Optical System for Time-keeping ^{87}Rb Fountain Clock

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***Abstract*—As laser-cooled atomic clock, optical system has a crucial impact on time-keeping ^{87}Rb fountain clock performance. This article presents an optical system for the clock that uses a highly reliable fiber laser with a miniaturized optical bench (integrated into a 600 mm × 500 mm × 100 mm aluminum box). The fiber laser acts as the cooling laser source and the bench enables laser frequency and power control. Some clever and modular designs in the bench simplify its complexity and reduce the number of components used, enhancing system continuous operation capability. Our time-keeping ^{87}Rb fountain clock based on the optical system now consistently reports data to the BIPM with little human intervention, proving that it meets the long-term operational requirements of fountain clocks.**

***Keywords*—time-keeping ^{87}Rb fountain clock, optical system, miniaturized optical bench,**

I. Introduction

Due to the excellent performance of fountain clocks and the inherently small collision frequency shift of ^{87}Rb atoms, some of the major international time laboratories have been developing time-keeping ^{87}Rb fountain clock to improve the performance of the local time scale [1,2,3,4,5,6]. As an atomic clock for time-keeping applications, continuous operation is of paramount importance. Optical system, as a subsystem of the time-keeping ^{87}Rb fountain clock, mainly determines the continuous operating capability of the clock [7].

Here we show an optical system based on operational requirements of our clock, using a highly reliable fiber laser and a miniaturized optical bench. The clock has reported to the BIPM and gained weights from October 2022 to the present, demonstrating that the optical system meets the requirements for long-term operation of a time-keeping ^{87}Rb fountain clock [8].

II. Optical System Design and Implementation

A. General description

The design idea of the optical system is as far as possible to follow the following principles: using highly reliable components, reducing the number of components, size and complexity. The schematic diagram of the optical system is shown in Fig. 1. The optical system consists of a cooling, repumping laser source and a miniaturized bench. The cooling laser source is a high-power fiber laser which using a highly reliable 1560 nm distributed feedback laser

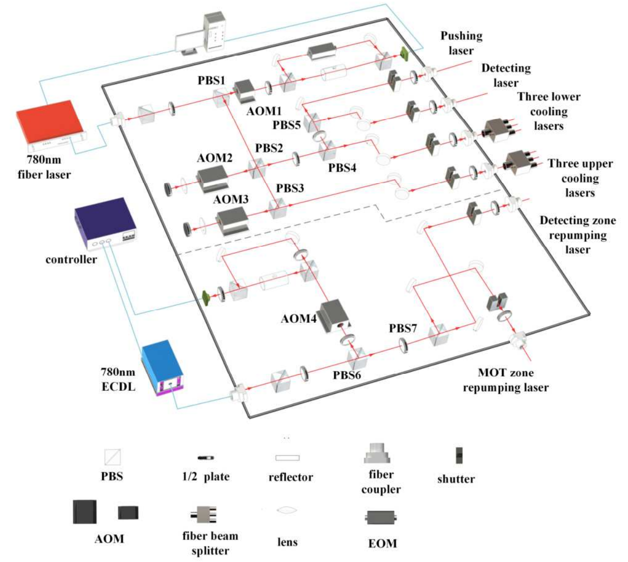

Fig. 1. Schematic diagram of the optical system. The blue dotted lines above and below represent the cooling and repumping paths, respectively.

(DFB) source amplified by erbium doped fiber amplifier (EDFA) and then doubled to 780 nm by a periodically poled lithium niobate (PPLN) crystal. The repumping laser source is a 780 nm external-cavity diode laser (ECDL). The bench is divided into a cooling path and a repumping path as shown by the dotted line in Fig. 1. The cooling path contains a frequency stabilized path using modulated transfer spectroscopy (MTS), the cooling and manipulation, pushing and the detection atomic path. The repumping path consists of a path for frequency stabilization by saturated absorption spectroscopy (SAS), and two fiber-coupled paths for transmitting repumping lasers to the magneto-optical trap (MOT)zone and the detecting zone, respectively. The bench is integrated in a 600 mm×500 mm×100 mm aluminium box. The rest of the article will introduce the optical system in terms of frequency control and power control.

B. Frequency Control

Frequency control comprises the following three aspects. The laser frequency requirements are shownin Fig. 2, where Γ is the natural line width of the ^{87}Rb atom D_2 line.

1) Frequency stabilization

Frequency stabilization of cooling laser is achieved with MTS, and the optical path is shown in Figure 1. The laser from the fiber laser is collimated by the coupler into the

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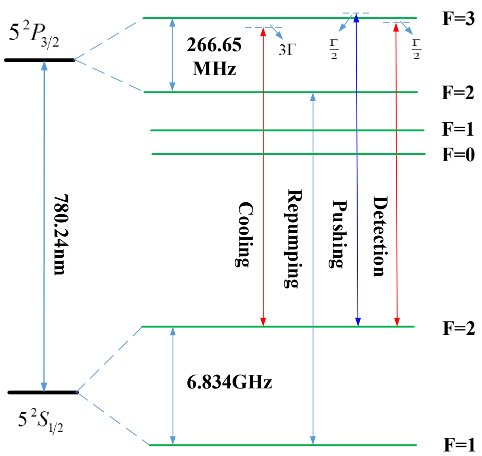

Fig. 2. Schematic Laser frequency detuning for the ^{87}Rb fountain clock.

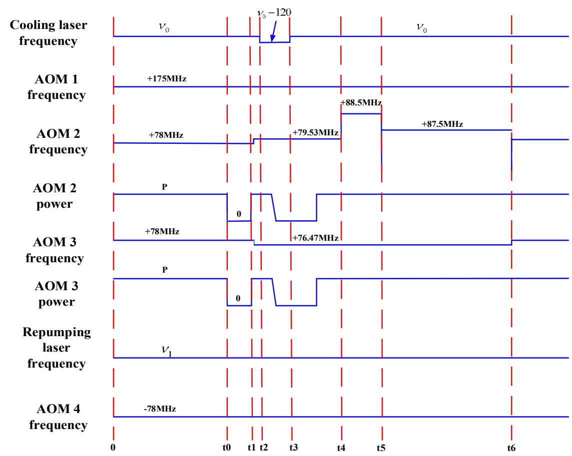

Fig. 3. The input signal frequency and power of AOMs in one operational cycle.

bench. It divided into two parts by polarization beam splitter1 (PBS1). One small part is blue-shifted by 175 MHz into MTS through acousto-optic modulator1 (AOM1). The input frequency, power and phase of the electro-optic modulator (EOM) as well as the frequency-stabilized optical path are optimized to obtain a good signal-to-noise ratio for the discriminative curve, which ultimately locks the cooling laser frequency to $|5^2S_{1/2}, F=2\rangle \rightarrow |5^2P_{3/2}, F=3\rangle$.

The cooling laser is digitally stabilized, with the starting time of the frequency stabilization coinciding with that of the clock operating cycle, and then corrected the fiber laser frequency every 20 ms.

The repumping laser is stabilized using SAS. The output laser of ECDL is divided into two parts by PBS9, and a small part is red-shifted 78 MHz into the SAS by AOM10. The laser is locked to the cross-peak between $|5^2S_{1/2}, F=1\rangle \rightarrow |5^2P_{3/2}, F=1\rangle$ and $|5^2S_{1/2}, F=1\rangle \rightarrow |5^2P_{3/2}, F=2\rangle$.

Both the MTS and SAS are designed as modules, which reduces the difficulty of adjustment and increases the reliability of the bench.

2) Frequency detuning

The MOT requires a red detuning of 19 MHz for the upper and lower three cooling beams. To obtain an initial vertical velocity of 4.13 m/s for atoms, the upper and lower cooling laser are red-detuned by 22.06 MHz and 15.94 MHz respectively. The above frequency detunings are achieved by double-passing through the AOM module. On the one hand, the input frequency of the AOM is changed to achieve detuning, on the other hand, double-passing AOM also ensures that the propagation direction of laser does not change when the input frequency of AOM changes, ensuring the stability of laser propagation direction.

As shown in Fig. 1, most of the laser from the fiber laser is divided into the three upper and lower cooling lasers, the pushing laser and the detection laser. The three upper cooling lasers pass through PBS3 with a double pass through AOM3. The lower cooling lasers, the pushing laser and the detection laser pass through PBS3 with a double pass through AOM3, and then are spatially separated by PBS4 and PBS5. As shown in Fig. 3, the above lasers act at different times in a clock cycle, so they can use an AOM2 to accomplish frequency shifting, which is one of the features of the bench. It simplifies the complexity of the laser path as well as reduces the number of components and improves the reliability of the bench.

The switching of the AOM input frequency is achieved by means of a high-speed microwave switch with a switching time of around 250 ns. Fig. 3 is a control diagram of the AOM input frequency and power at different phases of an operation cycle, where 0 to t6 represents one cycle duration, 0 to t0 represents capturing duration, v_0 and v_1 represents the frequency of cooling laser and repumping laser respectively, P represents the AOM input power.

3) Large frequency detuning

When the atomic samples are located at the intersection of the six cooling beams, sub-Doppler cooling is performed. The frequency of the cooling laser is red-detuned by about 120 MHz relative to $|5^2S_{1/2}, F=2\rangle \rightarrow |5^2P_{3/2}, F=3\rangle$. Such a large frequency detuning is achieved by changing the laser piezoelectric transducer (PZT) voltage of the laser with an adder. The two inputs of the adder are the AO signal and the laser frequency stabilization voltage signal respectively. In the cooling phase, the AO output is 0, and the voltage at the output of the adder is the frequency stabilization voltage $V1$. When sub-Doppler cooling begins, AO sweeps from 0 to v2, the output of the adder is $V1+V2$, and then returns to $V1$. Because the frequency stabilization of fiber laser is performed every 20 ms, and the duration of the large frequency detuning is 1.5 ms, the large frequency detuning does not affect the frequency stabilization of fiber laser. Compared to with using AOM, it achieves a large detuning amount and does not affect the laser power. This is another feature that distinguishes it from previous optical systems.

C. Power Control

1) Power control

In the sub-Doppler cooling phase, in addition to the large frequency detuning of the cooling laser, the power also needs to be attenuated to 0. Power attenuation is done by using a voltage-controlled attenuator (VCA).

When the voltage of VCA decays to 0 V, the input power of the AOM may not be completely decayed to 0, there is still residual laser. At this time, the shutters are turned off to ensure that the sub-Doppler cooling effect to play the best. this is a minor improvement. Of course the shutters have a more important role in reducing light shift [8].

2) Power transmission

The laser is coupled into polarization-maintaining fiber(PMF) through two 45-degree reflectors and couplers, and is then transmitted to the expanders in the physical package [9]. The 45-degree reflectors use low-drift optical mount with a diameter of 12.7 mm (Thorlabs), the coupler is a five-degree-of-freedom adjustable ultra-stable coupler (Thorlabs, model PAF2-7B). After the optical bench has been adjusted, user intervention is hardly required for six months or even longer. The coupling efficiency of the upward cooling laser (the three downward cooling laser) into PMF is close to 60% due to fiber beam splitter, and that of rest of lasers is above 70%. Although the coupling efficiency is slightly lower with fiber beam splitter, it reduces the number of PMFs and couplers used and improves the bench stability compared to previous optical systems [6].

3) Polarization alignment

Since the change in laser polarization (through the PMF) cause changes in optical power (polarization optical elements are included in the expander), A half-wave plate is installed before the coupler in the optical bench. By aligning the laser polarization direction with the slow axis of the PMF, a linear polarization extinction ratio of 25 dB or more can be achieved.

D. Other

The shutters are SR474s (SRS) with ultra-low vibration and negligible impact on the bench. The rise time is 500 μs (typical value), and the response time is about 2 ms (actual measurement value). Because the main function of shutter in the clock is to minimize light shift, there is no strict synchronization among the shutters. The rubidium cells used in MTS and SAS are placed in boxes made of permalloy. The optical system is placed on a commercially available vibration isolated platform with an ambient temperature variation of ±1.5 degrees. A picture of the miniaturized optical bench is shown in Fig. 4.

III. Discussion

The stability of the time-keeping ^{87}Rb fountain clock based on this optical system is shown in Fig. 5, with daily frequency stability of less than 6×10^{-16}.

The clock has been reporting data to BIPM since October 2022 to date, and the drift for each month is shown in Fig. 6.

All of the above indicate that the optical system described in the article meets the long-term operational requirements of a time-keeping ^{87}Rb fountain clock.

IV. Conclusions

This article describes the design and implementation of an optical system applied to our time-keeping ^{87}Rb fountain clock. The system uses a highly reliable fiber laser as the cooling laser source, and a miniaturized optical bench to achieve the control of laser frequency and power. Some clever and modular designs simplify its complexity and reduce the number of components used, thus enhancing its long-term operation capability.

Based on this optical system, the fountain clock has been reporting data to the BIPM, proving that it meets the needs of

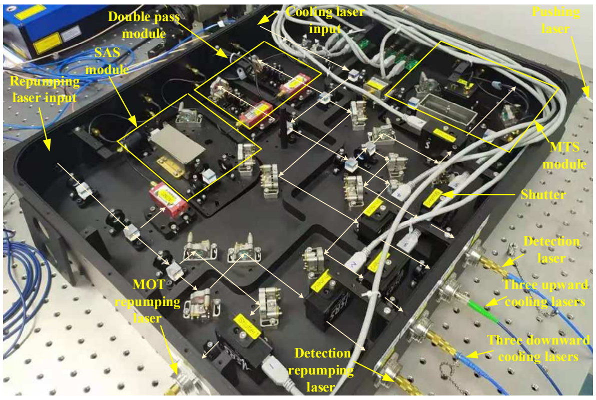

Fig. 4. A phtoto of the miniaturized optical bench.

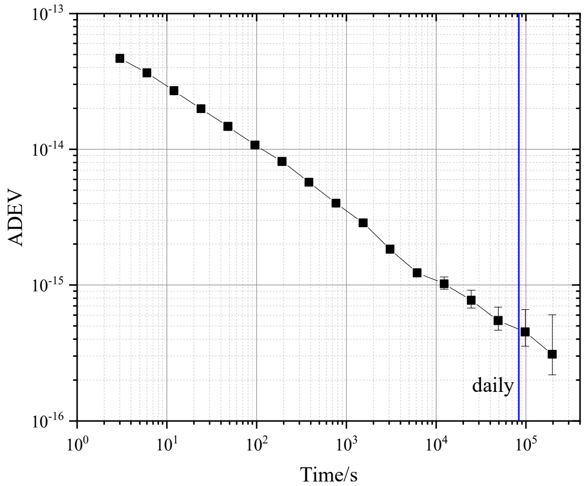

Fig. 5. Frequency stability of the ^{87}Rb fountain clock.

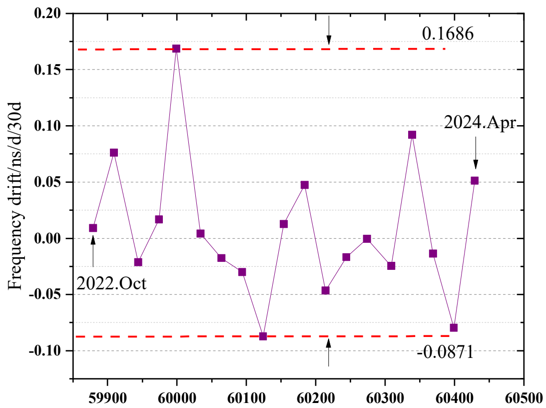

Fig. 6. Frequency drift of the the ^{87}Rb fountain clock.

the time-keeping ^{87}Rb fountain clock for long-term operation. The optical system can also be applied to other fountain clocks.

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