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Theoretical analysis of suppressing Dick effect in Ramsey-CPT atomic clock by interleaving lock*

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For most pulsed atomic clocks, the Dick effect is one of the main limits to reach its frequency stability limitation due to quantum projection noise. In this paper, we measure the phase noise of the local oscillator in the Ramsey-CPT atomic clock and calculate the Dick effect induced Allan deviation based on a three-level atomic model, which is quite different from typical atomic clocks. We further present a detailed analysis of optimizing the sensitivity function and minimizing the Dick effect by interleaving lock. By optimizing the duty circle of laser pulses, average time during detection and optical intensity of laser beam, the Dick effect induced Allan deviation can be reduced to the level of 10^{-14}.

Keywords: coherent population trapping, Dick effect, atomic clock

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1. Introduction

In recent years, the passive vapor cell frequency standards have made a great deal of progress and reached the frequency stability of $10^{-13}\tau^{-1/2}$ or even better.[1–8] These kinds of atomic clocks are suitable as secondary frequency standards where frequency stability, size and power consumption are of equal importance.[6] Among those vapor cell standards, atomic clocks based on coherent population trapping (CPT) seem to be rather promising, due to the simple all optical setup and good performance.[9] The small signal amplitude of CPT clocks can be enhanced by an optimized CPT pumping scheme[10–13] and the linewidth of clock transition can be reduced by Ramsey's method of separated oscillation fields.[11] However, the Dick effect is one of the main limits for the improvement of the frequency stability to the level of $10^{-14}\tau^{-1/2}$. In 1987, Dick pointed out that the down-conversion of the local oscillator's frequency noise degrades the atomic clocks' frequency stability,[14] and many subsequent analyses have explored how to minimize the Dick effect in the microwave atomic clocks[15–21] and optical atomic clocks,[23–25] respectively. Typically, there are two ways to reduce the Dick effect. One way is using an ultra-low phase noise local oscillator (LO), such as a cryogenic sapphire oscillator[26] or an ultra-stable laser stabilized by an optical cavity.[27] However, these oscillators are expensive and bulky. The other way is to interleaving lock the LO to two quantum systems.[25]

The analysis of the Dick effect in the Ramsey-CPT atomic clocks is rather different from other atomic clocks, and methods to minimize it are seldom discussed. For the Ramsey-CPT clock, there are no straightforward dead time and interrogation time as in the fountain clock, ion trap clock or optical lattice clock. The detection of clock signal takes place at the leading edge of one laser pulse, and atoms are prepared to the CPT dark states in the remnant part of the same laser pulse. Besides, the theoretical calculation of the sensitivity function of Ramsey-CPT is based on a three-level atomic model rather than a simple two-level model. These make it more challenging to analyze and optimize the Ramsey-CPT clock to reduce the Dick effect than other atomic clocks.

In this paper, we present a detailed analysis of the Dick effect in Ramsey-CPT clocks with an interleaving lock by two vapor cells. We find that the sensitivity function for the interleaved Ramsey-CPT clock is dependent on three parameters: the duty cycle of laser pulses, average time during detection and optical intensity of laser beam. According to our calculation, the Dick effect can be reduced from $6.11\times10^{-13}\tau^{-1/2}$ to the level of $1.64\times10^{-14}\tau^{-1/2}$ for the same LO.

2. Dick effect in Ramsey-CPT atomic clock

Coherent Population Trapping (CPT) is a quantum interference phenomenon which can be achieved in a three-level system,[28–30] as shown in Fig. 1. Two near resonant coherent laser fields with frequency ω_1 and ω_2 excite the alkali atoms

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confined in a vapor cell from two ground-state hyperfine levels $|1\rangle$ and $|2\rangle$ to the excited state $|3\rangle$ simultaneously. When the frequency differences of two laser fields ω_1–ω_2 generated by synthesizer exactly equal the hyperfine splitting of two ground states $\Delta\omega$, atoms are pumped into a "dark" state that the transparency of the incident light reaches maximum. As a result, a narrow resonance signal can be detected by a photo-diode. The servo system can adjust the frequency of the LO according to the resonance signal. The cell contains a buffer gas which can suppress the resonance linewidth.

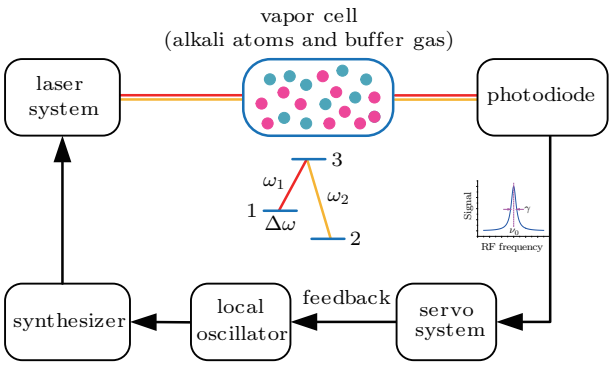


Fig. 1. (color online) Basic schematic diagram of a CPT atomic clock.

The Ramsey-CPT clock works in a pulsed mode.[31] The time sequence of this clock is presented in Fig. 2(a). First, the dichromatic light lasting for a time τ_L pumps the atoms to the dark states. Then the light is absent to let the atoms freely process for a duration of T. Next, the atoms' states are detected by a following optical pulse. The transmitted light signal is measured at the end of τ_m and averaged for a time (average time during detection) τ_A. Atoms are then pumped to the dark states again. The cycle time is $T_c = \tau_L + T$ in total.

The Dick effect induced Allan deviation (DEAD) of the locked LO can be expressed as[14]

$$\sigma_y^{\mathrm{Dick}}(\tau) = \left[\frac{1}{\tau}\sum_{m=1}^{\infty}\left(\frac{g_{ms}^2 + g_{mc}^2}{g_0^2}\right)S_y^{\mathrm{f}}\left(\frac{m}{T_c}\right)\right]^{1/2}, \tag{1}$$

where τ is the integrating time, $S_y^{\mathrm{f}}(m/T_c)$ is the one-side power spectral density (PSD) of the relative frequency fluctuations of the free-running LO at Fourier frequency m/T_c. g_{ms}, g_{mc}, and g_0 are respectively defined as

$$\begin{pmatrix} g_{ms} \\ g_{mc} \end{pmatrix} = \frac{1}{T_c}\int_0^{T_c} g(\theta)\begin{pmatrix} \sin(2\pi m\theta/T_c) \\ \cos(2\pi m\theta/T_c) \end{pmatrix} \mathrm{d}\theta \tag{2}$$

and

$$g_0 = \frac{1}{T_c}\int_0^{T_c} g(\theta)\mathrm{d}\theta, \tag{3}$$

where $g(\theta)$ is the sensitivity function.

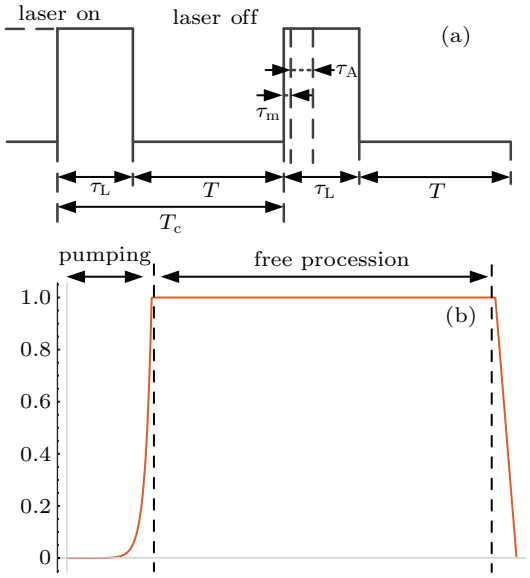


Fig. 2. (color online) (a) Time sequence of laser pulses for a typical Ramsey-CPT atomic clock; (b) Calculated sensitivity function $g(t)$ of a Ramsey-CPT system.

In the case of Ramsey-CPT, $g(t)$ can be calculated by a three-level atomic model and expressed as[32]

$$g(t) = \begin{cases} \exp\left(\dfrac{t-\tau_L}{\tau_p}\right), & (0 \le t \le \tau_L), \\ 1, & (\tau_L < t < \tau_L + T + \tau_m), \\ 1 - \dfrac{t-(\tau_L+T+\tau_m)}{\tau_A}, & (\tau_L + T + \tau_m \le t \le T_c + \tau_m + \tau_A), \end{cases} \tag{4}$$

where $\tau_p = \Gamma/\Omega^2$, Γ is the decay rate from the excited state, and Ω^2 is the quadratic sum of two optical transitions' Rabi frequencies. In our typical experiment condition, the τ_p is usually several microseconds. $g(t)$ is shown in Fig. 2(b). From the above equation, the CPT pumping time τ_L is equivalent to the dead time as in other atomic clocks, during which frequency fluctuation of LO is not detected by the atoms.

In order to calculate the DEAD in our atomic clock, the PSD of the frequency fluctuations of the LO needs to be measured. In our experiment setup, the LO is a 10-MHz oven controlled crystal oscillator (OCXO), and the microwave synthesizer is phase referenced to the LO to generate 6.834-GHz microwave. The single-side phase noise of 6.8 GHz is measured by a commercial signal source analyzer as shown in Fig. 3. Because the phase noise at the offset frequency from 1 Hz to 100 kHz has the dominated influence on the DEAD, our fol-

lowing calculation's cut-off frequency is restricted to 100 kHz. So the PSD of the relative frequency can be expressed as a function as follows (also shown in Fig. 3):

$$\begin{aligned} S_y^{\rm f}(f) \;=\; & 1.28\times10^{-24}f^{-2}+2.14\times10^{-26}f^{-1} \\ & +1.50\times10^{-26}f^{0}+6.42\times10^{-28}f^{1} \\ & +3.21\times10^{-32}f^{2}. \end{aligned} \tag{5}$$

In the case of our CPT clocks, the free procession time is usually set to 800 μs. Based on Eq. (1), the DEAD $\sigma_y^{\rm Dick}(\tau)$ is calculated for different duty cycles ($\tau_{\rm L}/T_{\rm c}$) while keeping the free evolution time T unchanged. The calculation results are shown in Fig. 4. As we can see, $\sigma_y^{\rm Dick}(\tau)$ is $6.11\times10^{-13}\tau^{-1/2}$ for our typical time sequence (duty cycle 20%), and increases rapidly as the duty cycle increases. This result is very close to the previously estimated short-term frequency stability.[33,34] Thus, the Dick effect is a big issue for this clock to improve the short-term frequency stability below $1\times10^{-13}\tau^{-1/2}$.

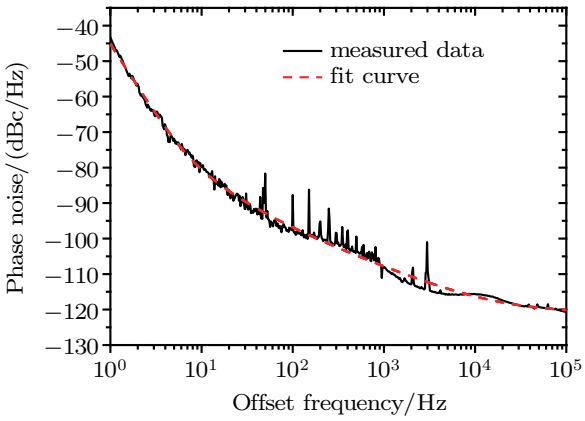


Fig. 3. (color online) The measured phase noise of the 6.834 GHz (black solid line) microwave synthesizer and the fitting curve (red dashed line).

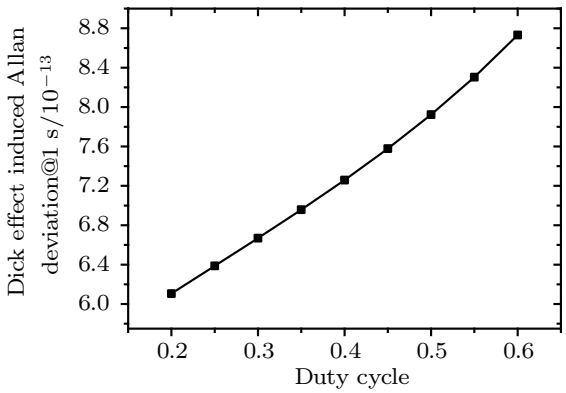


Fig. 4. Calculated Dick effect induced Allan deviation with 1-s sampling time versus the duty cycle for non-interleaved Ramsey-CPT atomic clocks. The duty cycles are defined as $\tau_{\rm L}/T_{\rm c}$.

3. Optimization of sensitivity function for interleaved Ramsey-CPT atomic clocks

According to Eq. (1), Fourier coefficients $(g_{ms}^2+g_{mc}^2)/g_0^2$ determine the frequency weight of LO's PSD in the calculation of DEAD. If $g(t)$ is a constant function, g_{ms} and g_{mc} are equal to zero, leading to a zero Fourier coefficient. In such an ideal situation, the Dick effect is completely eliminated. In the real operation of a single cell clock, $g(t)$ is zero over a considerable portion of one cycle due to the dead time, manifesting itself as a periodic function of $T_{\rm c}$ and resulting in a high value of Fourier coefficients. The interleaved operation of two quantum systems compensates the zero part of the sensitivity function and reduces Fourier coefficients substantially, as shown in Fig. 5 and Fig. 6.

To optimize the duty cycle, we first set the initial value of duty cycle to 50% and use the traversal method to calculate the corresponding Fourier coefficients for each duty cycle. The step size is set to 0.1% in our calculation. The process of optimization is towards the decrease of Fourier coefficients. When the first derivative of Fourier coefficients equals zero, the minimum of Fourier coefficients are determined. As a result, the DEAD is minimized. In this process we have found that Fourier coefficients reach minimum when the exponential rising part of the sensitivity function for one cell partially overlaps the linear falling of the other. The following part is an explanation of the optimization results.

Figures 5(a) and 5(c) show the time sequence and corresponding sensitivity function for vapor cell 1 and vapor cell 2, respectively. The duty cycles of the two pulsed laser beams are 50%, and phase difference is 180°. Figure 5(e) shows the sum of the two sensitivity functions for the double cell. As we can see, although the summed sensitivity function is equal to unity in most of the cycle time, there still exist obvious high spikes at the beginning and ending of each cycle. Due to these periodic spikes, the sensitivity function is still a periodic function of $T_{\rm c}$ and leads to non-zero Fourier coefficients. In order to obtain a more constant sensitivity function and reduce Fourier coefficients, the sequence can be optimized as shown in Fig. 5(b) and Fig. 5(d). The exponential rising part of the sensitivity function for one cell should partially overlap the linear falling for the other, as shown in Fig. 5(f). In this case, the areas above and below the line of $g(t)=1$ gradually equal to each other, and Fourier coefficients will approximate zero. A more quantitative analysis will be presented in the following parts.

In Fig. 6, we compare Fourier coefficients $(g_{\rm ms}^2+g_{mc}^2)/g_0^2$ of the sensitivity function for double cell before and after optimization with those for single cell at different frequencies. Black squares correspond to the sensitivity function in Fig. 1(b). Red solid circles and Blue triangles correspond to the sensitivity function in Figs. 5(e) and 5(f), respectively. As we can see, the Fourier coefficients of optimized double cell is about three orders of magnitude better than those of an unoptimized double cell when $m<20$. Based on these values, the calculated result of DEAD for the unoptimized double cell is $4.22\times10^{-13}\tau^{-1/2}$, which is improved slightly compared with a single cell's value of $7.92\times10^{-13}\tau^{-1/2}$ (duty cycle 50%). In contrast, the calculated DEAD for the optimized double cell decreases to $5.32\times10^{-14}\tau^{-1/2}$, which is much improved compared to a single cell clock.

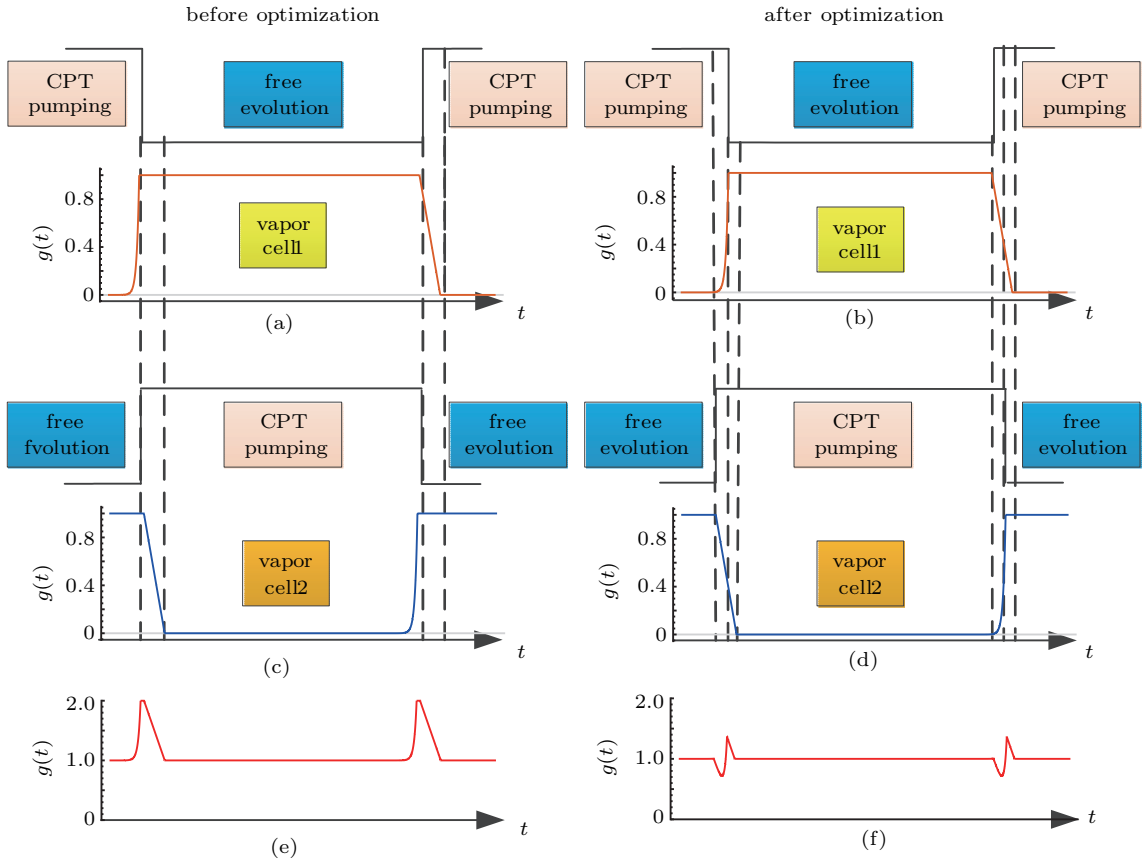


Fig. 5. (color online) Optimization of sensitivity function $g(t)$ for interleaved Ramsey-CPT clock. Panels (a) and (c) respectively show sensitivity function $g(t)$ for vapor cell 1 and cell 2 before optimization. Panel (e) is the numerical sum of panels (a) and (c) for the unoptimized double cell. Panels (b) and (d) respectively show sensitivity function $g(t)$ for vapor cell 1 and cell 2 after optimization. Panel (f) is the numerical sum of the two sensitivity functions for the optimized double cell.

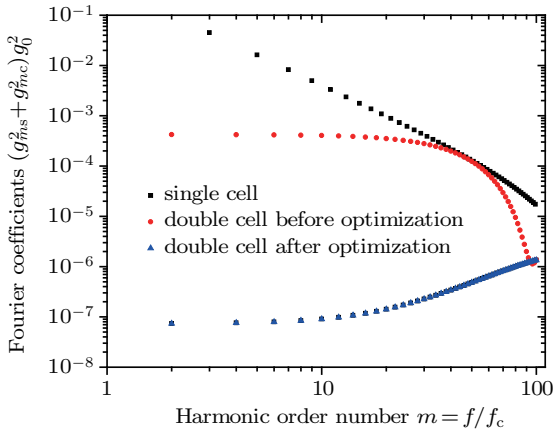


Fig. 6. (color online) Fourier coefficients for single cell(black squares), double cell before optimization (read circles) and double cell after optimization (blue triangles). f_c is defined as $1/T_c$.

Besides duty cycle, average time during detection and optical intensity of laser beam are also of vital importance for the optimization of the sensitivity function. The optical intensity is proportional to the CPT pumping rate and determines the rising edge of the sensitivity function. The average time during detection determines the falling edge. As a result, the two parameters alter the areas above and below the line of $g(t)=1$ more precisely. The following discussion will quantitatively describe the procedures of optimization. First, we maintain the optical intensity constant and calculate the DEAD with different average times during detection and duty cycles. The results are shown in Fig. 7. As we can see, for different duty cycles, there always exists an average time to minimize the DEAD. By the calculation, the optimal duty cycle is 50.9%, and the average time during detection is 6 μs for our setup.

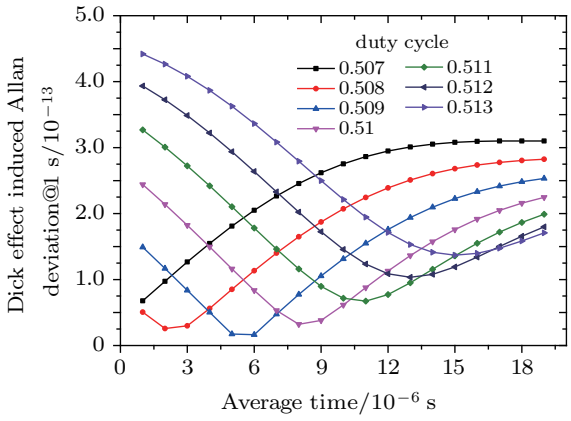


Fig. 7. (color online) Optimization of sensitivity function versus duty cycle and average time during detection. The cycle time T_c keeps constant while varying different duty cycle and average time during detection τ_A.

Since the optimal duty cycle and average time during detection have been determined, the DEAD is calculated by varying different optical intensity based on these two val-

ues, as shown in Fig. 8. The optimal optical intensity is 9 mW/cm^2, and the DEAD can be further suppressed to $1.64 \times 10^{-14}\tau^{-1/2}$, which is much less than the predicted Allan deviation limited by quantum projection noise of our atomic clock.[31]

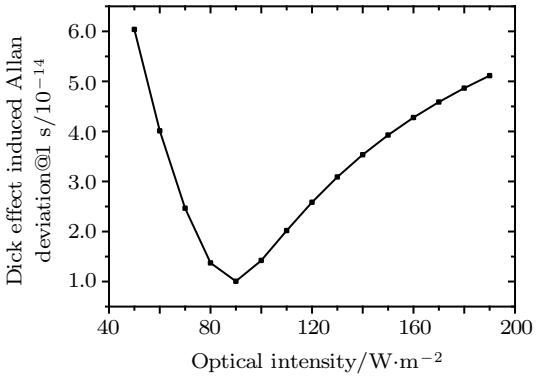


Fig. 8. Optimization of sensitivity function versus optical intensity (duty cycle is 50.9% with an average time during detection of 6 μs).

The above calculation and discussion are based on an approximation that the laser field is exactly resonant with the atoms. However, if the laser has a non-zero single-photon detuning δ, $\tau_{\rm p}(\delta)$ cannot be expressed in a simple form as shown in Eq. (4), but as a function of δ. The increase of δ will prolong the time of CPT state preparing time $\tau_{\rm p}$, leading to a modification of sensitivity function $g(t)$. Further investigation of the relationship between single-photon detuning δ and sensitivity function $g(t)$ requires a more exact analysis of $\tau_{\rm p}(\delta)$.

4. Conclusion

In summary, the sensitivity function of the Ramsey-CPT system is presented and the dead time during CPT pumping leads to degradation of the clock's frequency stability. Based on the experimentally measured phase noise of the frequency synthesizer for 6.834 GHz, we have successfully optimized the sensitivity function of the interleaved operating Ramsey-CPT atomic clock by adjusting the duty cycle of laser pulses, average time during detection and optical intensity of laser beam. Given the appropriate parameters, the Dick effect has been reduced to $1.64\times10^{-14}\tau^{-1/2}$ for our setup. It can be hoped that the interleaved operating Ramsey-CPT atomic clock will be a high-performance and compact atomic clock.[35–39]

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