Active Faraday optical frequency standard based on diffuse laser cooling of ^{87}Rb atoms

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***Abstract* — We proposed a scheme for realizing active Faraday optical frequency standards using diffuse laser cooling of alkali-metal atoms. A 1-m-long cold ^{87}Rb atomic cloud was prepared within a ϕ 2 cm × l 1 m vacuum glass tube, featuring a maximum optical density of 4. By utilizing this setup to construct the Faraday anomalous dispersion optical filter, we are able to achieve an ultra-narrowband laser gain close to the natural linewidth of the atomic transition and corresponding to the hyperfine transition frequency. This ultra-narrowband laser gain can directly determine the output frequency of the active Faraday optical frequency standard operating in the "bad cavity" regime, significantly suppressing the cavity-pulling effect. Furthermore, due to the suppression of atomic collision and Doppler frequency shifts by the cold atoms, it is expected to further narrow the laser linewidth of the cold-atom-based active Faraday optical frequency standard to Hz level.**

Keywords* — *active optical frequency standard, diffuse laser cooling, Faraday anomalous dispersion optical filter, ultra-narrowband laser gain, bad-cavity

I. Introduction

As the most precise scientific instruments, optical frequency standards are widely utilized in various fields, including laser spectroscopy [1], [2], cold atom physics [3], and quantum precision measurements [4], [5]. At present, most optical frequency standards operate in a passive mode, where they passively lock the laser frequency to the resonance frequency of a high-finesse optical cavity [6]-[9] or the hyperfine transition spectrum of atoms and molecules [10]-[12] to achieve a stable frequency output. However, when external mechanical or thermal vibrations affect the stability of the cavity, a significant cavity-pulling effect will lead to the drift of the output laser frequency, limiting the further improvement of the frequency stability of the optical frequency standard. Even with ultra-high vacuum and ultra-low temperature treatments, the complexity of the system does not facilitate its application in many fields.

Active optical frequency standard [13], [14] can well improve the robustness of laser to cavity length fluctuations. It operates in the bad-cavity regime, where the cavity-mode linewidth is larger than the gain bandwidth. The output laser directly originates from the stimulated emission of the quantum reference system, with a linewidth much smaller than the natural linewidth determined by spontaneous emission, and it has the advantage of suppressing the cavity-pulling effect. According to the transition energy levels of the quantum reference system, active optical frequency standards can be divided into three major categories: two-level [15], [16], three-level [17], [18], and four-level [19], [20] systems. The active Faraday optical frequency standard [21] is a typical two-level system, which utilizes Faraday atomic filters to provide a narrow-band laser gain. After the formation of stimulated radiation, the laser linewidth of the active Faraday optical frequency standard operating on the cesium $6^2S_{1/2}$ F=4 to $6^2P_{3/2}$ F'=4 and 5 crossover transition is reduced to 281 Hz, which was 1.9 × 10^4 times smaller than the corresponding natural linewidth [21]. While this represents a notable improvement compared to that of the passive Faraday optical frequency standard [22], [23], further narrowing the linewidth of the active Faraday optical frequency standard proves challenging due to collision and Doppler frequency shifts caused by high-speed motion of thermal atoms.

II. Methods

In this work, we proposed a scheme for narrowing the laser linewidth of the active Faraday optical frequency standard. Considering that cold atoms can overcome the collision and Doppler frequency shifts, as well as other factors related to atomic velocity that occur during the interaction between light and atoms, we innovatively combines cold atoms with the active Faraday optical frequency standard. By utilizing diffuse laser cooling technology [24] to slow down the velocity of atoms, we expect to achieve the cold-atom-based active Faraday optical frequency standard with laser linewidth at the level of 1 Hz magnitude. The relevant experimental setup is presented in Fig. 1.

A. Prepare cold ^{87}Rb atoms using diffuse laser cooling

Using saturation absorption spectroscopy (SAS) for frequency stabilization, the 780 nm cooling laser and the 780 nm repumping laser were locked to the $5^2S_{1/2}$ F=2 to $5^2P_{3/2}$ F'=3 transition and the $5^2S_{1/2}$ F=1 to $5^2P_{3/2}$ F'=2 transition, respectively. Then, we shifted the frequency of the cooling laser to generate a 10-15 MHz red detuning. The combined cooling and repumping lasers were divided into six beams with equal power, which were subsequently injected into the vacuum glass tube (The power of each cooling laser was about 30 mW, and each repumping laser was about 5 mW). The vacuum glass tube was a hollow cylinder, with 1 m long and 2 cm inner diameter, containing thin ^{87}Rb atomic vapors inside. Its outside surface was covered with a coating with reflectivity being more than 98% at the wavelength of 780 nm. Under the influence of radiation pressure generated by

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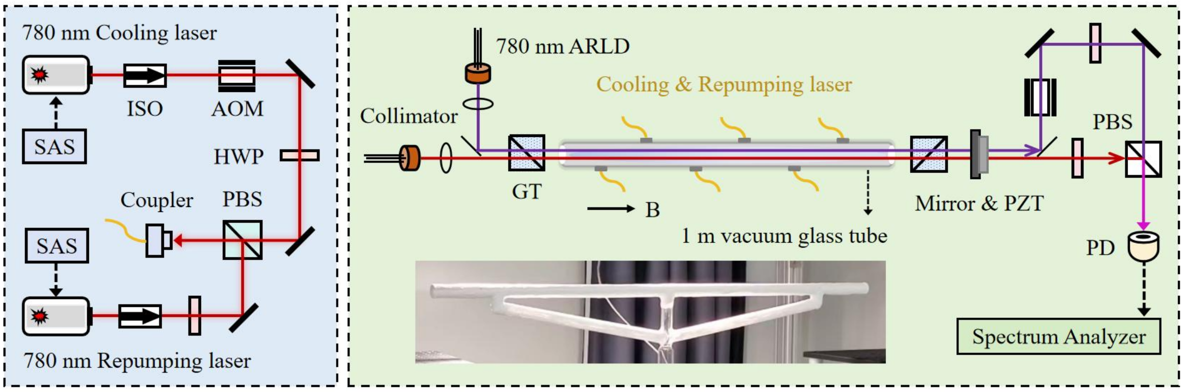

Fig. 1. Schematic of the experimental setup. ISO: isolator; AOM: acousto-optic modulator; HWP: half-wave plate; PBS: polarizing beam splitter; SAS: saturation absorption spectroscopy; ARLD: anti-refection coated laser diode; GT: Glan-Taylor prism; PZT: piezoelectric ceramic tube; PD: photo-electric detector.

multireflection of the cooling laser, ^{87}Rb atoms were cooled, and the entire 1-m-long vacuum glass tube was filled with cold ^{87}Rb atomic cloud. Figure 2 illustrates the relevant ^{87}Rb atomic energy levels and the absorption spectrum of the cold atomic cloud. Under the best operating conditions, the optical density of the cold atomic cloud can reach 4.

B. *Construct optical filter based on cold atoms*

The cold-atom Faraday anomalous dispersion optical filter (FADOF) consists of a clod atomic cloud situated in a constant magnetic field and two Glan-Taylor prisms with orthogonal directions. Due to the Faraday magneto-optical effect, the polarization plane of the linearly polarized light incident on the FADOF will rotate, resulting in an ultra-narrowband transmission that corresponds to the atomic hyperfine transition and is close to the natural linewidth of the atomic transition. This ultra-narrowband transmission can serve as the ultra-narrowband laser gain for the active Faraday optical frequency standard.

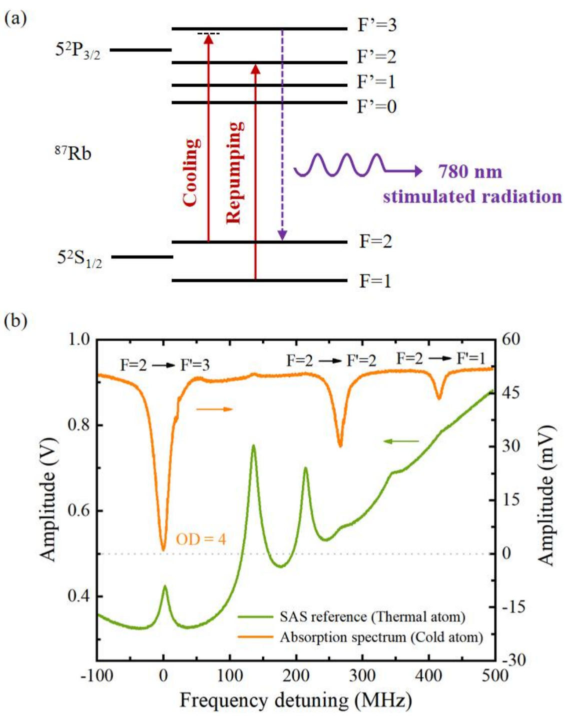

Fig. 2. (a) Relevant ^{87}Rb atomic energy levels. (b) Thermal-atom SAS reference (green curve) and cold-atom absorption spectrum (orange curve).

C. *External cavity feedback for achieving stimulated radiation*

Construct an external cavity feedback and control the cavity loss rate to operate the laser in a bad-cavity regime, where the cavity-mode linewidth is larger than the gain bandwidth. The light oscillates between the back surface of the anti-refection coated laser diode and the cavity mirror, resulting in stimulated radiation within the ultra-narrowband laser gain. This ultimately achieves a narrow-linewidth active cold-atom Faraday optical frequency standard, with the output laser frequency completely determined by the atomic hyperfine transition frequency.

III. Discussion

This experimental scheme is also applicable to other alkali-metal atoms, such as Cs. Currently, we have achieved ultra-narrowband transmission (laser gain) close to the natural linewidth of atomic transitions in a magneto-optical trap (MOT) [25], [26]. However, due to the influence of the MOT's gradient magnetic field, the cold-atom filters can only operate in pulse mode. The diffuse laser cooling scheme proposed in this work does not require a magnetic field, which can effectively solve the above problem and achieve active Faraday optical frequency standards for continuous operation. In addition, meter-scale diffuse laser cooling can increase the effective number of atoms, improve laser output power, and compensate for insufficient power caused by excessive cavity loss. The ultra-narrowband laser gain achieved by atomic filtering also directly corresponds to the atomic hyperfine transition, eliminating the need to passively lock the laser frequency to the atomic transition spectrum.

IV. Conclusion

In conclusion, this work proposed a scheme to realize active Faraday optical frequency standards by diffuse laser cooling of alkali-metal atoms. In comparison with existing passive Faraday optical frequency standards, the central frequency of the output laser is determined by the quantum transition frequency rather than the cavity-mode central frequency, effectively suppressing the influence of the cavity-pulling effect on laser frequency stability. Furthermore, in contrast to existing active thermal-atom Faraday optical frequency standards, this method utilizes laser cooling technology to slow down atoms, effectively suppressing atomic collision and Doppler frequency shifts. The ultra-stable laser with such a narrow linewidth can provide new principles and methods for precision atomic spectroscopy and can also serve as the local oscillator laser for passive optical clocks, potentially achieving atomic clocks with higher frequency stability.

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