CHIN. PHYS. LETT. Vol. 34, No. 6 (2017) 063702

Dick Effect in the Integrating Sphere Cold Atom Clock *

Xiu-Mei Wang(王秀梅)[1,2], Yan-Ling Meng(孟艳玲)[1], Ya-Ning Wang(王亚宁)[1,2], Jin-Yin Wan(万金银)[1], Ming-Yuan Yu(于明圆)[1,2], Xin Wang(王鑫)[1,2], Ling Xiao(肖玲)[1], Tang Li(李唐)[1], Hua-Dong Cheng(成华东)[1**], Liang Liu(刘亮)[1**]

[1]*Key Laboratory of Quantum Optics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800*

[2]*University of Chinese Academy of Sciences, Beijing 100039*

(Received 22 February 2017)

The Dick effect is an important factor limiting the frequency stability of sequentially-operating atomic frequency standards. Here we study the impact of the Dick effect in the integrating sphere cold atom clock (ISCAC). To reduce the impact of the Dick effect, a 5 MHz local oscillator with ultra-low phase noise is selected and a new microwave synthesizer is built in-house. Consequently, the phase noise of microwave signal is optimized. The contribution of the Dick effect is reduced to $2.5\times10^{-13}\tau^{-1/2}$ *(*τ *is the integrating time). The frequency stability of* $4.6\times10^{-13}\tau^{-1/2}$ *is achieved. The development of this optimization can promote the space applications of the compact ISCAC.*

PACS: 37.10.De, 42.50.Ct, 42.62.Fi DOI: 10.1088/0256-307X/34/6/063702

In sequentially operating atomic frequency standards,[1,2] the clock sequence is divided into three successive steps in each cycle: state preparation, the Ramsey interrogation, and clock signal detection. The atoms are interrogated only during a finite time, because the state preparation and clock signal detection are dead time. The clock signal corrects the frequency offset of local oscillator (LO) at the end of each cycle. This sampling process can mix down the frequency fluctuations of the interrogation signal into the clock signal, which is called the Dick effect.[3] This effect has been investigated widely.[4−7] However, very few studies addressed the Dick effect of the integrating sphere cold atom clock (ISCAC), which is very different from other microwave atomic clocks. For the ISCAC, the cycle time can be decreased to about 85 ms because of the recapture effect of cold atoms in the integrating sphere,[8] and the microwave interrogation duration is determined by the gravity on earth and the temperature of cold atoms in space.

In this Letter, the Dick effect is studied in the ISCAC. To reduce the impact of the Dick effect, a 5 MHz LO with ultra-low phase noise is selected and a new microwave synthesizer is built in-house. The phase noise characteristic of this synthesizer is measured using a second identical synthesizer. The phase noise of the microwave signal is optimized in comparison with the previous synthesizer. To compress the dead time in time sequence, the atoms are detected using the absorption intensity of cold atoms in single energy level $5^2\mathrm{S}_{1/2}|F=2\rangle$. Combined with the optimized time sequence, the impact of this new microwave synthesizer is decreased to $2.5\times10^{-13}\tau^{-1/2}$. We show that the microwave phase noise can be decreased by the microwave synthesizer built in-house and the frequency stability of the ISCAC is improved to $4.6\times10^{-13}\tau^{-1/2}$.

The schematic diagram of the ISCAC is shown in Fig. 1. The ^{87}Rb atoms are cooled to below 100 μK[9] by the isotropic cooling light, which is reflected by the inner face of the microwave cavity. Then the atoms are pumped to $5^2\mathrm{S}_{1/2},|F=1\rangle$ in preparation for the Ramsey microwave interrogation. Finally, the atoms experience the clock transition $5^2\mathrm{S}_{1/2},|F=1,m_F=0\rangle \rightarrow 5^2\mathrm{S}_{1/2},|F=2,m_F=0\rangle$ and the transition signal is detected by a standing wave probe light. In such a process, a microwave synthesizer generates the interrogation signal, which is coupled into the cavity by an antenna. The frequency of this microwave interrogation signal is hopped at each side of the full width at half maximum (FWHM) of the Ramsey fringe to obtain an error signal. The error signal corrects the frequency of LO and locks it to the atomic transition frequency. To measure the frequency stability, the locked frequency of this LO is compared with an H-maser.

In previous work, with the commercial microwave synthesizer the short-term frequency stability has been achieved to $7.3\times10^{-13}\tau^{-1/2}$.[8] The contribution of the Dick effect from microwave interrogation signal is estimated at $5\times10^{-13}\tau^{-1/2}$. However, to reduce the impact of the Dick effect, a new microwave synthesizer is built in-house based on an ultra-low phase noise 5 MHz oven controlled crystal oscillator (OCXO).

The power spectral density of fractional frequency

*Supported by the National Natural Science Foundation of China under Grant No 11604353, and the Youth Innovation Promotion Association of Chinese Academy of Sciences.

**Corresponding author. Email: chenghd@siom.ac.cn; liang.liu@siom.ac.cn

fluctuation of this new LO $S_y^{\mathrm{OCXO}}(f)$ is shown in Fig. 2. The reason for the selection of this 5 MHz OCXO is that the cycle rate in the ISCAC is 12 Hz and the fractional frequency noise of this oscillator presents lower than many OCXOs in the range of $f < 12$ Hz. This oscillator is suitable to be applied in the ISCAC and the new microwave synthesizer is built based on it.

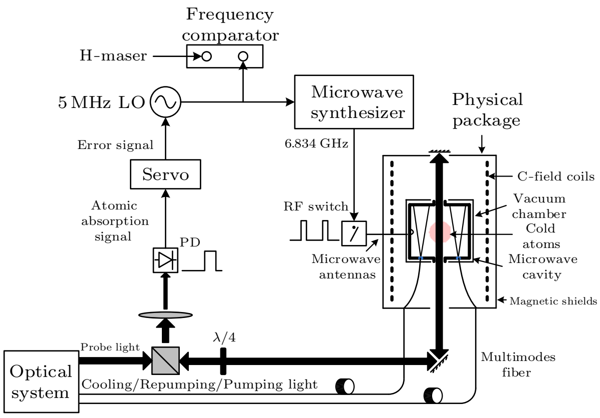

Fig. 1. The schematic diagram of the ISCAC.

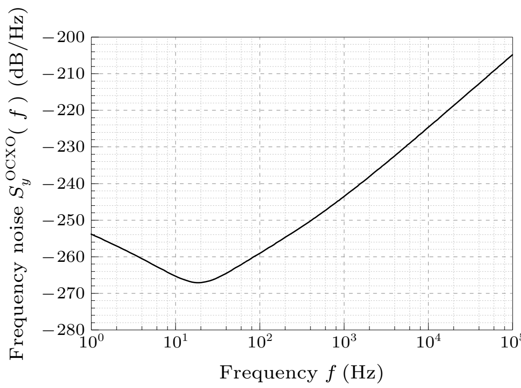

Fig. 2. The power spectral density of fractional frequency fluctuation of the selected 5 MHz OCXO.

The electronic architecture of the new microwave synthesizer is shown in Fig. 3. The LO generates a 5 MHz signal as reference. The reference signal is multiplied by 20 and 2 to generate a 200 MHz signal. The 200 MHz signal is split into 3 parts after a directional coupler (DC) and a splitter. In the first part, the 200 MHz signal is fed into the step-recovery diode (SRD), which is used to produce the 7 GHz signal. In the second part, the 200 MHz signal is a reference signal of the direct digital synthesizer (DDS), which is used to generate a 34 MHz signal. In the last part, the 200 MHz signal is mixed with a 7.034 GHz signal coming from a dielectric resonator oscillator (DRO) to generate an attenuated 6.8 GHz signal. Using a radio-frequency (RF) switch, the 6.834 GHz is triggered on or off.

There is a phase-locked loop in this architecture. The 7.034 GHz signal is locked to the 200 MHz signal and divided into two parts. One part is mixed with the 7 GHz signal from SRD to produce a 34 MHz signal. The 34 MHz signal is distinguished by a DDS to produce an error signal. The error signal feeds back the DRO after a low pass filter (LPF). Then the second part is used for producing the 6.834 GHz output signal.

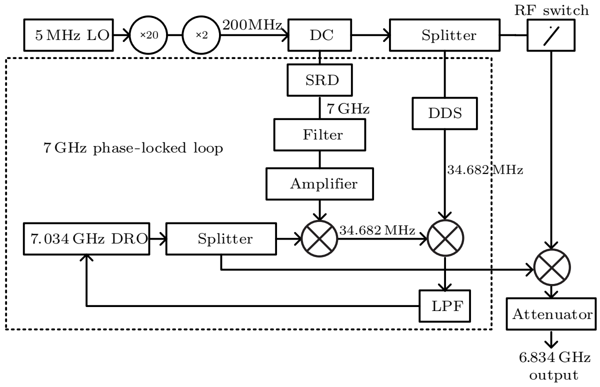

Fig. 3. Electronic architecture of the new microwave synthesizer.

A second identical synthesizer is implemented to measure the phase noise of this synthesizer. When both synthesizers are fed by two LOs and the two LOs are locked to each other, the phases in these two loops are orthogonal. By this means, the absolute phase noise of this synthesizer $S_\varphi^{\mathrm{a}}(f)$ is measured. When both synthesizers are fed by the same LO, the phase noise of the LO is canceled out. Then the residual phase noise of this synthesizer $S_\varphi^{\mathrm{b}}(f)$ is measured. The power spectrum density of the phase noise measured in a single synthesizer is shown in Fig. 4.

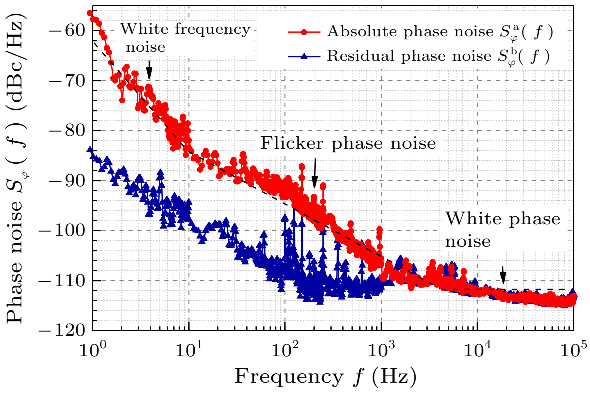

Fig. 4. The power spectrum density of the phase noise in the new microwave synthesizer. The red circle line and the blue triangle line represent the absolute phase noise and residual phase noise of the new microwave synthesizer, respectively.

There are three sources of noise contributing to the absolute phase noise $S_\varphi^{\mathrm{a}}(f)$: the white frequency noise (f^{-2}) in the range of 1–10 Hz, the flicker phase noise (f^{-1}) in the range from 10 Hz to 4 kHz, and the white phase noise floor of −114 dBc/Hz at 100 kHz. Here the contribution of the white phase noise is ignored, and it will be discussed hereafter. The fractional frequency noise $S_y^{\rm a}(f)$ contributing to the Dick effect can be obtained from the absolute phase noise,[10]

$$S_y^{\rm a}(f) = f^2 S_\varphi^{\rm a}(f)/\upsilon_{\rm WM}^2, \qquad (1)$$

where $\upsilon_{\rm WM}$ is the microwave frequency of 6.834 GHz.

In addition, the time sequence of the ISCAC is optimized,[11] as shown in Fig. 5. Because of the power stabilization of probe light background, the cycle time T is shortened to 85 ms without the second detection pumping pulse and it is divided into four steps. The atoms are cooled by diffused light and accumulated in the central area of the cavity ($T_{\rm c} = 52.8$ ms). The cold atoms are pumped from $F = 2$ to $F = 1$ by the optical pumping pulse ($T_{\rm p} = 0.5$ ms). Then the atoms are interrogated by two 6.834 GHz microwave pulses ($\tau_{\rm p} = 1$ ms). The duration of atomic free evolution $T_{\rm f}$ is increased to 24 ms. Therefore, the duty cycle $d = T_{\rm f}/T$ is increased to 0.28, which is significant to reduce the Dick effect. Finally, the atomic population is detected by the optical pulse ($T_{\rm d} = 5.7$ ms).

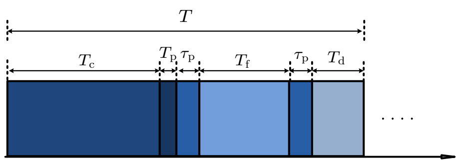

Fig. 5. The optimized time sequence of the ISCAC. Here T, $T_{\rm c}$, $T_{\rm p}$, $\tau_{\rm p}$, $T_{\rm f}$ and $T_{\rm d}$ are the duration of the clock cycle, cooling, pumping, microwave, free evolution and optical detection pulses, respectively.

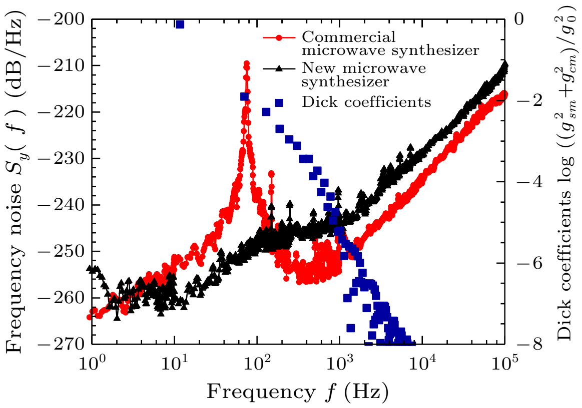

Fig. 6. The physical parameters for calculating the Dick effect. The red circle line and the black triangle line represent the fractional frequency noise of the commercial microwave synthesizer and the new microwave synthesizer, respectively. The blue square dots represent the Dick coefficients of the sensitivity function for the time sequence shown in Fig. 5.

The interrogation frequency noise $S_y(f)$ and the clock time sequence limit the achievable frequency stability by the Dick effect. The frequency stability degradation induced by the Dick effect has been given in Ref. [12],

$$\sigma_{y,\rm Dick}^2(\tau) = \frac{1}{\tau}\sum_{m=1}^{\infty}\Big(\frac{g_{\rm sm}^2 + g_{\rm cm}^2}{g_0^2}\Big) S_y^{(m/T)}, \qquad (2)$$

where $\sigma_{y,\rm Dick}^2(\tau)$ is the lower limit to achievable frequency stability for an integrating time τ, $S_y(m/T)$ is the power spectral density of interrogation fractional frequency noise at Fourier frequency m/T, and $g_{\rm sm}$, $g_{\rm cm}$ and g_0 are defined from the sensitivity function $g(t)$[12] as

$$\begin{pmatrix} g_{\rm sm} \\ g_{\rm cm} \end{pmatrix} = \frac{1}{T}\int_0^T g(t)\begin{pmatrix} \sin 2\pi mt/T \\ \cos 2\pi mt/T \end{pmatrix} dt, \qquad (3)$$

$$g_0 = \frac{1}{T}\int_0^T g(t)dt. \qquad (4)$$

The sensitivity function $g(t)$ is the response of the atomic system to a phase step of the interrogation signal, or the impulse response with respect to a frequency change occurring at time t. It is given by

$$g(t) = 2\lim_{\delta\varphi\to 0}\frac{\delta P(\delta\varphi, t)}{\delta\varphi}, \qquad (5)$$

where $\delta P(\delta\varphi, t)$ is the change of the probability induced by a phase step $\delta\varphi$ at time t. As shown in Eq. (2), the contribution of the Dick effect is equal to fractional frequency noise multiplied by the Dick coefficients of the sensitivity function $(g_{\rm sm}^2 + g_{\rm cm}^2)/g_0^2$. Figure 6 shows the Dick coefficients $(g_{\rm sm}^2 + g_{\rm cm}^2)/g_0^2$ at different frequencies as blue dots. They are clearly strong for frequencies lower than 4 kHz and negligible above 4 kHz. This property provides good immunity against the white phase noise of the microwave signal. Numerical calculation can be integrated to 4 kHz. Figure 6 also shows the fractional frequency noise of the new microwave synthesizer as the red circle line and the commercial microwave synthesizer based on the previous LO as black triangle line. The new synthesizer decreases the frequency noises in the range of 10–200 Hz. The optimization of these frequency noises reduces the impact of the Dick effect obviously.

Thanks to the selection of 5 MHz OCXO, the contribution of the Dick effect from this LO $S_y^{\rm OCXO}(f)$ is decreased to $1.0 \times 10^{-13}\tau^{-1/2}$, and the contribution from the new synthesizer $S_y^{\rm a}(f)$ is reduced to $2.5 \times 10^{-13}\tau^{-1/2}$ due to the optimization of phase noise. The short-term frequency stability of $4.6\times 10^{-13}\tau^{-1/2}$ is reached. The measured results are shown in Fig. 7. In addition to the Dick effect, there are other technique noise sources: feedback electronics, fluctuations of probe laser intensity and frequency, which will be reduced further in the following work.

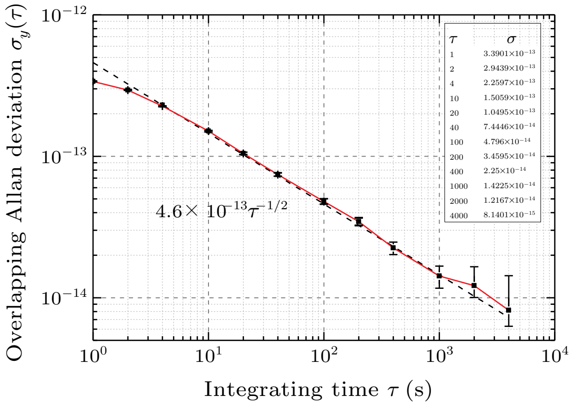

Fig. 7. The measured frequency stability of the ISCAC using the new microwave synthesizer.

In conclusion, we have studied the Dick effect in the ISCAC and have improved the short-term frequency stability. The Dick effect is reduced vastly to $2.5\times10^{-13}\tau^{-1/2}$ by the selection of the ultra-low frequency noise 5 MHz OCXO and the construction of the new microwave synthesizer. The new microwave synthesizer has not only low microwave phase noise but also small size and light weight, satisfying the requirements of space. As a result, the short-term frequency stability of $4.6\times10^{-13}\tau^{-1/2}$ is achieved. In future, the phase noise will be decreased further after replacing the SRD by a nonlinear transmission line in the synthesizer and the short-term frequency stability will be further improved.

References

[1] Godone A, Micalizio S and Levi F 2004 *Phys. Rev.* A **70** 023409
[2] Esnault F X, Holleville D, Rossetto N, Guerandel S and Dimarcq N 2010 *Phys. Rev.* A **82** 033436
[3] Dick G J 1987 *19th Precise Time and Time Interval (PTTI) Appl. Planning Meeting* (Redondo Beach California 1–3 December 1987) p 133
[4] Quessada A, Kovacich R P, Couttillot I, Clairon A, Santarelli G and Lemonde P 2003 *J. Opt. B: Quantum Semiclass. Opt.* **5** S150
[5] Danet J M, Lours M, Guérandel S and Clercq E 2014 *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **61** 567
[6] Szmuk R, Dugrain V, Mainrult W, Reichel J and Rosenbusch P 2015 *Phys. Rev.* A **92** 012106
[7] Chen Y H, She L, Wang M, Yang Z H, Liu H and Li J M 2016 *Chin. Phys.* B **25** 120601
[8] Liu P, Meng Y L, Wan J Y, Wang X M, Wang Y N, Xiao L, Cheng H D and Liu L 2015 *Phys. Rev.* A **92** 062101
[9] Wang X C, Cheng H D, Xiao L, Zheng B C, Meng Y L and Liu L 2012 *Acta Optic Sin.* **10** 080201 (in Chinese)
[10] Riehle F 2004 *Frequency Standards Basics and Applications* (London: Macmillan) p 58
[11] Liu P, Meng Y L, Wan J Y, Wang X M, Wang Y N, Xiao L, Cheng H D and Liu L 2016 *8th Symposium on Frequency Standards and Metrology* (Potsdam Germany 12–16 October 2016) **723** 012007
[12] Santarelli G, Audoin C, Makdissi A, Laurent P, Dick G J and Clairon A 1998 *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **45** 887