Active Optical Clock Based on Laser Cooling of Alkali-metal Atoms

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***Abstract*—Two feasible schemes are proposed by laser cooling of alkali atoms to realize the narrow-linewidth, continual superradiant lasing. Utilizing the D1 gray molasses to realize a cloud of cold Cs atoms for the two-level Faraday active optical clock (AOC), the effect of Doppler broadening on the transmission bandwidth of Faraday atomic filter will be effectively suppressed to the level of natural linewidth. Thus, the influence of mechanical or thermal vibrations of cavity mirrors on the clock laser will be decreased by about 102 times, which is expected to further narrow the laser linewidth by two orders of magnitude compared with the thermal atomic Faraday AOC to Hz level. Moreover, the four-level AOC based on the narrow linewidth cooling of Cs atoms using the 6S-7P transition is proposed. The 455 nm laser at $6S_{1/2}$-$7P_{3/2}$ transition plays two roles simultaneously, one is the cooling laser for a magneto-optical trap (MOT), another is the pumping laser for population inversion of 1470 nm clock transition, which is helpful to improve the compactness of the system. In the four-level structure, the frequency of pumping laser is far detuning from that of clock laser, therefore, the light shift resulting from the 455 nm laser is negligible. This four-level AOC based on cold atoms will further reduce the collision shift in thermal atom system to achieve a high-precision optical frequency reference.**

***Index Terms*—two-level Faraday active optical clock, four-level active optical clock, laser cooling, alkali-metal atoms**

I. INTRODUCTION

Current state-of-the-art neutral optical lattice clocks and single-ion optical clocks have achieved the frequency stability of 10^{-18} [1]–[3] by adopting ultra-stable optical cavities. However, the improvements of the frequency instability are limited by the Brownian thermal noise of the cavity [4]. Therefore, the cavity is usually cooled down to a ultra-low temperature, which will increase the system complexity.

As the counterpart, active clocks [5]–[7] were proposed, which utilize optical stimulated emission on atomic transition line with coherent weak feedback to maintain collective phase information from different atoms. The stimulated radiation is used as the frequency standard directly, working in the bad-cavity limit with the cavity dissipation rate being much bigger than the atomic decay rate. Thus, the laser frequency is robust to the cavity-pulling effect. Moreover, in the bad-cavity limit, the laser linewidth becomes independent of the cavity decay rate but instead relies on the smaller laser gain profile.

The active optical clock can provide a highly stable frequency standard with ultra-narrow linewidth, which has attracted widespread attentions over the last decade. Recently, a superradiant pulse emitted from the ultra-narrow optical clock transition in the cold ^{87}Sr atoms with a fractional Allan deviation of 10^{-16} level has been realized [8]. The pulsed superradiant lasing have also been demonstrated on the narrow transitions in Ca atoms [9] and ^{88}Sr atoms [10]. Moreover, a method to realize the continuous superradiant lasing had been proposed using the steady-state magneto-optical trap (MOT) of fermionic strontium on a narrow-line transition [11]. However, the spontaneous emission rate of the upper clock level is extraordinarily slow of the narrow-linewidth atomic transition, which will increase the laser threshold and reduce the laser power. In this work, we choose the Cs 894 nm (or 1470 nm) transition with natural linewidth of 4.55 MHz (or 1.81 MHz) as the clock laser.

II. METHODS

Here, the two-level Faraday AOC and the four-level AOC with cold Cs atoms as the frequency reference and the gain medium, respectively, are proposed to realize the continuous superradiant lasing with linewidth being smaller than 1 Hz.

Fig. 1 depicts the energy level and the working schematic of the two-level Faraday AOC. The typical characteristic of Faraday AOC scheme is that the gain medium and the frequency reference are spatially separated. The gain is provided by the semiconductor, while the frequency reference is realized by a narrow-bandwidth Faraday atomic filter. Compared with other schemes, the Faraday AOC is easier to achieve a superradiant lasing with the weak optical feedback in bad-cavity regime. Figure 2 gives a schematic depiction about the four-level AOC. A standard MOT are utilized for cooling Cs atoms confined in the low-finesse cavity. The cooling laser stabilized to the Cs $6S_{1/2}$ (F=4) - $7P_{3/2}$ (F=5) transition is also used as the pumping laser to build the population inversion between the $7S_{1/2}$ - $6P_{3/2}$ clock transition.

III. DISCUSSION

This experimental scheme is also applicable to other alkali-metal atoms, such as Rb. At present, as for the two-level

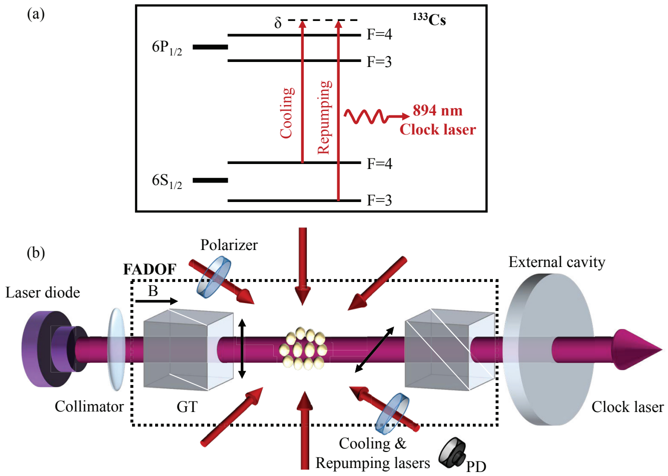

Fig. 1. Energy-level diagram and the working schematic of the Cs Faraday AOC. (a) The laser detuning for molasses is expressed as δ for both cooling and repumping lasers. The cooling and the repumping lasers are separately blue-tuned to the F=4-F'=4 and F=3-F'=4 transitions of D1 line. (b) The Faraday atomic filter is composed of cold atoms confined in a small range by the gray molasses, a pair of polarization-orthogonal Galn-Taylor prisms (GTs), and weak homogeneous magnetic field. A pair of polarization-orthogonal polarizers are placed in the propagation direction of one of the repumping/cooling beams to measure the transmittance of the atomic filter, and recorded by the photodetector (PD). The 894 nm clock laser is realized with the weak feedback of the low-finesse cavity.

Faraday AOC, we have realized the ultranarrow bandwidth Faraday atomic filter approaching natural linewidth based on cold Rb atoms [12]. The transmittance of the filter has been increased from 2.6% to 10%. As for the four-level AOC, we have observed a hybrid blue MOT by replacing one pair of 780 nm laser beams with the 420 nm beams. Next, the blue MOT composed by six blue laser beams will be built. Moreover, the active optical clock using laser cooling of Cs atoms will also be explored.

IV. Conclusion

In conclusion, to reduce the collision broadening in the Cs AOC [13] using the thermal atoms as the gain medium, this work proposed two experimental schemes to realize the continuous active lasing by laser cooling of alkali-metal atoms. In bad-cavity limit, the clock-laser linewidth becomes independent of the cavity decay rate but instead rely on the much smaller laser gain profile. Therefore, an active optical frequency standard with laser linewidth being smaller than 1 Hz is achievable, which has wide-ranging impact in precision measurements.

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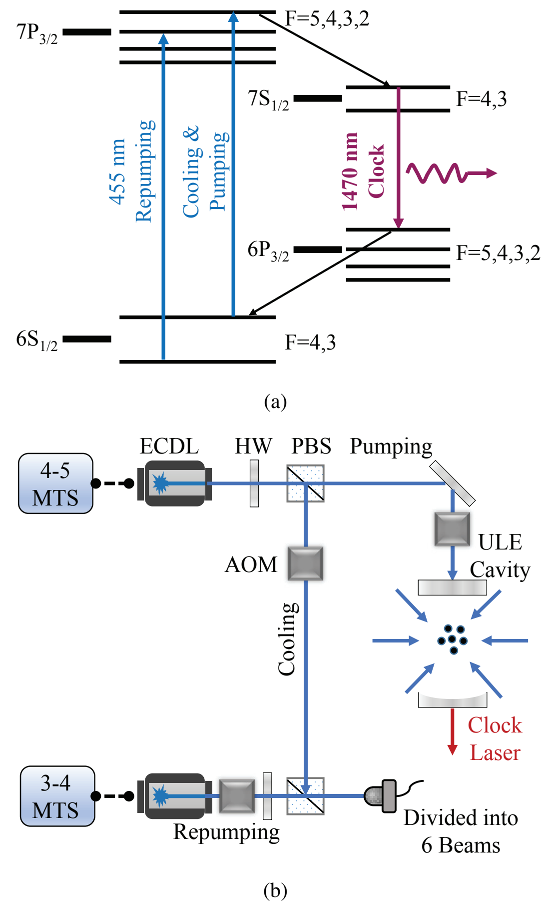

Fig. 2. Energy-level diagram and working schematic for the blue MOT at 455 nm to realize the four-level AOC. (a) The laser at 6S$_{1/2}$ (F=4) - 7P$_{3/2}$ (F=5) transition is used as the pumping laser and the cooling laser simultaneously. To avoid the influence of linear Zeeman effect on the clock laser,7S$_{1/2}$ (F=4, mF=0) - 6P$_{3/2}$ (F=5, mF=0) is selected as the clock transition. (b) The laser frequencies of the two external-cavity diode lasers (ECDLs) are stabilized to Cs 6S$_{1/2}$ (F=4) - 7P$_{3/2}$ (F=5) and 6S$_{1/2}$ (F=4) - 7P$_{3/2}$ (F=4) transitions, respectively, by the modulation transfer spectroscopy (MTS). The cooling and the repumping lasers are superimposed and divide into six balanced laser beams. HW: Half-wave plate; PBS: Polarization beam splitter; AOM: Acousto-optic modulator.

References

[1] T. Bothwell, D. Kedar, E. Oelker, et al., "JILA SrI optical lattice clock with uncertainty of 2×10^{-18}," Metrologia **56**, 065004 (2019).

[2] W. F. Mcgrew, X. Zhang, H. Leopardi, et al., "Towards the optical second: verifying optical clocks at the SI limit," Optica **6**, 448-454 (2019).

[3] S. M. Brewer, J.-S. Chen, A. M. Hankin, et al., "$^{27}Al^{+}$ quantum-logic clock with a systematic uncertainty below 10^{-18}," Phys. Rev. Lett. **123**, 033201 (2019).

[4] D. G. Matei, T. Legero, S. Häfner, et al., "1.5 μm lasers with sub-10 mHz linewidth," Phys. Rev. Lett. **118**, 263202 (2017).

[5] J. Chen, and X. Chen, "Optical lattice laser," in IEEE International Frequency Control Symposium and Exposition (2005).

[6] J. Chen, "Active optical clock," Chinese Sci. Bull. **54**, 6–10 (2009).

[7] D. Meiser, J. Ye, D. R. Carlson, et al., "Prospects for a millihertz-linewidth laser," Phys. Rev. Lett. **102**, 163601 (2009).

[8] M. A. Norcia, J. R. K. Cline, J. A. Muniz, et al., "Frequency measurements of superradiance from the strontium clock transition," Phys. Rev. X **8**, 021036 (2018).

[9] T. Laske, H. Winter, and A. Hemmerich, “Pulse delay time statistics in a superradiant laser with calcium atoms,” Phys. Rev. Lett. **123**, 103601 (2019).

[10] S. A. Schäffer, M. Tang, M. R. Henriksen, et al., “Lasing on a narrow transition in a cold thermal strontium ensemble,” Phys. Rev. A **101**, 013819 (2020).

[11] R. G. Escudero, C. Chen, S. Bennetts, et al., “A steady-state magneto-optical trap of fermionic strontium on a narrow-line transition,” arXiv:2104.06814.

[12] W. Zhuang, Y. Zhao, S. Wang, et al., “Ultranarrow bandwidth Faraday atomic filter approaching natural linewidth based on cold atoms,” Chin. Opt. Lett. **19**, 030301 (2021).

[13] T. Shi, D. Pan, and J. Chen, “Realization of phase locking in good-bad-cavity active optical clock,” Opt. Express **27**, 22040-22052 (2019).