High-Stability Rb Optical Clock Based on Pulse-Modulated Broad-Spectrum Comb-Tooth Laser

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***Abstract*—We have proposed a new scheme to realize the Rb optical clock using a pulse-modulated broad-spectrum multi-frequency laser. By applying a pulse-modulated signal to a 420 nm external cavity diode laser, a broad-spectrum comb-tooth laser with multiple frequency components is generated, which can interact with almost all the Rb atoms with different transverse velocities, so that more Rb atoms in the Rb cell can contribute to the frequency stabilization signal of the clock transition spectral line. The effective atomic number is expected to be improved by a factor of 10^2 - 10^3, which will significantly improve the signal-to-noise ratio of spectrum, so as to optimize the frequency stability of Rb optical clock. The Rb optical frequency standard with high stability can be widely used in laser physics and precision measurement.**

Keywords—pulse-modulated; broad-spectrum; multi-frequency; effective atomic number; frequency stability

I. Introduction

Among the alkali metal elements, Rb atoms have the advantages of low melting point, high storage and easy extraction. In general, sufficient saturated vapor pressure can be prepared by heating the thermal atomic cell above room temperature to realize the atomic clock system. Therefore, Rb atom is one of the most classical quantum references in the development of atomic clock. At present, Rb atoms have been used in space cold atomic clock [1], laser-pumped atomic clock [2-5] and coherent-population-trapping atomic clock [6-9], all of which show a broad research prospect and wide application range.

However, the existing preparation technologies of Rb optical clock all use single-frequency laser output [10-12], so that only a few Rb atoms with near-zero transverse velocities can contribute to the frequency stabilization signal of the clock transition spectral line. The effective utilization rate of Rb atoms is very low, which limits the further improvement of the frequency stability of Rb optical clock.

Here, we innovatively propose a new scheme to realize the Rb optical clock using a pulse-modulated broad-spectrum multi-frequency laser. By applying a pulse modulation signal to the 420 nm external cavity diode laser, a broad-spectrum comb-tooth laser with multiple frequency components is generated, which can interact with almost all the Rb atoms with different transverse velocities, so that more Rb atoms in the Rb cell can participate in the contribution to the clock transition spectral line. It can greatly improve the effective utilization rate of Rb atoms, and then achieve extremely high signal-to-noise ratio, so as to improve the frequency stability of Rb optical clock. This new scheme can well solve the problem that only a few ground-state atoms contribute to the transition spectral line in the existing technologies, which leads to the low utilization rate of Rb atoms and further limits the improvement of the Rb optical clock's frequency stability.

II. Methods

The scheme of the experimental setup is shown in Fig. 1. The driving control system applied a pulse-modulated signal to the 420 nm external cavity diode laser (ECDL) to obtain a 420 nm comb-tooth multi-frequency laser signal. The total spectrum width of the 420 nm multi-frequency laser signal can be adjusted from 1 GHz to 50 GHz, and the frequency interval between any two adjacent comb teeth can be adjusted from 5 MHz to 20 MHz. It matches the Doppler broadening of atomic spectral line in the corresponding temperature of Rb cell, and the single comb-tooth linewidth is less than the transition energy level linewidth.

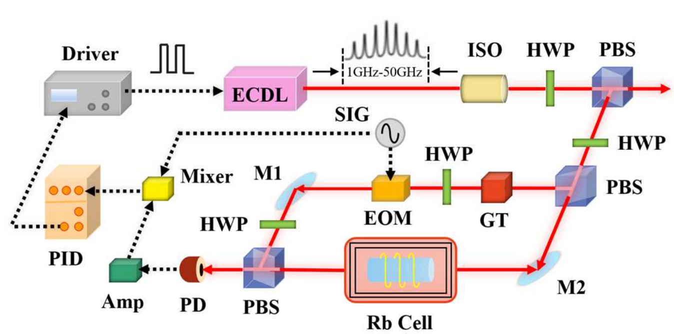

Fig.1. Scheme of the experimental setup (internal modulation). ECDL: external cavity diode laser; ISO: isolator; HWP: half-wave plate; PBS: polarizing beam splitter; GT: Gran-Taylor prism; EOM: electro-optic modulation crystal; M: mirror; PD: photo-electric detector; SIG: signal generator; Amp: amplifier; PID: proportion-integral-derivative locking system.

Then, after passing through the optical isolator (ISO) used to isolate stray light, the 420 nm broad-spectrum comb-tooth laser is divided into two beams by the polarizing beam splitter (PBS). One beam is used for beating frequency comparison with other systems, and the other beam is used to interact with atoms to generate quantum reference spectral line for closed-loop locking. In this scheme, we use the modulation transfer spectrum (MTS) technology to stabilize the 420 nm broad-spectrum multi-frequency laser. After the processing of frequency mixing and demodulation, the error signal is transmitted to PID controller to generate servo signal to control the driving control system, so as to realize the Rb optical clock with high frequency stability.

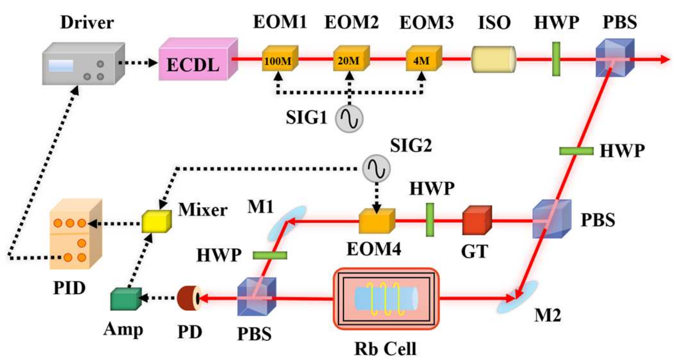

Fig. 2. Scheme of the experimental setup (external modulation). ECDL: external cavity diode laser; EOM: electro-optic modulation crystal; ISO: isolator; HWP: half-wave plate; PBS: polarizing beam splitter; GT: Gran-Taylor prism; M: mirror; PD: photo-electric detector; SIG: signal generator; Amp: amplifier; PID: proportion-integral-derivative locking system.

In addition to the above internal modulation scheme, we also provide an external modulation scheme to generate the broad-spectrum comb-tooth laser signal. The scheme of the experimental setup is shown in Fig. 2. Laser from the 420 nm external cavity diode laser (ECDL) passes through three electro-optic modulation crystals (EOM1, EOM2, and EOM3) with modulation frequency of 100 MHz, 20 MHz and 4 MHz, respectively. The proportion of the three modulation signals is 5 times strictly controlled by the signal generator (SIG1). Each electro-optic modulation crystal can modulate the dominant frequency laser into a ±2 order sideband, thus generate 125 broad-spectrum comb-tooth laser with multiple frequency components. Fig. 3 depicts the generation process of the broad-spectrum comb-tooth laser signal with multiple frequency components generated by EOM three times modulation.

III. DISCUSSION

This experimental scheme is not only suitable for 420 nm Rb optical clock, but also can be used in different spectral lines of different alkali metal atoms, such as Cs. It provides a new idea and method to improve the frequency stability of other alkali metal atom optical clocks. At present, as shown in Fig. 4, we have experimentally observed the saturation absorption spectrum (SAS) and modulation transfer spectrum (MTS) of Rb atom 420 nm single frequency laser, and achieved the frequency

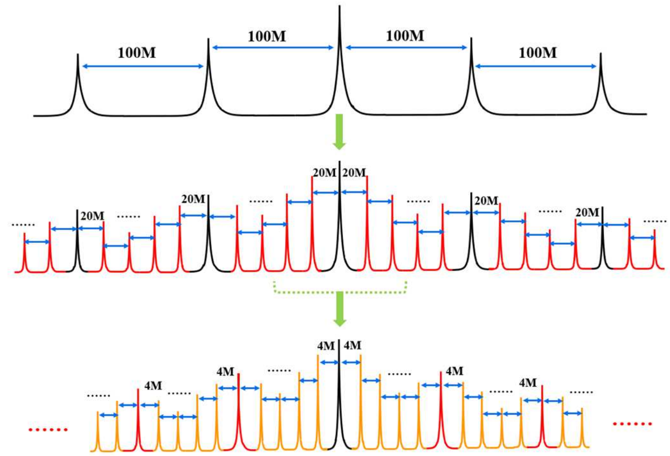

Fig. 3. Broad-spectrum comb-tooth laser signal with multiple frequency components generated by EOM three times modulation.

stability of 6×10^{-15} at 1 s under self-evaluation. Next, we will build a 420 nm broad-spectrum comb-tooth laser with multiple frequency components, and apply it to the Rb optical clock, hoping the frequency stability of Rb optical clock can be further improved.

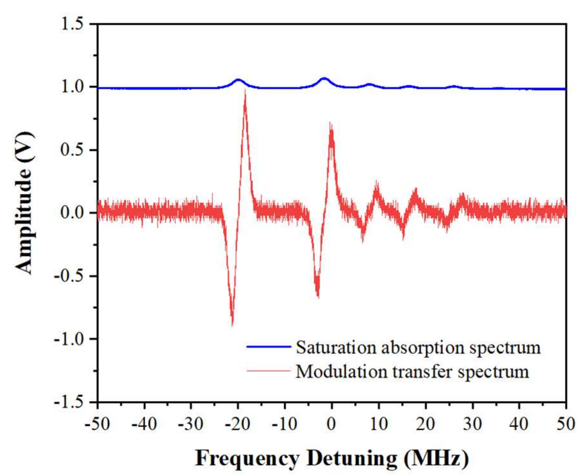

Fig. 4. The saturation absorption spectrum and modulation transfer spectrum of Rb at $5S_{1/2}$ (F=3) - $6P_{3/2}$ transition.

IV. CONCLUSIONS

In order to make more atoms in the Rb cell participate in the contribution to the clock transition spectral line, we innovatively propose a new scheme of building Rb optical clock using a pulse-modulated broad-spectrum comb-tooth laser. This kind of broad-spectrum multi-frequency laser can interact with almost all the Rb atoms with different transverse velocities, the effective atomic number is expected to be improved by a factor of 10^2 - 10^3. Based on this, the signal-to-noise ratio of the clock transition spectral line can be greatly improved, so as to optimize the frequency stability of Rb optical clock. Such a Rb optical clock with high frequency stability will have promising applications in diverse areas, including laser physics and precision measurement.

ACKNOWLEDGMENT

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