Active optical clock signal based on ^{87}Rb atoms cooled by 780 nm diffuse laser

Jia Zhang[1], Xiaolei Guan[1], Xun Gao[1], Jianxiang Miao[1], Tiantian Shi[2] and Jingbiao Chen[1,3]
Email: zjia@stu.pku.edu.cn tts@pku.edu.cn jbchen@pku.edu.cn
[1]State Key Laboratory of Advanced Optical Communication Systems and Networks, Institute of Quantum Electronics, School of Electronics, Peking University, Beijing 100871, China
[2]National Key Laboratory of Advanced Micro and Nano Manufacture Technology, School of Integrated Circuits, Peking University, Beijing 100871, China
[3]Hefei National Laboratory, Hefei 230088, China

***Abstract*—The cavity-pulling suppression advantage of active optical clocks (AOCs) helps to realize atomic clocks with superior performance. However, realization of continuous-wave cold-atom AOCs is a highly challenging task. In this work, we proposed an AOC scheme with diffuse-laser-cooled atoms. Combining the advantages of diffuse laser cooling to easily prepare cold-atom cloud with large volume on the scale of meters and the four-level structure to greatly reduce the light shift, it is expected to realize the continuous output of AOC superradiant signals. We experimentally realized a 100-cm-long cold ^{87}Rb atom cloud as the gain medium. The 1367 nm AOC superradiant signal with a power of 0.3 μW has been achieved without resonant cavity feedback. In the future, we will continue to advance the experiment and also conduct research on 420 nm blue light cooling.**

Keywords—active optical clock, superradiant laser, cold atom, diffuse laser cooling, atomic clock

I. INTRODUCTION

Atomic clocks, as the instrument with the highest measurement accuracy, are of great value in the fields of basic physics research and precision measurement. At present, the best performance optical clocks belong to passive optical clocks, whose stability has broken through the 10^{-19} order of magnitude towards higher indicators [1,2]. Most of the local oscillator lasers of passive atomic clocks are frequency stabilized using PDH technique [3,4], which cannot be separated from the high finesse resonant cavity. However, further improvement of their performance is difficult, and the stabilization is limited by cavity-length thermal noise. This limitation can be overcome using the principle of active optical clock (AOC) [5-7], which utilizes the weak feedback of optical cavity to realize multi-atom stimulated emission of radiation. AOCs, with the advantages of cavity-pulling suppression and linewidth narrowing, draw many research groups based on different atoms as well as transition energy levels.

Until now, JILA employed laser cooling of ^{87}Sr atoms with transition linewidth on the order of mHz, experimentally realizing a fractional Allan deviation of 6.7×10^{-16} at 1 s [8]. The Niels Bohr Institute succeeded in realizing an AOC superradiant laser using ^{88}Sr atoms [9]. Currently, they demonstrated collectively enhanced Ramsey readout by cavity sub- to superradiant transition [10]. For Ca atom, AOC superradiant laser output with linewidth on the order of mHz is theoretically possible [11, 12]. Experimentally, the University of Hamburg observed a hyperbolic secant-type superradiant light field based on the $^1S_0$ - $^3P_1$ transition [13]. In the case of Yb atom, FEMTO-ST is building ^{171}Yb-based AOC on the spin- and dipole-forbidden $^1S_0 \rightarrow {}^3P_0$ narrow-linewidth transition [14,15]. Universität des Saarlandes investigate lasing threshold and frequency properties of the lasing action observed on the $^1S_0 \rightarrow {}^3P_1$ transition of magneto-optically-trapped ^{174}Yb atoms [16,17]. Peking University realized a continuous output 1470 nm AOC superradiant laser based on thermal Cs atoms under extremely bad-cavity conditions [18]. In addition, there are a number of works that theoretically demonstrate the superior performance of AOCs [19-26].

However, a truly continuously operable cold-atom AOC has not yet been realized. In order to realize continuous output, Vienna University of Technology [27], University of Amsterdam [28], Niels Bohr Institute [29], JILA [30], and others have carried out moving optical lattice schemes. Similarly, we are seeking cold-atom AOC schemes that can achieve truely continuous output. Here we present AOC based on diffuse-laser-cooled atoms. Diffuse laser cooling ensures that the atom clouds are large, and the four-level structure ensures that the light shift introduced by the pump light is very small. Therefore, it is expected to realize AOC superradiant laser with continuous output on the order of microwatts.

II. EXPERIMENT SETUP

We adopt the same four-level structure as the previous thermal-atom AOCs [18,21,22] (see Fig. 1(a)), where the energy levels of pump laser and the clock laser are separated from each other. This can reduce the light shift introduced by the pump light, thus helping to realize continuous pumping and continuous output, and finally obtaining a continuous AOC superradiant signal with stable output. In the experiment, cold ^{87}Rb atoms are used as a quantum frequency reference and provide a narrow-bandwidth gain, and the coherent stimulated radiation is directly output as a clock laser, realizing a cold-atom AOC signal that can be continuously output.

The experimental schematic is shown in Fig. 1(b), two 780 nm lasers were utilized as the cooling light and the repumping light, respectively. In order to ensure a sufficient number of gain medium atoms, we used the diffuse laser cooling technique to prepare a large volume of cold ^{87}Rb cloud. A 100 cm long vacuum atomic glass tube was used to confine cold atoms, and the outer wall of the tube was uniformly coated with barium sulfate diffuse reflective coating to ensure high reflection of the cooling light and repumping light. The reflectivity of the coating is higher than

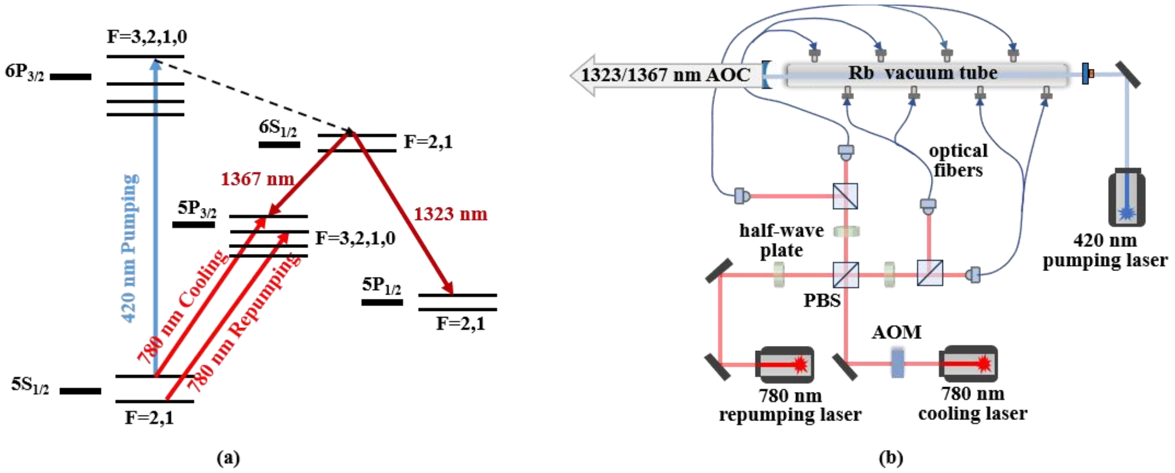

Fig.1. (a) Relevant energy levels. 780 nm cooling light corresponds to $5S_{1/2}$ ($F = 2$) - $5P_{3/2}$ ($F' = 3$) with red detuning of 15 MHz, 780 nm repumping light is locked to $5S_{1/2}$ ($F = 1$) - $5P_{3/2}$ ($F' = 2$), and the 420 nm pump light corresponds to $5S_{1/2}$ ($F = 2$) - $6P_{3/2}$. Under different resonant cavity conditions, it is possible to output AOC superradiant laser at 1323 nm or 1367 nm. (b) Experimental system.

98% for the 780 nm band and 95% for the 420 nm band. A 40 L/s ion pump was utilized to maintain the vacuum at E-6 Pa to provide a good vacuum environment for the preparation of cold atoms.

Cooling light corresponded to $5S_{1/2}$ ($F = 2$) - $5P_{3/2}$ ($F' = 3$) with red detuning 2.5 times the natural linewidth, and repumping light was locked to $5S_{1/2}$ ($F = 1$) - $5P_{3/2}$ ($F' = 2$) to prepare an isotropic diffuse light field, so that atoms with a certain velocity interact with a specific red-detuned laser in order to compensate for the Doppler shift. Instead of adding timing sequence to detect cold atoms, we utilized another set of 780 nm interference filter configuration external cavity diode laser as the probe light. After confirming that the cold atoms had been prepared, a 420 nm laser was utilized as the pump light. In order to achieve excellent pumping effect, the narrow linewidth laser spectral property of Rb atom's second excited state was used. The ground state $5S_{1/2}$ to the second excited state $6P_{3/2}$ was selected as the transition energy level, and the high signal-to-noise modulation transfer spectroscopy stabilization technique was used to lock the 420 nm pump laser.

III. Experimrntal Results

We optimized the number of cold atoms by improving the optical depth (OD). Since there is no time sequence, the cooling light and the repumping light were also kept on when we utilized the 780 nm weak light for probing. By optimizing the power of the cooling light, the detuning of the cooling light, the power of the repumping light, and the detuning of the repumping light, we determined the best operating parameters.

The OD of the cold atoms reached a maximum value of 4 at a cooling light power of 250 mW, a detuning of 15 MHz with respect to the $5S_{1/2}$ ($F = 2$) - $5P_{3/2}$ ($F' = 3$) transition, and a repumping light power of 30 mW, locked to the $5S_{1/2}$ ($F = 1$) - $5P_{3/2}$ ($F' = 2$) transition. We calibrated the OD by the amplitude of the cold atom's absorption of the 780 nm probe light. For thermal Rb atoms, if the 780 nm probe light is injected in, the observed absorption spectrum will be a large-range Doppler absorption spectrum. For cold Rb atoms, we can then observe the three absorption spectra corresponding to ^{87}Rb $5S_{1/2}$ ($F = 2$) - $5P_{3/2}$ ($F' = 3,2,1$) shown in Fig. 2, whose widths approximate the natural linewidth.

After the state of the cold atoms was optimized to the best, the higher number of cold atoms as well as the larger density of cold atoms provide large gain medium for the subsequent realization of the AOC superradiant laser. A 420 nm light was pumped from one end of the one meter long vacuum glass tube. In the presence of 420 nm pump light, cold Rb atoms was pumped from the ground state $5S_{1/2}$ to the second excited state $6P_{3/2}$ and then drop to the upper level $6S_{1/2}$ of the clock laser. We have previously done relevant theoretical calculations on the four-level AOC of thermal Rb atoms, and the results show that the population inversion can be formed between $6S_{1/2}$ and $5P_{1/2}$, $5P_{3/2}$. That is to say, under different resonant cavity conditions, it is promising to generate superradiant lasers with two wavelengths of 1323 nm (corresponding to $6S_{1/2}$ and $5P_{1/2}$) and 1367 nm (corresponding to $6S_{1/2}$ and $5P_{3/2}$).

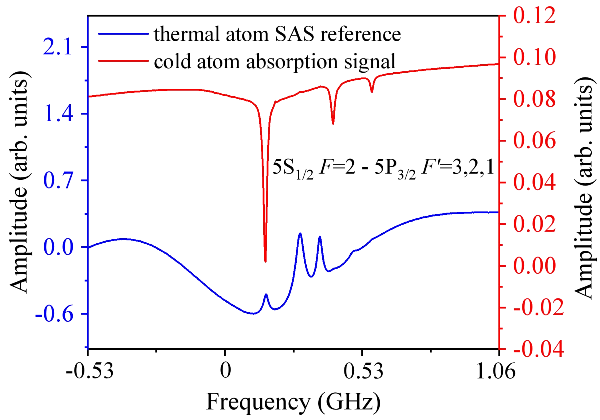

Fig. 2. Cold atomic absorption spectral line (red). Corresponding to ^{87}Rb $5S_{1/2}$ ($F = 2$) - $5P_{3/2}$ ($F' = 3,2,1$), we observe three absorption peaks. The blue spectral line is the corresponding thermal atomic saturation absorption spectrum for reference.

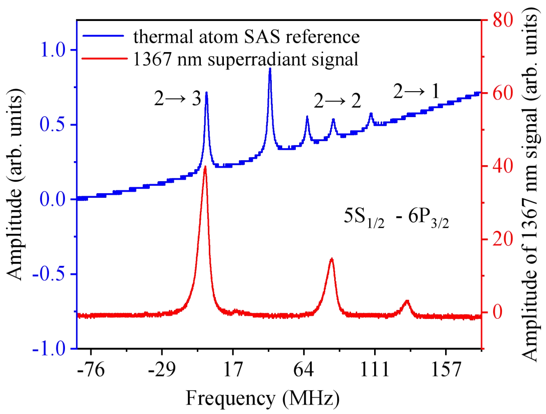

Fig. 3. 1367 nm superradiant signal (red). The blue spectral line is the corresponding thermal atomic saturation absorption spectrum (^{87}Rb $5S_{1/2}$ ($F = 2$) - $6P_{3/2}$ ($F' = 3,2,1$) for reference.

Considering that our 780 nm cooling light occupies the $5P_{3/2}$ level, we prefer to be able to directly realize a 1323 nm AOC superradiant laser corresponding to the $6S_{1/2}$ and $5P_{1/2}$ energy levels. Since we have not yet added a resonant cavity to the experimental system, we first observed the cavityless signal without cavity feedback. In previous experiments, we realized a 1470 nm cavityless laser with a four-level structure based on thermal Cs atoms [18]. This cavityless laser, which abandons the cavity and whose center frequency is immune to cavity-pulling effect, is expected to become an absolute frequency standard [33].

Here, without feedback from the resonant cavity, we initially observed a 1367 nm signal corresponding to a cold ^{87}Rb atom (see Fig. 3) with a power of up to 0.3 μW. At the current experimental precision, the 1323 nm signal is hardly observed, probably because of the large transition intensity corresponding to the 1367 nm signal. Without feedback from the cavity, the 1323 nm signal is more difficult to achieve coherent amplification. Subsequently, the resonant cavity will be further constructed, with a view to realizing a truly continuous output of cold-atom-based AOC signal under the effect of weak coupling between the cavity and the atoms.

IV. Discussion

For the two- and three-level AOCs, the pump light and the clock laser share energy levels and thus tend to introduce large light shift. However, for four-level AOC, the energy levels corresponding to the pump light and the clock laser are separated from each other, so the light shift is smaller and almost negligible. At the same time, the pumping process and the stimulated radiation process of the clock laser can be carried out simultaneously, thus realizing a continuous output. In terms of cold atoms, common magneto-optical trap and optical lattice schemes, while having many advantages, are challenging to achieve continuous operation. When cold atoms are prepared and pumped light is injected, it is easy to directly knock the atom clouds away, thus requiring the cold atoms to be prepared again.

Here, our scheme is to use diffuse laser field to cool the atoms. This cooling scheme has a relatively low atomic density, but the cold atom cloud can be prepared to meter scale length, so the total atomic number is guaranteed. Moreover, when pumping light, the cooling light and the repumping light can be turned on at the same time to cool and pump the atoms, and the surrounding cold atoms can be quickly replenished. Therefore, our proposal is to adopt a four-level structure combined with diffuse laser cooling to realize a continuously operable cold-atom AOC.

In our existing experimental system, the upper energy level of the 780 nm cooling light is $5P_{3/2}$, so for the 1367 nm AOC superradiant laser, the light shift it brings is still large. However, we have observed the 1367 nm superradiant signal without resonant cavity. If this 1367 nm AOC is to be continued, the above system needs to be turned into a pulsed output to eliminate the lighr shift. In order to maintain the initial intention of continuousity, we plan to utilize a high-power 420 nm laser to provide the cooling light as well as the pumping light, and sharing a single laser will improve the integration of the system. Moreover, compared with 780 nm/795 nm cooling, laser cooling with a 420 nm laser with a narrower natural linewidth reduces the Doppler-cooling-limited temperature in theory, suppresses the Doppler effect to a greater extent, and results in better performance of cold-atom AOC.

To overcome this difficulty, we have accomplished the frequency locking as well as frequency shifting of the 420 nm high-power laser. Although the efficiency of 420 nm laser cooling is much lower compared with that of 780 nm cooling, we have initially realized the cooling of Rb atoms directly using 420 nm laser. Blue light cooling is also a hot topic internationally, and reports on blue light cooling are now rare. Diffuse laser cooling based on 420 nm blue light is even more unreported, and we will write a separate article to report on it.

V. Conclusion

In conclusion, this study provides a solution for realizing an AOC superradiant laser that can be continuously output using diffuse-laser-cooled atoms. The effect of light shift is attenuated by a four-level structure, and the preparation of a large volume of cold Rb atom clouds by diffuse laser cooling scheme is expected to realize a truly continuous AOC signal output. Experimentally, we realized a cavityless superradiant signal output at 1367 nm using cold ^{87}Rb atoms without constructing a resonant cavity. Subsequently, we will also further advance this scheme as well as 420 nm laser cooling. This laser can further advance the study of laser physics, and is expected to find applications in precision measurements, cavity electrodynamics, and quantum many-body physics.

References

[1] S. M. Brewer, J.-S. Chen, et al. "$^{27}Al^{+}$ quantum-logic clock with a systematic uncertainty below 10^{-18}," Physical Review Letters, vol. 123, pp. 033201, 2019.

[2] W. F. McGrew, X. Zhang, et al. "Atomic clock performance enabling geodesy below the centimetre level," Nature, vol. 564, pp. 87-90, 2018.

[3] R. V. Pound. "Electronic frequency stabilization of microwave oscillators.," Review of Scientific Instruments, vol. 17, pp. 490-505, 1946.

[4] R. W. P. Drever, J. L. Hall, et al. "Laser phase and frequency stabilization using an optical resonator," Applied Physics B, vol. 31, pp. 97-105, 1983.

[5] J. Chen, "Active optical clock," arXiv:physics/0512096, 2005.

[6] J. Chen and X. Chen, “Optical lattice laser,” in Proceedings of the IEEE International Frequency Control Symposium and Exposition, pp. 3, 2005.

[7] J. Chen, “Active optical clock,” Chinese Science Bulletin, vol. 54, pp. 348-352, 2009.

[8] M. A. Norcia, J. R. Cline, J, et al. “Frequency measurements of superradiance from the strontium clock transition,” Physical Review X, vol. 8, pp. 021036, 2018.

[9] S. L. Kristensen, E. Bohr, J. Robinson-Tait, T. Zelevinsky, J. W. Thomsen, and J. H. Müller, “Subnatural linewidth superradiant lasing with cold ^{88}Sr atoms”, Physical Review Letters, vol. 130, pp. 223402, 2023.

[10] E. A. Bohr, S. L.Kristensen, et al. “Collectively enhanced Ramsey readout by cavity sub-to superradiant transition,” Nature Communications, vol. 15, pp. 1084, 2024.

[11] W. Zhuang and J. Chen, “Progress of active optical frequency standard based on thermal Ca atomic beam,” in IEEE International Frequency Control Symposium, pp. 222–223, 2010.

[12] H. Liu, S. B. Jäger, et al. “Rugged mHz-linewidth superradiant laser driven by a hot atomic beam,” Physical Review Letters, vol. 125, pp. 253602, 2020.

[13] T. Laske, H. Winter, and A. Hemmerich, “Pulse delay time statistics in a superradiant laser with calcium atoms,” Physical Review Letters, vol. 123, pp. 103601, 2019.

[14] F. Ponciano-Ojeda, J. El Badawi, M. Hauden, M. Matusko, and M. Delehaye, “Progress on a ^{171}Yb-based active optical atomic clock,” in Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium, pp. 1–2, 2023.

[15] M. Hauden, M. Matusko, J. El Badawi, Y. Kersalé, F. Ponciano-Ojeda, and M. Delehaye, “Ultra-stable and tunable fabry-perot cavity for an ytterbium based superradiant laser,” in Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium, pp. 1–2, 2023.

[16] H. Gothe, D. Sholokhov, A. Breunig, M. Steinel, J. Eschner. “Continuous-wave virtual-state lasing from cold ytterbium atoms,” Physical Review A, vol. 99, pp. 013415, 2019.

[17] D. Sholokhov, S. Shaju, K. Li, S. B. Jäger, J. Eschner. “Threshold and frequency properties of a cold ytterbium laser,” arXiv:2404.16765 [quant-ph], 2024.

[18] J. Zhang, T. Shi, J. Miao, D. Yu, and J. Chen, “An extremely bad-cavity laser,” arXiv:2310.14240 [physics.optics], 2023.

[19] S. A. Schäffer, M. Tang, M. R. Henriksen, A. A. Jørgensen, B. T. Christensen, and J. W. Thomsen. “Lasing on a narrow transition in a cold thermal strontium ensemble,” Physical Review A, vol. 101, pp. 013819, 2020.

[20] A. Bychek, C. Hotter, D. Plankensteiner, and H. Ritsch. “Superradiant lasing in inhomogeneously broadened ensembles with spatially varying coupling,” Open Research Europe, vol. 1, 2021.

[21] C. Hotter, D. Plankensteiner, L. Ostermann, and H. Ritsch. “Superradiant cooling, trapping, and lasing of dipole-interacting clock atoms,” Optics express, vol. 27, pp. 31193, 2019.

[22] C. Hotter, D. Plankensteiner, G. Kazakov, and H. Ritsch. “Continuous multi-step pumping of the optical clock transition in alkaline-earth atoms with minimal perturbation,” Optics Express, vol. 30, pp. 5553, 2022.

[23] Y. Zhang, C. Shan, and K. Mølmer. “Active frequency measurement on superradiant strontium clock transitions,” Physical Review Letters, vol. 128, pp. 013604, 2022.

[24] D. Pan, B. Arora, Y. Yu, B. Sahoo, and J. Chen. “Optical-lattice-based Cs active clock with a continual superradiant lasing signal,” Physical Review A, vol. 102, pp. 041101, 2020.

[25] D. Yu, F. Vollmer, and S. Zhang. “Proposal for an active whispering-gallery microclock,” Quantum Science and Technology, vol. 8, no. 2, pp. 025005, 2023.

[26] G. A. Kazakov, S. Dubey, A. Bychek, U. Sterr, M. Bober, M. Zawada. “Ultimate stability of active optical frequency standards,” Physical Review A, vol. 106, pp. 053114, 2022.

[27] G. A. Kazakov, T. Schumm. “Active optical frequency standard using sequential coupling of atomic ensembles,” Physical Review A, vol. 87, pp. 013821, 2013.

[28] C. Chen, S. Bennetts, R. G. Escudero, B. Pasquiou, F. Schreck. “Continuous guided strontium beam with high phase-space density,” Physical Review Applied, vol. 12, pp. 044014, 2019.

[29] M. Tang, S. A. Schäffer, J.H. Müller. “Prospects of a superradiant laser based on a thermal or guided beam of ^{88}Sr,” Physical Review A, vol. 106, pp. 063704, 2022.

[30] J. Cline, V. Schäfer, Z. Niu, D. Young, T. Yoon, J. Thompson. “Continuous collective strong coupling between atoms and a high finesse optical cavity,” arXiv:2211.00158 [physics.atom-ph], 2022.

[31] T. Shi, D. Pan, J. Chen. “Realization of phase locking in good-bad-cavity active optical clock,” Optics Express, vol. 27, pp. 22040-22052, 2019.

[32] T. Shi, D. Pan, J. Chen. “An inhibited laser,” Communications Physics, vol. 5, pp. 208, 2022.

[33] D. Yu, J. Zhang, S. Zhang, J. Chen. “Prospects for an active optical clock based on cavityless lasing,” Advanced Quantum Technologies, vol. 7, pp. 2300308, 2024.