Faraday-laser-pumped cesium beam clock

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(Received 11 July 2024; revised 2 November 2024; accepted 31 January 2025; published 10 March 2025)

We realize a high-performance compact optically pumped cesium beam atomic clock utilizing the Faraday laser simultaneously as the pumping and detection lasers. The Faraday laser, which is frequency stabilized by the modulation transfer spectroscopy (MTS) technique, has a narrow linewidth and superior frequency stability. Measured by the optical heterodyne method between two identical systems, the linewidth of the Faraday laser is 2.5 kHz after MTS locking, and the fractional frequency stability of the Faraday laser is optimized to $1.8 \times 10^{-12}/\sqrt{\tau}$. Based on this high-performance Faraday laser, the cesium beam clock realizes a signal-to-noise ratio of 39 600 in 1-Hz bandwidth when the cesium oven temperature is 130 °C. Compared with hydrogen maser, the fractional frequency stability of the Faraday-laser-pumped cesium beam clock can reach $1.3 \times 10^{-12}/\sqrt{\tau}$ and decreases to 1.4×10^{-14} at 10 000 s when the cesium oven temperature is set at 110 °C. This Faraday-laser-pumped cesium beam clock demonstrates its excellent performance and its great potential in the fields of timekeeping, navigation, and communication. Moreover, as a high-performance optical frequency standard, the Faraday laser can contribute to the development of other applications in quantum metrology, precision measurement, and atomic physics.

DOI: 10.1103/PhysRevApplied.23.034018

I. INTRODUCTION

Since being constructed [1], cesium beam clocks have been widely used in the fields of frequency and time and promote the development of timekeeping, high-speed communication, navigation, and fundamental research [2,3]. There are two main types of cesium beam clocks: magnetic state selecting cesium beam clocks [4–7] and optically pumped cesium beam clocks [8–16]. Compared with magnetic-state-selecting cesium beam clocks, optically pumped cesium beam clocks have a significantly higher atomic utilization, leading to better frequency stability and longer service life. Optically pumped cesium beam clocks are of increasing interest to researchers.

The frequency stability of optically pumped cesium beam clocks can be further optimized mainly by reducing the shot noise of cesium atoms and frequency noise of the laser. Increasing the number of interacting atoms can effectively reduce the shot noise of cesium atoms, which can be realized by increasing the atomic beam flux. In practice, the atomic beam flux is adjusted to an appropriate finite value, taking into account the lifetime of the cesium clock. When the atomic beam flux is constant, the frequency stability of optically pumped cesium atomic clocks can be greatly improved by adopting a laser with a narrow linewidth, low frequency noise, and high power stability, which can effectively improve the signal-to-noise ratio (SNR) of the Ramsey fringes of the optically pumped cesium beam clock [17]. Additionally, miniaturization and transportability also need to be considered. The volume of the cesium beam clock is mainly limited by the cesium beam tube, but the shortening of the free drift region reduces the Ramsey evolution time, which widens the linewidth of the Ramsey fringes and leads to the deterioration in frequency stability of the cesium beam clock. However, the optimization of the SNR can ensure that the cesium beam clock still has excellent

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performance. Therefore, lasers with narrow linewidths and low-frequency noise are essential.

To optimize the frequency stability of optically pumped cesium beam clocks, we use a frequency-stabilized Faraday laser [18–23] as the pumping and detection lasers. Compared with traditional external-cavity semiconductor lasers (ECDLs), such as lasers whose frequency is selected by interferences and gratings, the Faraday laser has the advantages of being immune to the temperature and current variations of the laser diode, and the Faraday laser can automatically operate at the frequency of atomic transition lines once it is switched on, because the Faraday laser is frequency selected by an atomic filter [18–20]. Moreover, the modulation transfer spectroscopy (MTS) technique [24–26] is applied to lock the Faraday laser. Compared with other frequency stabilization methods, such as saturation absorption spectroscopy (SAS) [27–29], polarization spectroscopy (PS) [30,31], and dichroic atomic vapor laser lock (DAVLL) [32,33], the MTS technique is background-free and can effectively suppress low-frequency noise due to high-frequency modulation, which leads to a high SNR. Moreover, the MTS technique has a steeper slope, so it has high resolution and sensitivity [24,34].

In this work, we achieve a high-performance Faraday-laser-pumped cesium beam clock, which applies an 852-nm Faraday laser frequency stabilized by the MTS technique as pumping and detection lasers. We measure the performance of the frequency-stabilized Faraday laser using the optical heterodyne method, and the result shows that the fractional frequency stability of each system is 1.8×10^{-12} at 1 s, The most probable linewidth of the heterodyne beating signal is 12.7 kHz when Faraday lasers are free running, which implies that of the single system is 9.0 kHz. The most probable linewidth is 3.5 kHz with Faraday lasers being frequency-locked by MTS; thus that of the single system is 2.5 kHz. We use such Faraday laser with narrow linewidth and low-frequency noise as the pumping and the detection lasers to build an optically pumped cesium beam atomic clock, which optimizes the SNR of the Ramsey fringe. Thus, the fractional frequency stability of the Faraday-laser-pumped cesium beam clock can reach 7.9×10^{-13} at 1 s and 1.3×10^{-13} at 100 s, dropping to 1.4×10^{-14} at 10 000 s when the cesium oven temperature is 110 °C.

II. EXPERIMENT

Figure 1(a) shows the overall structure of the experiment. The Faraday laser is an integrated system with the MTS technique for frequency stabilization, and all components are integrated onto a single aluminum base. The Faraday laser is beam-split and frequency-shifted to serve as the pumping and detection lasers for the cesium beam clock.

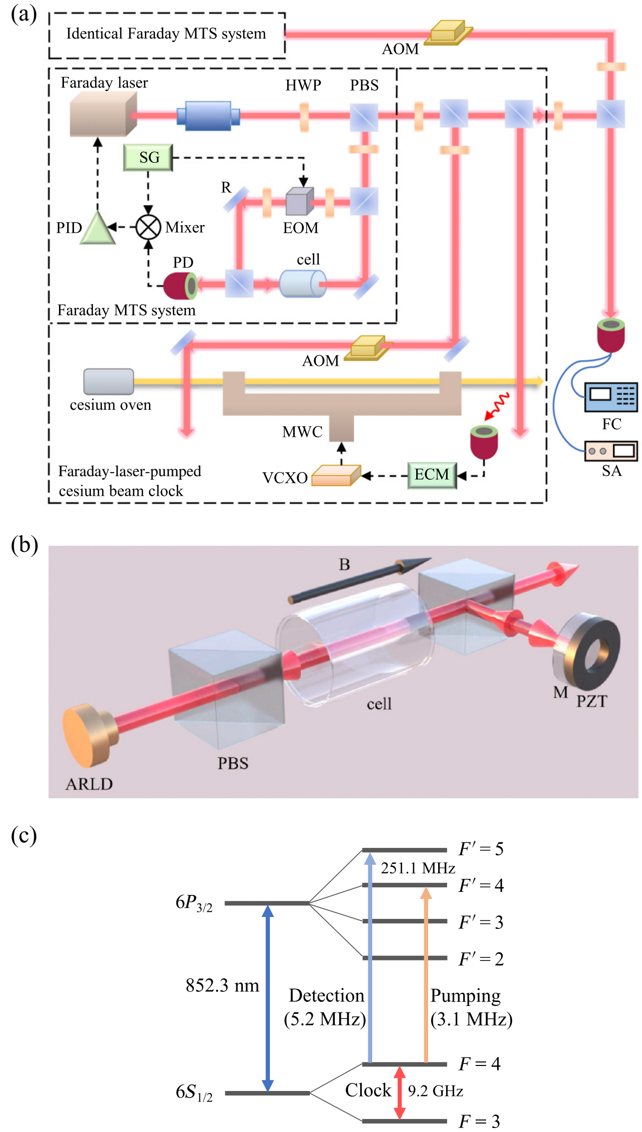

FIG. 1. (a) Experimental setup. Cell, cesium vapor cell of MTS; ISO, isolator; HWP, half-wave plate; PBS, polarization beam splitter; EOM, electro-optic modulator; PD, photoelectric detector; SG, signal generator; A, amplifier; PID, proportional integral derivative controller; ECM, electronic control module; VCXO, voltage-controlled crystal oscillator; MWC, microwave cavity; FC, frequency counter; SA, spectrum analyzer. (b) Schematic diagram of the Faraday laser. ARLD, antireflection-coated laser diode; cell, cesium vapor cell; M, high-reflectivity mirror; PZT, piezoelectric transducer; B, magnetic field. The permanent magnet provides a longitudinal magnetic field of 900 G. The temperature of the vapor cell is controlled at 66 °C within 0.1 °C. (c) Cesium-relevant energy-level diagram. The pumping laser is used to pump all population from the $F = 4$ state into the $F = 3$ state. After excitation by the microwave at approximately 9.2 GHz in the microwave cavity, there are atoms in the $F = 4$ state. These atoms can be detected by exciting them with the detection laser and monitoring the fluorescence photons from this decay. The linewidths of transitions of $6s^2S_{1/2}|F = 4\rangle - 6p^2P_{3/2}|F' = 5\rangle$ and $6s^2S_{1/2}|F = 4\rangle - 6p^2P_{3/2}|F' = 4\rangle$ is 5.2 MHz and 3.1 MHz, respectively.

The structure of the Faraday laser is depicted in Fig. 1(b). We use an antireflection-coated laser diode (ARLD) as the gain medium. The antireflection coating superbly suppresses the impact of the internal cavity modes, which are formed between the front and rear surfaces of the ARLD, on the laser modes. Two PBSs, a cesium vapor cell, and permanent magnets compose the Faraday anomalous dispersion optical filter (FADOF) [35–38] which is for frequency selection. The vapor cell is filled with cesium atoms and 10 Torr argon buffer gas, with a diameter of 1.5 cm and a length of 3 cm. The cesium vapor cell is surrounded with a twisted copper heating wire driven by a heater temperature controller and enclosed by thermal insulation materials. The temperature of the cesium vapor cell is controlled at 66 °C with a temperature fluctuation of 0.1 °C. The permanent magnets are placed around the cesium vapor cell to form a 900-G longitudinal magnetic field. Under the action of the magnetic field, the energy levels of the cesium atoms in the vapor cell undergo Zeeman splitting, which introduces the Faraday effect. The polarization direction of the linearly polarized light passing through the first PBS rotates as it propagates through the cesium vapor cell; ultimately, only the light whose polarization direction has rotated by $n\pi + \pi/2 (n = 0, 1, 2, \ldots)$ can pass through the second PBS. Thus, only a very narrow frequency range of light that corresponds to the spectral lines of the atoms can pass through the FADOF. Then the light is reflected back to the laser diode by a high-reflectivity mirror to form the external cavity feedback. Additionally, a piezoelectric transducer (PZT) is affixed to the high-reflectivity mirror to enable the laser frequency to be tuned by adjusting the external cavity length. Due to the use of FADOF, Faraday lasers are immune to the changes in current and temperature of the laser diode, a characteristic that distinguishes them from other types of ECDLs.

In the MTS system, the frequency of the Faraday laser is locked to the cycling transition of $6s^2S_{1/2}|F = 4\rangle - 6p^2P_{3/2}|F' = 5\rangle$ by the MTS technique, as shown in Fig. 1(c). The Faraday laser beam is divided into pump laser and probe laser for MTS locking by a half-wave plate (HWP) and a PBS. The pump laser is modulated by an electro-optic modulator (EOM) with a modulation frequency of 4.6 MHz. Then the modulation of the pump laser is transferred to the probe laser, which is received by the photoelectric detector (PD). The electrical signal of the PD is first amplified by an amplifier and then demodulated by a mixer with a demodulation frequency of 4.6 MHz to derive the MTS signal, as shown in Fig. 2. The MTS error signal is processed by a proportional integral derivative (PID) circuit (Vescent D2-125) to form a control signal, which is sent to the laser controller and laser diode for the low- and high-speed servo, respectively. In the low-speed servos, the control signal is processed by the laser controller and then fed back to

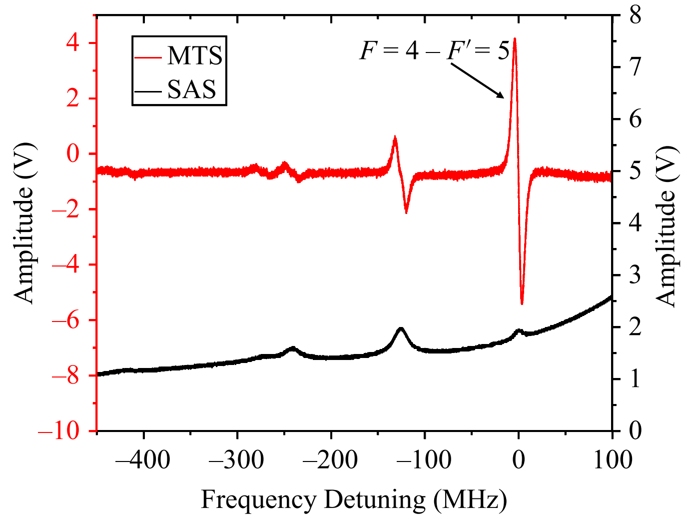

FIG. 2. Modulation transfer spectroscopy (red line) and saturation absorption spectroscopy (black line) of the Faraday laser.

the current and piezoelectric ceramic (PZT) of the Faraday laser.

As shown in Fig. 1(a), we implement two identical 852-nm frequency-stabilized Faraday laser systems to realize the optical heterodyne measurement. One of the identical Faraday lasers is frequency shifted by 350 MHz using an acousto-optic modulator (AOM). When both Faraday lasers are free running, the signal derived by the PD is sent into the spectrum analyzer; then, we can obtain the fitted full width at half maximum (FWHM) of the heterodyne beating signal, as shown in Fig. 3(a). Thirty sets of data are measured to obtain the most probable linewidth of the free-running Faraday laser, which is statistically calculated to be 12.7 kHz, so that the most available linewidth for a single laser is 9.0 kHz, as shown in Fig. 3(b). When both laser systems are locked, the linewidths of the 852-nm MTS systems are obtained using the same method. The corresponding heterodyne beating signal is shown in Fig. 3(c). The most probable linewidth between the two frequency-stabilized Faraday lasers is 3.5 kHz, so the most allowable linewidth of a single laser is 2.5 kHz, as shown in Fig. 3(d). The MTS technique greatly reduces the noise of the free-running Faraday laser. The narrow linewidth characteristic of the frequency-stabilized Faraday laser can significantly expand its application range.

Simultaneously, the heterodyne beating signal from the PD is sent into a frequency counter (Keysight 53230A) to measure the frequency stability of the Faraday laser. The frequency stability of the free-running Faraday laser measured by the heterodyne method is 3.0×10^{-10} at 1 s, as shown in Fig. 4. With both laser systems locked, the corresponding calculated frequency stability is shown in Fig. 4. The frequency stability of the heterodyne beating signal is 2.6×10^{-12} at 1 s, so the frequency stability of the single

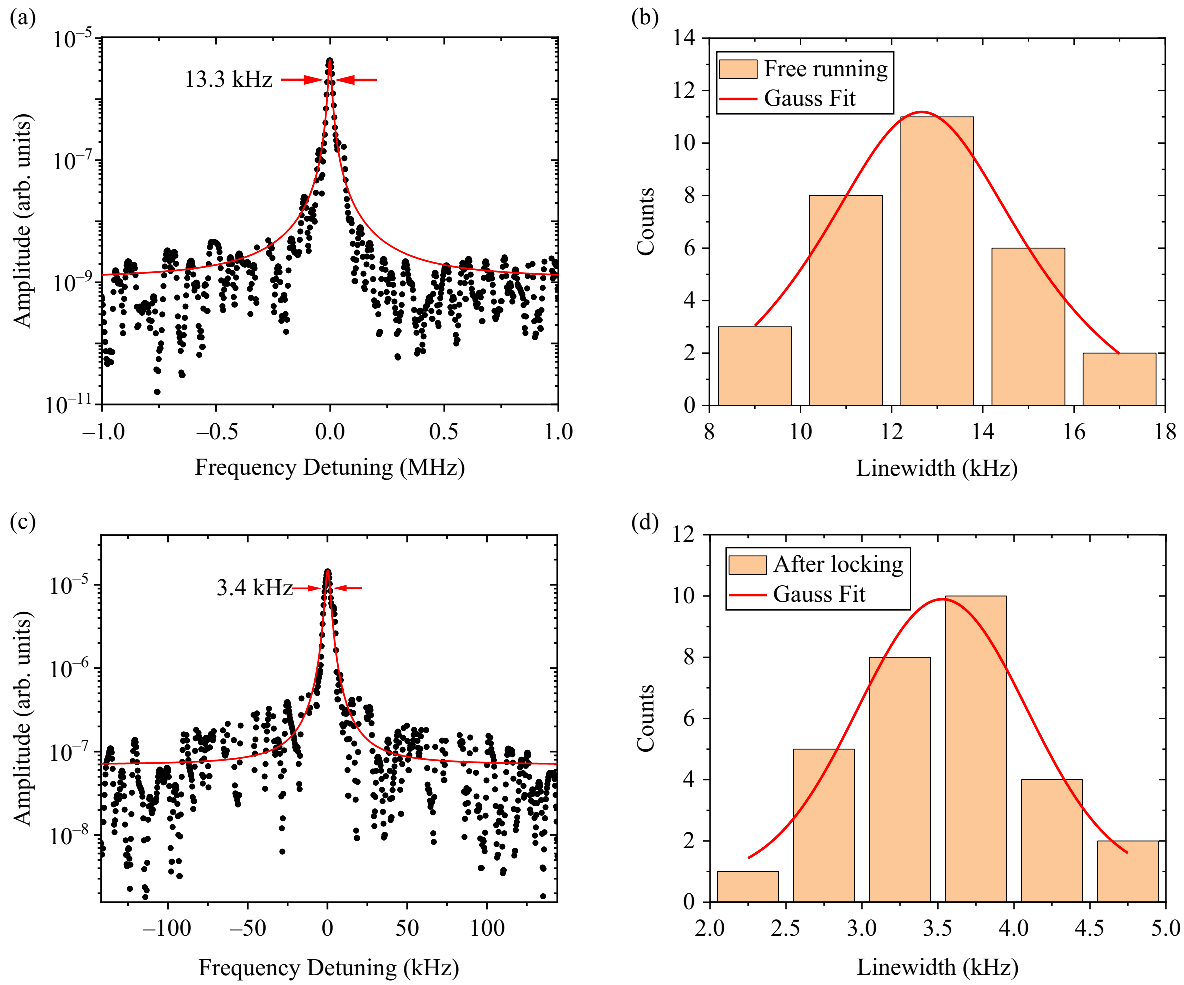

FIG. 3. (a) Typical beating signal of two identical 852-nm Faraday lasers when they are free running. (b) Histogram of repeated measurements of the fitted beating linewidths when the two identical 852-nm Faraday lasers are free running. (c) Typical beating signal of two identical 852-nm MTS systems when they are locked. The background of the beating signal mainly comes from mechanical vibration and the stabilization loop. (d) Histogram of repeated measurements of the fitted beating linewidths when the two identical 852-nm MTS systems are locking. In (a),(c), the black dots represent the experimental results of the beating signal, and the red line represents the Lorentz fit of the experimental results. The reduced chi squared of the fits in (a),(c) are 5.58×10^{-15} and 5.40×10^{-14}, respectively. In (b),(d), the red lines represent the Gauss fit of the histogram data.

frequency-stabilized Faraday laser is 1.8×10^{-12} at 1 s. In the MTS system, we use a double-layer vapor cell as the absolute frequency reference. The space between the two quartz layers of the double-layer vapor cell is pumped into a vacuum, so the double-layer vapor cell can effectively suppress the drift in the frequency of the cesium transition lines, which is caused by the ambient temperature fluctuations.

In the cesium beam clock, the pumping and detection lasers are derived from the same Faraday laser frequency stabilized on the cesium cycling transition. The output of the Faraday laser is split into two beams. One beam is directly used as the detection laser, whereas the other beam is frequency shifted by 251.1 MHz using an AOM and subsequently used as the pumping laser, which has a frequency corresponding to the $6s^2S_{1/2}|F=4\rangle - 6p^2P_{3/2}|F'=4\rangle$ transition line. The corresponding atomic transitions are schematically shown in Fig. 1(c). Both the pumping and the detection lasers pass through the beam expanders before being injected into the cesium beam tube, enlarging the interaction area between laser beams and cesium beam by a factor of approximately 10. In the area where the cesium beam interacts with the pumping laser, a reflector is mounted on the back of the cesium beam tube to reflect the pumping laser to interact with the cesium beam again to improve the pumping efficiency.

III. RESULTS

A microwave signal synthesized by a 10-MHz voltage-controlled crystal oscillator (VCXO) acts on the microwave cavity and tuned with a center frequency of

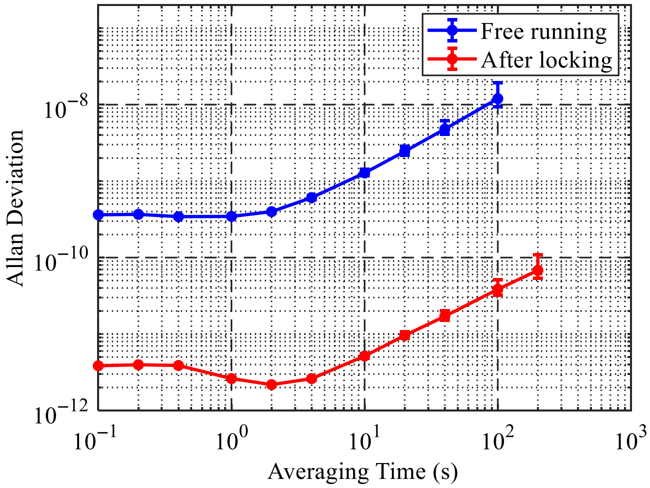

FIG. 4. Frequency stability of the free-running Faraday laser and frequency-stabilized Faraday laser measured by the heterodyne measurement method. The frequency drift of the free-running Faraday laser is mainly caused by fluctuations in the external cavity length and in the laser diode temperature. The deterioration in frequency stability of the frequency-stabilized Faraday laser is mainly caused by the drift of temperature within the cesium vapor cell in the MTS system, which is used as frequency reference.

9.192631770 GHz. The cesium oven temperature is set at 110 °C. The linewidth and amplitude of the Ramsey fringe are 551.4 Hz and 461.85 mV, respectively, as shown in Fig. 5. The cesium beam clock operates at a modulation frequency of 137 Hz, and the noise of the Ramsey fringe signal is analyzed using a fast Fourier transform spectrum analyzer (Stanford Research Systems, SR770). The noise at 137 Hz is 20.45 $\mu V/\sqrt{Hz}$. Thus, the SNR in 1-Hz bandwidth at 137 Hz is SNR $= S/N \approx 22\,600$, where S is the amplitude of the Ramsey fringe and N is the noise of the Ramsey fringe at 137 Hz. The Ramsey fringe signal is modulated and demodulated to produce an error signal, which is used to stabilize the output frequency of the VCXO via servo circuits.

After locking the 10-MHz VCXO of the cesium beam clock, we compare the 10-MHz output of the VCXO with that of a hydrogen maser (VREMYA-CH, VCH-1003M, option L) using high-performance phase noise and Allan deviation analyzer (Microsemi, 5120A). The frequency stability of the Faraday-laser-pumped cesium beam clock is 2 times better than that of the DFB laser-based cesium beam clock [39], as shown in Fig. 6. In addition, the Faraday-laser-pumped cesium beam clock has significantly better frequency stability than the cesium beam clock based on the interferometer ECDL [13], which is 3.7×10^{-13} at 100 s. The three cesium beam clocks are only different in the laser categories; in other words, they use the same cesium beam tube and electronic system, and their cesium oven temperatures are all set at 100 °C. Thus, the comparison results highlight the superiority of the Faraday laser, which has a narrow linewidth and superior frequency stability.

We try different cesium oven temperatures, which directly affect the SNR of the Ramsey fringe. As shown in Fig. 7, when the cesium oven temperature is increased to 110 °C, the frequency stability of the cesium beam clock reaches $1.3 \times 10^{-12}/\sqrt{\tau}$, which decreases to 1.4×10^{-14} at 10 000 s. The Faraday-laser-pumped cesium beam clock has better frequency stability than any reported compact cesium beam atomic clocks to our knowledge, which is

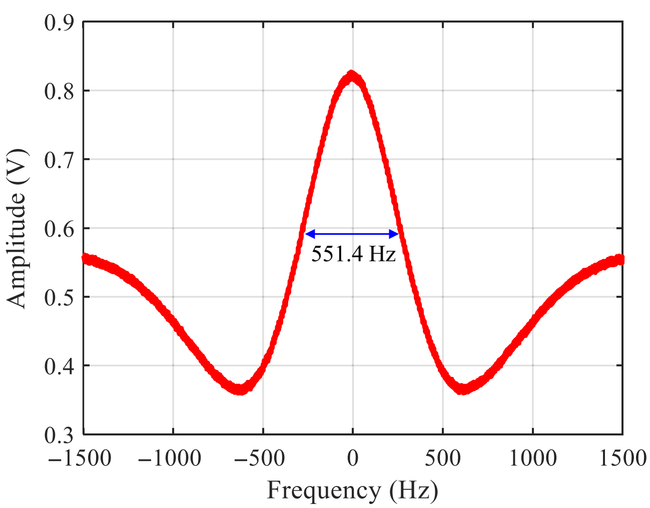

FIG. 5. Ramsey fringe of the microwave clock transition which has a central frequency corresponding to the cesium transition $6s^2S_{1/2}|F=3, m_F=0\rangle - 6s^2S_{1/2}|F=4, m_F=0\rangle$. The linewidth of the Ramsey fringe is 551.4 Hz.

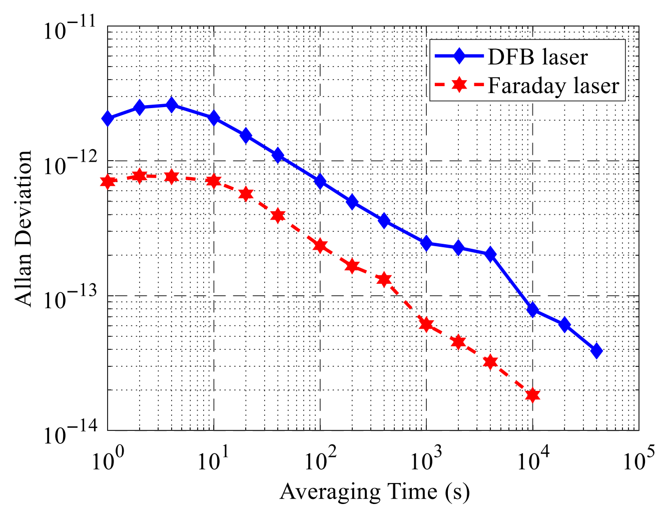

FIG. 6. Frequency stability of the cesium beam clocks based on different types of lasers. The blue line shows the result of Ref. [39] using the DFB laser. The red line shows the result of the Faraday-laser-pumped cesium beam clock.

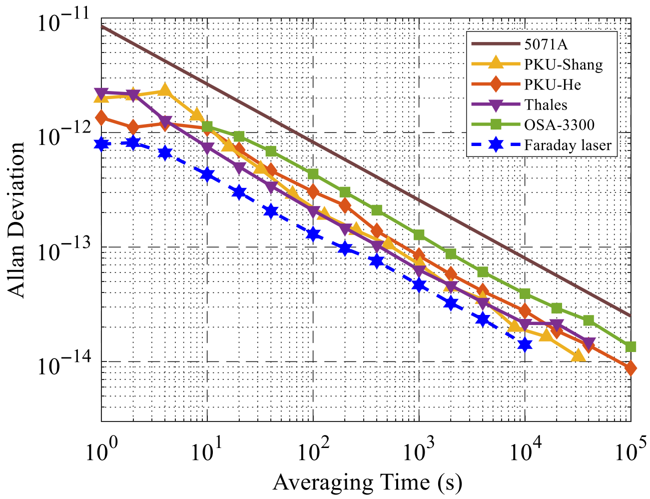

FIG. 7. Frequency-stability comparison of the cesium beam clocks. The brown line shows the frequency stability of the magnetic-state-selecting cesium beam clock called 5071A. The other lines show several frequency stabilities of optically pumped cesium beam clocks. The yellow line shows the result by Shang *et al.* [13]. The orange line shows the result by He *et al.* [15]. The purple line shows the result by Thales [12]. The green line shows the result of OSA-3300 by Oscilloquartz [16]. The blue line shows the result of the Faraday-laser-pumped cesium beam clock.

attributed to the narrow linewidth and low frequency noise of the Faraday laser system resulting in a high SNR of the Ramsey fringe. Moreover, the frequency stability of our clock is 7.9×10^{-13} at 1 s, which first reaches the 10^{-13} magnitude. When the cesium oven temperature is 130 °C, the SNR of the Ramsey fringe in 1-Hz bandwidth at 137 Hz will reach 39 600, which can result in frequency stability. Considering the lifetime of the cesium beam tube, the oven temperature is set at 110 °C. The increase in signal intensity caused by the increase in oven temperature does not necessarily directly lead to a higher SNR, which requires the support of a laser with low frequency noise [17].

In the future, we will apply autolocking circuits to extend the measurement time of the cesium beam clock by automatically locking and relocking the Faraday laser, which will fully demonstrate the excellent long-term performance of the cesium beam clock.

IV. CONCLUSION

We implement a Faraday-laser-pumped cesium beam clock. The application of the Faraday laser to a cesium beam clock has several advantages. First, the Faraday laser is immune to the changes in current and temperature of the laser diode. Second, because the Faraday laser uses atoms as a frequency reference, the Faraday laser can automatically operate at the frequency of the atomic spectra once switched on and does not require manual tuning. Third, the frequency-stabilized Faraday laser based on the MTS technique has narrow linewidth and high-frequency stability. Measured by the optical heterodyne method, the linewidth of the frequency-stabilized Faraday laser is 2.5 kHz, and the frequency stability of the frequency-stabilized Faraday laser is 1.8×10^{-12} at 1 s because of the high SNR of the MTS signal. Thus, the application of the Faraday laser to a cesium beam clock can enhance the SNR of the Ramsey fringes, leading to the optimization of the cesium beam clock's performance. When the cesium oven temperature is 110 °C, the cesium beam clock achieves an SNR in 1-Hz bandwidth of 22 600, and the frequency stability of the cesium beam clock is $1.3 \times 10^{-12}/\sqrt{\tau}$, and decreases to 1.4×10^{-14} at 10 000 s. When the cesium oven temperature is 130 °C, the cesium beam clock achieves an SNR in 1-Hz bandwidth of 39 600. This Faraday-laser-pumped cesium beam clock has great potential and value in the fields of timekeeping, navigation, and communication. Moreover, the frequency-stabilized Faraday laser in this experiment can be applied in the field of precision measurements to further improve the performance of atomic clocks, atomic gravimeters, atomic magnetometers, and other applications. In our future work, we will aim to improve the atomic utilization efficiency of the cesium beam by a hexapole magnetic system [14] and two-laser pumping scheme [40] and optimize the linewidth and noise of the Faraday laser to improve the performance of the cesium beam clock.

ACKNOWLEDGMENTS

This study was funded by China Postdoctoral Science Foundation (Grant No. BX2021020), National Natural Science Foundation of China (NSFC) (62405007), Wenzhou Major Science & Technology Innovation Key Project (Grant No. ZG2020046), and Innovation Program for Quantum Science and Technology (Grant No. 2021ZD0303200).

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