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# Compact optically pumped cesium beam atomic clock with a 5-day frequency stability of $7 \times 10^{-15}$

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**Compared to other commercial atomic clocks in the time keeping field, the greatest advantage of cesium beam atomic clocks is their superior long-term stability. Compared to magnetic state-selection clocks, optically pumped cesium beam atomic clocks have more interacting atoms, which results in better stability potential. To achieve good long-term stability, we propose methods including stabilization of laser power and reconstruction of circuits. They play a key role in the long-term stability of cesium beam atomic clocks. After 75 days of continuous running and measurement, we released the 5-day stability results ($7 \times 10^{-15}$ Allan deviation) of our optically pumped cesium beam atomic clock. To the best of our knowledge, this is the best 5-day stability result ever reported for compact optically pumped cesium beam atomic clocks.**

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## 1. INTRODUCTION

Atomic clocks have been used in many aspects of human life [1–5]. Since Ramsey proposed the technology of separating oscillatory fields in 1950 [6], people have progressively entered the era of atomic time. Cesium beam tube (CBT) atomic clocks are products commonly used this technology. Magnetic state-selection CBT atomic clocks [1,7,8] are the largest contributors of TAI and UTC.

An optically pumped CBT atomic clock was first proposed and realized in 1980 [9]. Cesium atoms can be configured to the required energy level by using an optical pumping technique [10]. At the same time, the detection of atomic states can also be completed by laser-induced fluorescence spectroscopy of atomic beams. Comparing magnetic state-selection and optically pumped CBT atomic clocks, the latter has advantages of atomic utilization and detection efficiency, atomic utilization is the essential advantage of optically pumped CBT atomic clocks. It means an enhanced cesium beam can be used and a better signal-to-noise ratio (SNR) can be obtained. The number of interacting atoms is an important factor that determines atom shot noise and limits the stability of CBT atomic clocks [11]. Atomic utilization also results in a potentially longer lifetime than magnetic state-selection CBT atomic clocks.

Many groups have been devoted to research on long primary or miniature optically pumped CBT atomic clocks [12–23], and Oscilloquartz and Chengdu Spaceon have released commercial optically pumped CBT atomic clocks. Existing results, $(1-3) \times 10^{-12}/\sqrt{\tau}$, have proven the advantage of these clocks with respect to short-term stability. However, another important aspect of CBT atomic clocks is long-term stability. Strictly speaking, long-term stability should be achieved with an average Allan deviation of at least 5 days, which means the long-term stability results need to be measured for at least 75 days (15 times the average duration makes the result credible). Therefore, 5-day stability is also important besides short-term stability in compact CBT atomic clocks. This is different from rubidium atomic clocks and H-masers. There are no clear reports of such indicators, and credible results for optically pumped CBT atomic clocks have not yet been released.

In this paper, we review the principles and structure of our optically pumped CBT atomic clock briefly in Section 2. In Section 3, we propose crucial improvements to make the optically pumped CBT atomic clock break through the stability of the 1-day averaging time and obtain long-term stability. We obtain a 5-day stability of $7 \times 10^{-15}$, which demonstrates the superiority of optically pumped CBT atomic clocks for the first time.

## 2. PRINCIPLES AND STRUCTURE

Most compact optically pumped CBT atomic clocks have the same basic structure (length of the CBT, shape of the microwave

**Table 1. Parameters in the Optically Pumped Cesium Beam Atomic Clock**

| Parameters | Value | Note |
|---|---|---|
| Distance of two cavities ($L$) | 16.7 cm | – |
| Oven temperature ($T_{\text{oven}}$) | 100°C | <0.01°C |
| Cesium atomic beam ($I_a$) | $4.13 \times 10^{13}$ atoms/s | $<4.13 \times 10^8$ atoms/s |
| Vacuum ($V$) | $10^{-7}$ Pa | – |
| Zeeman shift ($f_Z$) | 60 kHz | <1 mHz |
| Microwave power ($P_m$) | 1 mW | <0.01 dBm |
| Linewidth of laser ($\nu$) | 0.6 MHz | – |
| Pumping laser power ($I_{\text{pump}}$) | 2 mW | <0.02 μW |
| Probing laser power ($I_{\text{probe}}$) | 2 mW | <0.02 μW |
| Laser beam size | $6 \times 2$ mm$^2$ | – |
| Linewidth of the Ramsey ($\Delta\nu$) | 580 Hz | – |
| Modulation frequency ($f_c$) | 100 Hz | – |
| Modulation depth ($f_m$) | 280 Hz | – |
| Rated power | 60 W | <100 W |
| Weight | 30 kg | – |
| Volume (L × W × H) | $500 \times 440 \times 175$ mm$^3$ | – |

cavity, structure of the instrument). The information and parameters of our optically pumped CBT atomic clock are shown in Table 1 (principles and working processes of the clock are shown in Fig. 1; see [22,24] for more details). We review only the key characteristics in this paper. Compared with other optically pumped CBT clocks, our clock uses a distributed feedback (DFB) laser (EYP-DFB-0852) to generate laser beams in the Cs-133 D2 line for optical pumping (Cs-133 D2 $|F=4\rangle - |F'=4\rangle$ transition line) and state probing (Cs-133 D2 $|F=4\rangle - |F'=5\rangle$ cyclic transition line). The realization of long-term stability still requires a DFB laser for support. An acousto-optical modulator (AOM) with an injected radio frequency of 251 MHz (frequency difference between $|F=4\rangle - |F'=4\rangle$ and $|F=4\rangle - |F'=5\rangle$ lines) is used in the optical path. A cesium atomic beam is emitted from the Cs oven and interacts with the pumping laser, a microwave signal (twice), and the probing laser in turn. The microwave signal is generated based on an oven-controlled crystal oscillator (OCXO, MV200). The Ramsey signal is obtained from the photodetector (PD3) in the detection area. We use slow square-wave frequency modulation to stabilize the frequency of the OCXO by Ramsey spectroscopy. The microwave power is stabilized at the point where the transition probability is maximal [25]. The servo method is shown in Fig. 1(b). The error signal ($\propto (S_{P1} - S_{P2})$) of microwave power is obtained by square-wave amplitude modulation. The C field was stabilized by fixing $f_Z$. The two servo systems operate for 1 s every 2 min each. During the frequency servo of the OCXO, the microwave power and C field remain unchanged. A compatible ultralow noise source management system is applied in our clock. The whole machine is 4U in size (L × W × H, $500 \times 440 \times 175$ mm$^3$). It weighs approximately 30 kg. The rated power is 60 W. The accuracy of compact CBT atomic clocks is limited to the uncertainty of an end-to-end phase shift caused by the different lengths of the two cavity arms [13]. This shift cannot be measured or compensated for in a compact CBT atomic clock. The length difference of our two microwave cavity arms is approximately

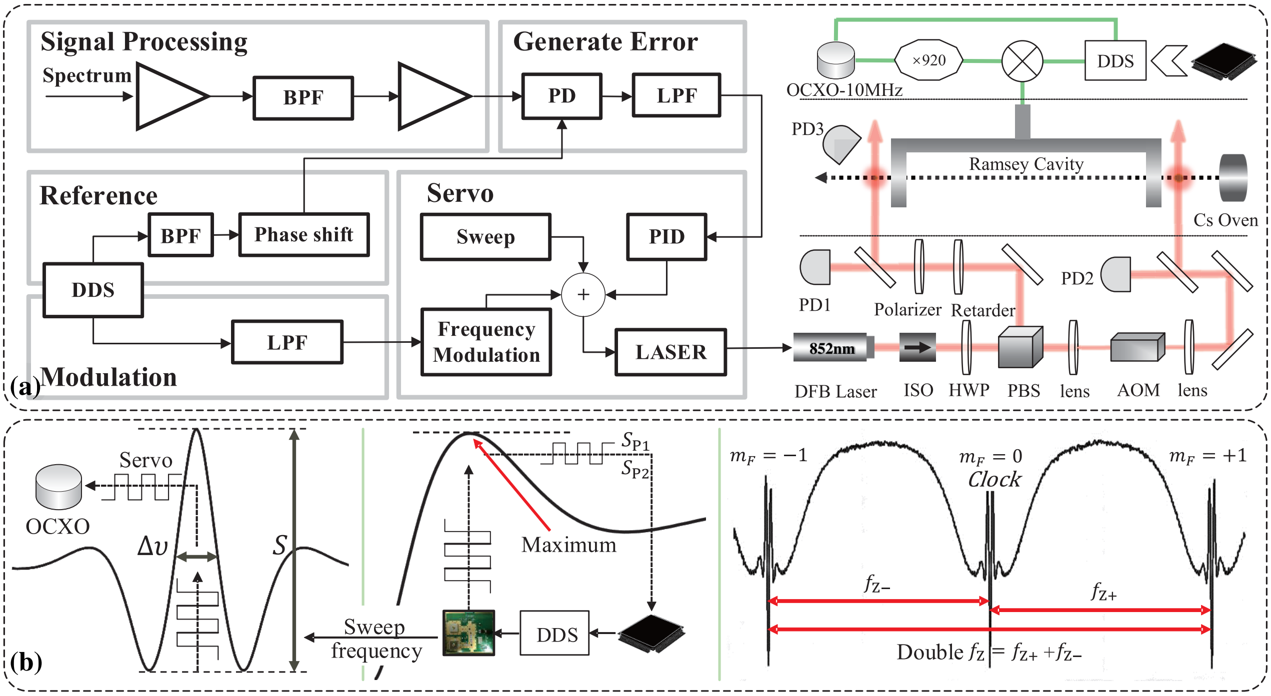


**Fig. 1.** (a) Diagram of the optically pumped CBT atomic clock. The laser system is the most distinctive part, and the laser frequency stabilization system is the core technique that makes our atomic clock remarkable. PD, phase detector; LPFs, BPFs low- and bandpass filters. The optical part of the atomic clock includes a laser, isolator (ISO), half-wave plate (HWP), polarizing beam splitter (PBS), AOM, phase retarder, polarizer, two convex lenses, and multiple reflectors. PDxs, photodetectors. A direct digital synthesizer (DDS) is used in the circuit to generate the interrogation signal. (b) Frequency servo of the OCXO, power servo of the microwave source, and C field servo. They are important characteristics of digital circuit control systems.

±0.025 mm in the manufacturing process, corresponding to a phase difference of $\Delta\phi = 10$ μrad at worst. Therefore, the fractional frequency shift and uncertainty budget from the effect is $2.39 \times 10^{-13}$ [14]. Uncertainty budgets from the other physical effects are of the order of $10^{-14}$ or $10^{-15}$ [13,22]. Therefore, the total uncertainty is evaluated within $3 \times 10^{-13}$.

## 3. MEASUREMENT AND IMPROVEMENT

High-precision instruments are easily affected by environmental fluctuations [26]. We establish an appropriate room with controllable environmental conditions for the experiment. The temperature and humidity in the room are kept stable to provide a long-term frequency comparison. The temperature is set to 23°C, and the ambient humidity is approximately 45%. These are basic conditions of our laboratory, which are in line with the application environment of compact CBT atomic clocks. We use the output signal from a calibrated hydrogen maser as the reference.

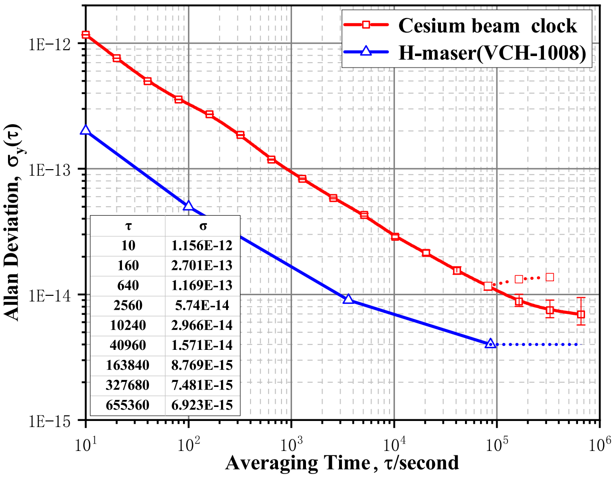
The improvement of laser performance plays the most important role. Compared with magnetic state-selection CBT atomic clocks, additional modules are included in the clock to control the frequencies and powers of the two lasers. We use the laser-induced fluorescence spectrum of a cesium atomic beam to stabilize the laser frequency instead of the traditional saturated absorption spectrum (SAS) in a cesium vapor cell [27]. The laser-induced fluorescence spectrum in the Cs-133 $|F=4\rangle - |F'=5\rangle$ transition line has a higher SNR than other spectra, which is good for laser stability. The utilized automatic frequency stabilization system ensures that the laser frequency can be locked for a long time in the presence of external disturbances. Once the DFB laser is unlocked (the fluorescence decreases rapidly by more than 60%), the automatic stabilization system can find the spectrum rapidly and relock. The modulation frequency we used in laser frequency stabilization is 10 kHz, and the modulation depth is approximately 3 MHz. The frequency stability of the laser is $3.5 \times 10^{-11}/\sqrt{\tau}$. The diagram of the laser frequency stabilization is shown in Fig. 1(a).

A frequency shift related to laser power is one of the new factors introduced in optically pumped CBT atomic clocks. In the past, an absolute laser power stabilization method [22] was used in our optical system to stabilize the light shift. The intensities of the pumping laser and probing laser were stabilized using the AOM and a phase retarder. PD1 and PD2 were used for probing the two laser powers. The laser powers emitted into the CBT could be stabilized in $10^{-5}$. When the temperature of the cesium oven was quite stable (<0.01°C), we found that the fluorescence in interaction areas still drifted $10^{-2}$ in a long-term measurement. That meant the number of photons emitted from the atomic beam was not stabilized. The above fluorescence photons were the direct reason for the light shift in reality. The mechanical deformation of the physical systems including the tube and optical path in long-term measurement led to the phenomenon, and it could hardly be predicted or measured. Therefore, the absolute laser power stabilization method [22] was limited. In addition, we know that the power of the probe laser directly affects the peak-to-peak value of the Ramsey signal, and the peak-to-peak value of the Ramsey signal directly affects the feedback strength. Reference [28] proposed that the Ramsey signal should be maintained by modifying the gain of the amplifiers. Considering both situations, we realize the scheme of fixing the fluorescence signal in the detection area by controlling the probe laser power

$$
\begin{aligned}
E_{0+m} &\propto S_{0+m} - S_c, \\
E_{0-m} &\propto S_{0-m} - S_c,
\end{aligned}
\tag{1}
$$

where $S_c$ is a constant, and it is related to the set point of the laser power. $S_{0+m}$ and $S_{0-m}$ are obtained by sampling in the process of frequency modulation, at the positions $f_0 + f_m$ and $f_0 - f_m$, respectively. $E_{0+m}$ is the error signal of the laser power stabilization, and $E_{0-m}$ is the error signal feedback to the OCXO. Besides PD3 in the detection area, we add a photodetector to the pump area. Then, the fluorescence detected in the pump area is fixed by controlling the pump laser power. In this way, the total number of photons emitted from the atomic beam is stabilized ($10^{-5}$), and the feedback strength is also stabilized. Therefore, the frequency instability induced by laser power fluctuation ($4 \times 10^{-13}$/mW) is lower than $1 \times 10^{-17}$, and the stability of the atomic clock reaches $7 \times 10^{-15}$ in measurement. The improvement can reduce the laser power used for power detection in the original optical system, which enhances the efficiency of the laser. Thus, the laser can work under a lower current. It can mitigate the burdens and aging of the laser, which is important for long-term operation of the clock.

The circuit system is greatly improved. For precise instruments such as CBT atomic clocks, the interconnection and isolation of the signals in circuits need to be well designed. We follow a few guidelines: (1) possible loop current between each pair of modules is isolated; (2) directions of the signals in the system are unique, and there is no case in which the same physical transmission line is shared; (3) all wires in our clock are coaxial; (4) system has electromagnetic shielding and is connected to the Earth through a conductive chassis; (5) connection between each signal ground point and the ground plane is less than 5 cm. Therefore, the cross talk in the circuits is suppressed, which reduces the degree of unpredictable noise coupling. This



| τ | σ |
|---|---|
| 10 | 1.156E-12 |
| 160 | 2.701E-13 |
| 640 | 1.169E-13 |
| 2560 | 5.74E-14 |
| 10240 | 2.966E-14 |
| 40960 | 1.571E-14 |
| 163840 | 8.769E-15 |
| 327680 | 7.481E-15 |
| 655360 | 6.923E-15 |

**Fig. 2.** Line with red squares represents the stability of the optically pumped cesium beam atomic clock, and the red dotted line shows the previous. The blue triangle line is the Allan deviation of the reference (VCH-1008), and the blue dotted line is the estimated value. The specific calculated data are shown in Table 1.

improvement ensures the long-term normal operation of the atomic clock.

The measurement result is shown in Fig. 2. The clock obtains $3 \times 10^{-12}/\sqrt{\tau}$ short-term stability and becomes gradually closer to the reference over an approximately 5-day averaging time. At the same time, the relative frequency shift between the optically pumped CBT atomic clock and the calibrated (by UTC) H-maser is $2.30 \times 10^{-13}$. The results obtained from 75 days of measurement show that the stability of the clock reaches $7 \times 10^{-15}$ in 5 days.

## 4. CONCLUSION

In conclusion, we realized a high-performance optically pumped CBT atomic clock that reached a stability value of $7 \times 10^{-15}$ within 5 days from 75 days of measurement. The accuracy of the clock is $3 \times 10^{-13}$. This result is the best long-term stability value ever measured in a compact optically pumped CBT atomic clock. Compared with the techniques of previous works, the proposed methods of controlling the laser power and improvement of the circuits play key roles. Furthermore, limited by materials in terms of physical parts and device technology, we think that it is difficult to improve upon the obtained result under our current structure and conditions. The utilization of lasers with narrower (100 kHz typically) linewidths, such as extended-cavity diode lasers, could enhance the stability of optically pumped CBT atomic clocks [15,16,18,29]. Therefore, we think that the factor limiting the stability of our optically pumped CBT atomic clock is the frequency uncertainty of the DFB laser while maintaining the current atomic flux (according to [11]), which will be our next research direction. An important part of this process is to address the long-term reliability of these narrower linewidth lasers, which is a considerable problem. At present, the long-term stability we obtained is sufficient to meet the needs of positioning, navigation, timing systems, and high-speed communication systems. Our commercial optically pumped CBT atomic clocks will be released within a few years, and the CBT atomic clock will still be one of the main atomic clocks in the field of time keeping in the next few decades.

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**Data Availability.** Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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