Suppression of Dick Effect in Ramsey-CPT Atomic Clock by Interleaving Lock

Pengfei Cheng®, Xiaolin Sun, Jianwei Zhang®, and Lijun Wang

Abstract—The Dick effect is one of the main limitations of short-term frequency stability for most atomic clocks operating in the pulsed mode. Rather than employing better local oscillators with ultralow phase noise, using the interleaving lock technique to eliminate the dead time is a promising approach to suppress the Dick effect. In this paper, we demonstrate the suppression of the Dick effect by the interleaving lock technique in a pulsed Ramsey-coherent population trapping clock with two identical Cs atomic ensembles. The Dick effect is expected to be reduced by a factor of 24 theoretically. The measured short-term Allan deviation is improved from $1.3 \times 10^{-11}$ at 1 s to $3.0 \times 10^{-12}$ at 1 s. What is even more remarkable is that the Allan deviation curve exhibits $1/\tau$ slope from 0.01 to 2 s.

Index Terms—Dick effect, interleaving lock, Ramsey-coherent population trapping (CPT).

I. INTRODUCTION

There is a great demand for compact atomic clocks with both low power consumption and high performance in many domains of applications [1]. In recent years, vapor cell atomic clocks with high expectations, especially those based on coherent population trapping (CPT) have made great progress, and the frequency stability of $10^{-13} \sqrt{\tau^{-1/2}}$ has been achieved [2]–[10]. New pumping schemes [11]–[14] and Ramsey’s method of separate oscillation fields [12] are applied to enhance the amplitude of the CPT signal and to reduce the linewidth of the clock transition, respectively.

Due to the continual improvements of frequency stability of microwave and optical frequency standards, Dick effect becomes one of the main limitations [15]–[20]. Dick effect generally refers to the atomic clock’s frequency stability degradation caused by down-conversion of the local oscillator’s (LOs) frequency noise, as first pointed out by Dick [21] and Santarelli et al. [22]. Typically, there are mainly two ways to suppress the Dick effect. One is to reduce the phase noise of LOs, such as developing ultralow-phase-noise frequency synthesizer [23], even applying the cryogenic sapphire oscillators [24] in microwave frequency standards or ultrastable lasers stabilized by an optical cavity in optical frequency standards. The other one is to eliminate the dead time by interleaving locking the LO to two atomic ensembles, which are proposed and developed in [25]–[31]. The cryogenic sapphire oscillator and the ultrastable lasers have been successfully applied in frequency standards to reduce the Dick effect, but they are bulky and expensive. Developing a state-of-the-art ultralow-phase-noise frequency synthesizer is a direct solution, especially for compact atomic clocks [23], whose shot noise limits are about $10^{-14}$. However, the interleaving lock by two atomic ensembles is another promising way to suppress the Dick effect in similar costs and sizes to achieve the frequency stability of $10^{-14}$ for pulsed mode atomic clock [32], and $10^{-17}$ for optical frequency standards [30]. Moreover, the interleaving lock technique makes the clock to continually measure the LO’s phase error, which results in faster decrement than $1/\sqrt{\tau}$ for an Allan deviation. For the Ramsey-CPT clock developed in our laboratory, the Dick effect is one of the main limitations to the short-term frequency stability. We proposed the Ramsey-CPT atomic clocks with interleaving locking by two atomic vapor cells. A detailed analysis of the Dick effect is discussed and the theoretical optimized-independent parameters have been presented in previous work [32]. These parameters include the duty cycle of the laser pulse, the average time during the detection, and the optical intensity of the laser beam. In this paper, we report the successful reduction of the Dick effect in a Ramsey-CPT atomic clock in the experiment by using two Cs atomic ensembles. In Section II, numerical calculation of the Dick effect in a Ramsey-CPT atomic clock with both single and interleaving lock will be addressed. Section III illustrates a brief introduction to our experimental setup and a detailed analysis of the experimental results. Conclusions are given in Section IV.

II. THEORY

The scheme of lin/lin Ramsey-CPT clocks was introduced previously [33]–[35]. The time sequence of a typical Ramsey-CPT atomic clock is shown in Fig. 1. Coherent dichromatic laser light pumps the atoms into CPT dark state during each...
laser pulse, then the clock signal is detected at the leading edge of the following pulse and averaged for $t_m$. The Allan deviation limits due to the Dick effect is given by [21]

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

where $\tau$ is the integration time, $S_y(m/T_c)$ is the one-side power spectral density (PSD) of the relative frequency fluctuations of the free-running LO at Fourier frequency $m/T_c$. $g_{\text{ms}}$, $g_{\text{mc}}$, and $g_0$ depend on the sensitivity function $g(\theta)$. According to (1), optimizing the sensitivity function $g(\theta)$ to minimize the Fourier coefficients ($g_{\text{ms}}^2 + g_{\text{mc}}^2/g_0^2$) is a way to suppress the Dick effect. The parameters $g_{\text{ms}}$, $g_{\text{mc}}$, and $g_0$ are given, respectively,

$$\left( \begin{array}{c} g_{\text{ms}} \\ g_{\text{mc}} \end{array} \right) = \frac{1}{T_c} \int_0^{T_c} g(\theta) \left( \begin{array}{c} \sin(2\pi m\theta/T_c) \\ \cos(2\pi m\theta/T_c) \end{array} \right) d\theta$$  \hspace{1cm} (2)

and

$$g_0 = \frac{1}{T_c} \int_0^{T_c} g(\theta) d\theta.$$  \hspace{1cm} (3)

Thus, keeping the sensitivity function $g(\theta)$ as a constant leads to zero Fourier coefficients of the LO’s frequency noise PSD contributing to Dick effect. The sensitivity function $g(\theta)$ in the Ramsey-CPT atomic clocks is varied from the fountain clocks, ion trap clocks, and the optical lattice clocks due to its unique pumping procedure. In this case, the sensitivity function $g(t)$ is calculated by a three-level atomic model and expressed as [36]

$$g(t) = \begin{cases} 
\exp\left(\frac{t - \tau_L}{\tau_p}\right), & (0 \leq t \leq \tau_L) \\
1, & (\tau_L < t < \tau_L + T + \tau_d) \\
1 - \frac{t - (\tau_L + T + \tau_d)}{\tau_m}, & (\tau_L + T + \tau_d \leq t \leq T + \tau_d + \tau_m)
\end{cases}$$  \hspace{1cm} (4)

where $\tau_p = \Gamma/\Omega^2$, $\Gamma$ is the decay rate from the excited state and $\Omega^2$ is the quadratic sum of two optical transitions’ Rabi frequencies. While employing the interleaving locking, the total sensitivity function, which is the sum of two identical parts of $g(t)$ with opposite phase, is given as

$$g_{\text{total}}(t) = g(t) + g(t + T_c/2).$$  \hspace{1cm} (5)

The total sensitivity function $g_{\text{total}}(t)$ can be made to be close to a constant by optimizing the duty cycle of the time sequence of laser pulses, which can result in a minimum Fourier coefficients according to (2) and (3). Thus, the Dick effect is completely eliminated in that ideal situation. We have thoroughly discussed the parameters of sensitivity function of using two vapor cells by interleaving lock, and the results showed that in optimized conditions, Allan deviation can be reduced by at least one order of magnitude [32]. Moreover, the LO’s phase is compared with the man-made phase continued Cs atomic ensembles by applying the interleaving lock technique. Thus, the frequency stability in Allan deviation is averaged as $1/\tau$ for a certain period of time due to the phase-lock approach [29].

### III. Experiments

To demonstrate the suppression of Dick effect by interleaving lock in a Ramsey-CPT atomic clock, an experimental setup with two atomic ensembles is constructed. The schematic is shown in Fig. 2. All the parameters are selected carefully for optimizing the signal-to-noise ratio (SNR) and suppressing of Dick effect, simultaneously. The 894.5-nm laser is generated by a distributed Bragg reflector laser diode. A small part of it is split and frequency shifted +65 MHz by using an acoustic-optical modulator (AOM), and then frequency locked to the $6^2S_{1/2}(F = 4) \rightarrow 6^2P_{1/2}(F = 3)$ transition of Cs $D_1$ line via the saturation absorption spectrum technique. Therefore, the output laser that is the carrier from the AOM is frequency shifted $-65$ MHz compared to the atomic transition frequency. Then, the laser is split into two beams with the power of 50 mW in each. With the help of a fiber electro-optical phase modulator, which is modulated at 9.2 GHz with about 24-dBm microwave power, about 60% of the carrier’s power is transferred proximately equally into the ±1 order sidebands. Here, the carrier and +1 order sideband are used as the coherent CPT resonance fields in each beam, while the $-1$ order is far from resonating with the atomic transitions.
Then, the laser is pulse modulated by an AOM to implement Ramsey’s interrogation method in each beam. The AOM is used to stabilize the laser intensity via a feedback on the AOM’s driving power during every pulse, and detailed description can be found in [37]. Since $t_d$ and $t_m$ (see Fig. 1) are very short, the suppression of laser intensity noise during detection by the control loop is greatly limited. Thus, the laser intensity noise still limits the performance of a clock. The driving frequency of the AOM is 80 MHz. Combining with the $-65$ MHz frequency shifted in the locking procedure, the frequency of the laser is totally shifted $-145$ MHz to the $6^2 S_{1/2}(F = 4) \rightarrow 6^2 P_{1/2}(F = 3)$, which compensates for the buffer gas-induced optical frequency shift. Two identical physical packages of atomic ensembles consist of Cs vapor cells, temperature control modules, solenoids, and three-layer magnetic shields. The laser beam is expanded to a radius of 15 mm, and the power is 1 mW before the vapor cell. Two nearly orthogonal polarizers are placed before and after the Cs cell to implement the dispersion detection method [34]. Two identical cylindrical Cs vapor cells, 30 mm diameter and 28 mm long, are filled with the mixed buffer gas of 11.0-torr nitrogen and 5.5-torr argon. The cells’ temperature is stabilized to about 34°C, and the static magnetic field along the direction of the cell axis is set to $1.54 \times 10^{-5}$ T. Two frequency synthesizers are applied to generate the 9.2-GHz microwave signals. Thanks to the electronic controller based on field-programmable gate array (FPGA), the timing accuracy of the time sequence is only a few nanoseconds, which is a significant factor to optimize the sensitivity function, and gives the chance to implement the real-time data acquisition processing and feedback due to its remarkable computing power [37].

The schematic of the clock frequency stabilization method and the timing sequence, including the laser pulses generation, the transmitted signal detection, and the square-wave phase modulation of the 9.2-GHz microwave, is shown in Fig. 3. In the case of our interleaving locked Ramsey-CPT atomic clock shown in Fig. 3(b), the duty cycle in each atomic ensemble is set to be 50%, for instance, the free evolution time $T = 1.5$ ms as well as the optical pump time $t_L = 1.5$ ms, and the cycle time $T_c = T + t_L = 3$ ms. The time delay of the optical pumping laser pulse is set to $t_d = 125$ ns to ensure the phase modulation is settled. The detection time delay of $t_d$ is set to be 500 ns. The full width at half maximum is measured to be 286 Hz for the two atomic ensembles’ central Ramsey fringes, which is narrower than 1/2 $T$ [10]. The two Ramsey fringes are shown in Fig. 4. The SNRs of the two Ramsey signals are both approximately 220. According to the well-known equation $\sigma_y(t) = (1/\pi\cdot Q \cdot \text{SNR})\sqrt{T_c/\sigma}$, where $Q = 3.2 \times 10^7$ is the quality factor of the atomic resonance, the short-term frequency stability is estimated to be $2.5 \times 10^{-12}/\sqrt{T}$, where the impacts of the noises due to the Dicker effect and the servo loop are not included. The averaging time of each signal detection is set to $t_m = 16$ $\mu$s. The phase of the 9.2-GHz microwave is modulated with an amplitude of 90° by a square wave via synthesizers’ built-in phase modulation. As shown in Fig. 3, $L_{1k}$ and $L_{2k}$ are the $k$th detections where the phase of the 9.2-GHz microwave is 0° during the corresponding laser pulses. The numbers 1 and 2 are corresponding to laser 1 and laser 2, respectively. Since the phase difference between the detection pulse and pump pulse is $-90$°, the obtained Ramsey fringe in Fig. 3(a) (black solid curve). When the frequency of the 9.2-GHz microwave is exactly resonant with the atoms, the detected signal is at

\[
\begin{align*}
\text{SNR} &= \frac{1}{\pi Q \cdot \text{SNR}} \sqrt{T_c/\sigma}, \\
Q &= 3.2 \times 10^7.
\end{align*}
\]
the half-maximum point. \( R_{1k} \) and \( R_{2k} \) are the \( k \)th detections where the phase of the microwave is 90°. The phase difference between the detection pulse and pump pulse is +90°, and the obtained Ramsey fringe in Fig. 3(a) (gray dashed curve). Here, \( L \) and \( R \) stand for the left side and right side of a Ramsey fringe, respectively.

To implement the interleaving lock, the atomic ensembles are interrogated in a relay style. During the interrogation of the 9.2-GHz microwave signal in the first atomic ensemble, the second atomic ensemble is in the phase of detecting and optical pumping. Once the interrogation is completed with the first ensemble, interrogation is continued with the second ensemble. Ideally, the dead time can be eliminated completely since the interrogation is operating without any dead time. However, the sensitivity function’s fluctuations induced during the handover of interrogation between two atomic ensembles cannot be avoided in practice, due to the complex properties of the sensitivity function at the edges of the laser pulses. In the interleaving locking mode, the LO’s frequency error is calculated to be

\[
\text{ERR}_k(v_0) = (L_{1k} + L_{2k}) - (R_{1k} + R_{2k})
\]

in the \( k \)th detection and

\[
\text{ERR}_{k+1}(v_0) = (R_{1k} + R_{2k}) - (L_{1k+1} + L_{2k+2})
\]

in the \((k+1)\)th detection. The clock frequency \( v_0 \) is locked to the mean of the resonating frequencies of the two individual Cs vapor cells \( v_{\text{cell1}} \) and \( v_{\text{cell2}} \), which have a slight difference about 3 Hz mainly due to the inconsistency during the manufacture. The Allan variance of the clock in midterm and long-term will be degraded by the sum of the Allan variances of each single cell. The locked clock frequency \( v_0 \) is given as

\[
v_0 = (v_{\text{cell1}} + v_{\text{cell2}}).
\]

Alternatively, by manually setting the output of photodetector (PD)1 \( (L_1 = R_1 = 0) \) or PD2 \( (L_2 = R_2 = 0) \) to zero, the clock is solely locking to ensemble 2 or ensemble 1, respectively. The LO’s frequency error is corrected via an FPGA-based digital proportional—integral—differential module and the sampling frequency of the digital-to-analog converter is 333.3 Hz in both single and double atomic ensembles locking modes.

The measured single-sideband (SSB) phase noise and its fitting curves of the 9.2-GHz microwave are shown in Fig. 5. Due to the cycle time \( T_c = 3 \) ms, the phase-noise offset frequency with the range of 300 Hz–1 MHz is measured. Since \( S(f) = S(f) f^2 / v_0^2 \) (v_0 = 9.2 GHz is the carrier’s frequency), combine (1)–(5), the Dick effects for the clock locked by single atomic ensemble and double atomic ensembles are calculated to be \( 1.25 \times 10^{-11} / \sqrt{\tau} \) and \( 5.2 \times 10^{-13} / \sqrt{\tau} \), respectively. Hence, the Dick effect limit can be suppressed by a factor of 24, theoretically.

In Fig. 6, we present the measured Allan deviations of the LO in free running, by the conventional locking with the single atomic ensemble and by interleaving locking with the double atomic ensembles, along with the theoretical Dick effect limits. The frequency stabilities are measured by the phase noise and Allan deviation test set (5120A, Microsemi), and a commercial hydrogen maser (MHM-2010, Microsemi) is applied as the frequency reference. Since the Allan deviations of the LO locked to each single atomic ensemble are very similar, only one of them is shown in Fig. 6. In the single atomic ensemble locking condition, the Dick effect is the leading limit of the short-term frequency stability. In this situation, one cannot improve the short-term frequency stability further through optimizing the SNR, except suppressing the Dick effect. By the interleaving locking, the frequency stability is improved to \( 3.0 \times 10^{-12} \tau^{-0.96} \) in the average time of 0.01–2 s, and then

![Image](https://example.com/image1.png)

**Fig. 5.** SSB phase noise of the 9.2-GHz (black solid line) microwave synthesizer measured by E5052B and E5053A (Agilent, now Keysight) and the fitting curves (red dashed lines) in four frequency ranges (300 Hz–1 kHz, 1 kHz–3 kHz, 3 kHz–80 kHz, and 80 kHz–1 MHz marked by pink arrows). The measured data are averaged by a factor of 16, and several spikes in the measured data are ignored while applying the nonlinear fitting.

![Image](https://example.com/image2.png)

**Fig. 6.** Frequency stability of Ramsey-CPT atomic clocks in conventional single atomic ensemble locking mode and double atomic ensembles interleaving lock mode. Black triangle dots: LO’s frequency stability in free running. Green circle dots: single locking model. Red squared dots: interleaving locking model. All data’s error bars are shown in the figure. Three dashed lines are the theoretical Dick effect limits in single clock mode (pink dashed line) and interleaving locking mode (brown dashed line), and the linear fitting line of the Allan deviation measured in interleaving locking mode with a slope of \( 1/\tau^{0.96} \) (blue dashed line).
it reaches the flicker floor near $1.3 \times 10^{-12}$. It is clear that the implementation of interleaving locking improves the short-term stability of our Ramsey-CPT clock significantly from $1.3 \times 10^{-11}$ at 1 s to $3 \times 10^{-12}$ at 1 s. However, considering the theoretically suppressed Dick limit as shown in Fig. 6 (brown dashed line), the potential to further improve the frequency stability is very promising. Theoretically, the slope of $1/\tau$ lasts for a certain time $t_0$ that should satisfy $t_0 = \tau_2 \Delta \phi_0^2 / \delta \theta^2$ [29], where $\Delta \phi_0$ is the maximum phase fluctuation of the microwave during the free-evolution period $T$, and $\delta \theta$ is the phase error of the measurement and locking process in each cycle. In other words, after the period of $t_0$, the accumulated phase error induced in the measurement and locking process is comparable to the LO’s phase-noise intensity. As shown in Fig. 6, $t_0 = 2$ s. Compared to the previous estimation of short-term frequency stability by SNR, the frequency stability of the clock in single lock mode is mainly limited by the Dick effect. For the clock with interleaving lock technique, the Dick effect is greatly suppressed. Thus, we may assert that the interleaving lock technique is effective to suppress the Dick effect and achieve the stability limit rapidly. However, it is difficult to suppress other kinds of noises by interleaving locking. We have investigated the influence to the frequency stability due to the fluctuations of cell temperature, magnetic field, laser frequency, and laser intensity. It is believed that the frequency stability of $\tau > 2$ s of our Ramsey-CPT clock is mainly limited by the laser intensity noise so far [38].

IV. CONCLUSION

In summary, we built a Ramsey-CPT atomic clock with interleaving locking technique based on two Cesium atomic ensembles and demonstrated the suppression of the Dick effect. By applying the interleaving locking technique, the short-term frequency stability is improved from $1.3 \times 10^{-11} \sqrt{7}$ to $3 \times 10^{-12} e^{-0.96}$ in 0.01–2 s, and finally achieved the flicker floor near $1.3 \times 10^{-12}$, which is far better than the Dick effect limit in the conventional locking mode. Interleaving locking is an efficient technique to suppress the Dick effect, and especially for the compact atomic clocks based on atomic vapor cells to avoid the requirement of the ultrastable LO.

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