comes primarily from the flicker frequency noise of the oscillator and that the white phase does not affect the results[8]:

$$\sigma_y(\tau) \approx \sqrt{h_{-1}} \left| \frac{\sin(\pi d)}{\pi d} \right| \sqrt{\frac{T_c}{\tau}}. \quad (3)$$

Here,  $\tau$  is the sampling time.  $d$  is the ratio of the interrogation time  $T$  and the cycle time  $T_c$  ( $T_c = 1.5s$ ,  $T = 0.5s$ ). The frequency instability of the cesium atomic fountain clock according to (3) is at the level of  $1 \times 10^{-15}$  at 1s.

Figure 5 shows the frequency instability for microwave frequency synthesizer at 9.192 GHz calculated by 2MHz, and this is usually expressed by Allan variance[11-12]. The frequency stability of microwave synthesizer 9192631770Hz is  $2.2 \times 10^{-15}/s$  at 1 s integration time.

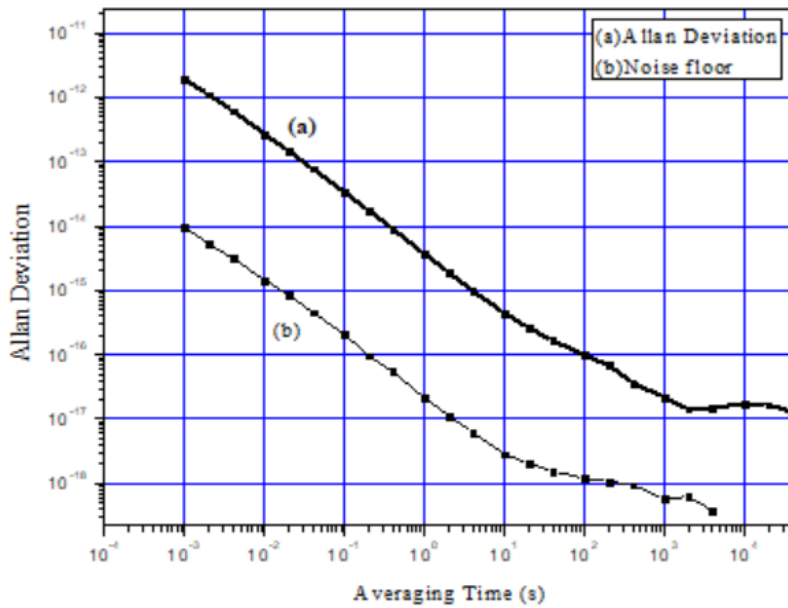


Figure 5. Allan variance of the 9.192GHz signal. (a) Allan Deviation of microwave frequency synthesizer. (b) Noise floor.

## Summary

We have reported a high-performance means of a low-noise microwave frequency synthesizer from 100 MHz signal to 9.192 GHz through a divider chain. The design is very simple without multiplication. A voltage-controlled DRO is locked to 100MHz hydrogen maser signal through a divider chain. The required frequency 9192631770 Hz is generated by mixed with 7368230 Hz and 400 MHz signal. The experimental results show that the output signal at 9.192 GHz is -88dBc/Hz@ offset 1Hz. By calculation, the frequency stability is  $2.1758 \times 10^{-15}$ . Besides, in order to prevent microwave signal leakage, the whole device should be putted into the magnetic shielding box.

## Acknowledgement

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