Continuous-Wave Mirrorless Lasing at 1.47 μm in Blue-Light Pumped Cs Vapor

Tiantian Shi[1], Jianxiang Miao[1], and Jingbiao Chen[1,*]
1 State Key Laboratory of Advanced Optical Communication, Systems and Networks,
Department of Electronics, and Center for Quantum Information Technology,
Peking University, Beijing 100871, China
Email: *jbchen@pku.edu.cn

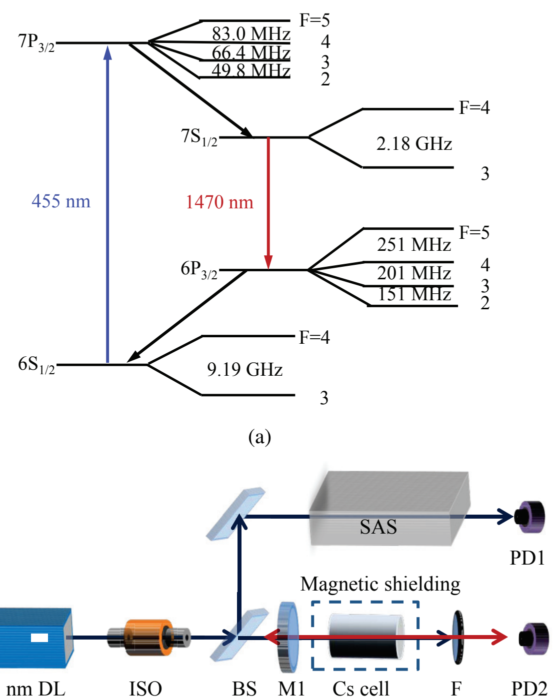
***Abstract*—Population inversion on the $7S_{1/2} - 6P_{3/2}$ transition of cesium atoms is built by 455 nm diode laser pumping, and continuous-wave (cw) lasing is observed without the feedback on the gain medium from cavity mirrors. The stimulated emission at 1.47 μm infrared wavelength is restricted to a narrow angle along the direction of propagation of the pumping laser. Evidence of threshold-like characteristic is demonstrated in the cw mirrorless lasing dependence on pumping laser detuning, atomic density, and pumping light intensity. This compact structure can be used to generate mirrorless laser in a number of infrared wavelengths applied for the communication area. Moreover, it is expected to realize the narrow-linewidth optical frequency standard from an ultralow-finesse optical cavity.**

***Index Terms*—continuous-wave mirrorless lasing, vapor cell, threshold-like characteristic**

I. Introduction

The coherent light amplification in cesium (Cs) vapor by selective optical pumping with 388.8 nm helium lamp is firstly proved by Rabinowitz et al. in 1961 [1]. Laser action is observed at 7.2 μm and 3.2 μm transition. After, laser with transition of $7P_{1/2} - 7S_{1/2}$ in helium-buffered Cs vapor was produced in 1969 [2]. Until 1981, the continuous-wave (cw) mirrorless lasing in optically pumped Cs atomic vapor is firstly demonstrated by Happer's group [3]. Happer et al. proved that without cavity mirror for feedback and under weak pumping light condition, the light amplification by stimulated emission of radiation can be also realized. Besides, utilizing the three-level pump scheme with direct optical excitation, the lasing at 894 nm ($6P_{1/2} - 6S_{1/2}$) [4] and at 459 nm ($7P_{1/2} - 6S_{1/2}$) [5] is produced in a mixture of Cs vapor and buffer gas. More recently, a mirrorless laser using Cs vapor with 459 nm laser pumping is reported [6]. Also, the simultaneous cw mirrorless lasing on multiple optical transitions is realized by pumping the Cs vapor with 388 nm laser [7].

In this work, we report the cw mirrorless lasing at 1.47 μm in thermal Cs vapor with weak 455 nm optically pumping. Detecting along the propagation direction of pumping laser, the power of the cw mirrorless lasing is up to 67 μW. The spectral property and the threshold-like characteristic of mirrorless lasing are analyzed. By further adding an low-reflectivity cavity mirror, this system is expected to generate an active optical clock [8]–[14] with ultra-narrow linewidth.



(b)

Fig. 1. (a) Cs energy level showing optical pumping of $7P_{3/2}$ by 455 nm radiation. (b) Experimental setup for mirrorless laser generation. 455 nm DL, 455 nm diode laser; ISO, optical isolator; BS, beam splitter; Cs cell, Cs vapor cell; F, filter; SAS, saturation absorption spectroscopy; PD, photodetector. M1 is a plane mirror coated with anti-reflectivity at 455 nm, and reflectivity at 1470 nm of 50%. Blue line represents the 455 nm pumping laser, and the red line is the 1470 nm cw mirrorless lasing.

II. Methods

The energy level and the experimental diagram are given in Fig. 1(a) and Fig. 1(b), respectively. An external-cavity diode laser (ECDL), whose center wavelength is 455.5 nm, is used to pump the thermal Cs vapor. After interacting with the atoms, the atoms is pumped from the $6S_{1/2}$ state to the $7P_{3/2}$ state. Then, the fluorescence on the $7S_{1/2}$ - $6P_{3/2}$ transition is realized. The plane mirror M1 in Fig. 1(b) is coated with anti-reflectivity at 455 nm, and with reflectivity of 50% at 1470 nm. The 1470 nm spontaneous radiation is amplified by the

978-1-6654-3935-0/21/$31.00 ©2021 IEEE

mirror M1 with low reflectivity, and output the cw mirrorless laser.

Pure Cs atoms contained in a 5 cm long quartz-glass cell are maintained at temperature in the range 120°C–195°C with temperature-control precision being around 0.1°C. The magnetic shielding composed of two layers of μ metal is used to reduce the influence of external magnetic field on the atoms. The 455 nm pumping power is tunable from 1mW to 6.5 mW with spot size of 0.605×0.485 mm^2. The light output from the ECDL is divided into two parts. One part is used in the saturation absorption spectrum (SAS) to provide the frequency reference. The other part is used to pump the Cs atoms to observe the resonance spectrum of 1470 nm cw mirrorless lasing on photodetector (PD2), which is around 20 cm away from the output window of the atomic vapor. It also reflects that the 1470 nm mirrorless lasing has a strong directional characteristic.

III. Experimental results

The mode-hop-free range of the ECDL is about 7 GHz, which covers the hyperfine splitting of the second excited state. The pumping light is resonant with Cs $6S_{1/2}$ (F=4) to $7P_{3/2}$ transition, and the corresponding SAS is shown in the upper of Fig. 2. The bottom is the 1470 nm resonance spectrum at different vapor temperatures with pumping power of 6 mW, and the insert is an example at 132.9°C. The 1470 nm lasing is detected when the 455 nm laser is resonant with $6S_{1/2}$ (F=4) to $7P_{3/2}$ (F=5) transition. With the increase of the vapor temperature, the power of 1470 nm lasing corresponding to the pumping laser frequency far detune from the $6S_{1/2}$ (F=4)-$7P_{3/2}$ (F=5) transition increases gradually. However, the 1470 nm laser power increases first and then reduces with increasing of vapor temperature, when the pumping laser is resonant with the $6S_{1/2}$ (F=4)-$7P_{3/2}$ (F=5) transition.

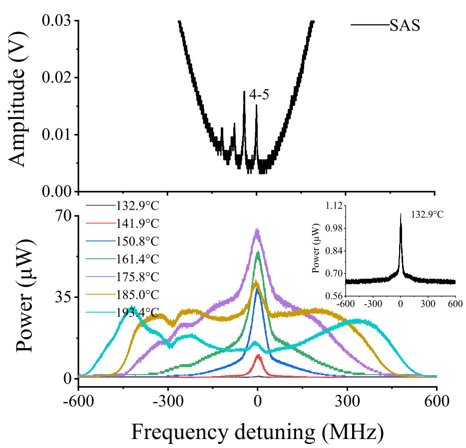


Fig. 2. The upper curve is the 455 nm saturation spectroscopy corresponding to $6S_{1/2}$(F=4) - $7P_{3/2}$. The bottom represents the 1470 nm resonance spectrum at different temperatures with pumping laser power of 6 mW and spot size of 0.605×0.485 mm^2. The inset is a typical resonance spectrum at 132.9°C, which is around threshold temperature.

As shown in Fig. 3, the 1470 nm laser power reaches the maximum when the vapor temperature rises to 170°C, then the laser power decreases with the further increase of vapor temperature. This may be interpreted as the enhanced atomic collision with increasing temperature, which leads to the transition on $7S_{1/2}$-$6P_{1/2}$ being dominant. Limited by the highest heating temperature of 200°C, the temperature threshold at higher temperature is not given in Fig. 3.

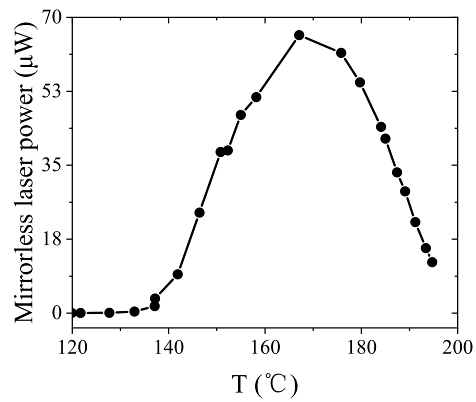


Fig. 3. The 1470 nm laser power as a function of Cs vapor temperature. The pumping power is 6 mW with spot size of 0.605×0.485 mm^2. Here the 1470 nm laser power is measured by the intensity of the highest peak corresponding to $6S_{1/2}$(F=4) - $7P_{3/2}$(F=5) transition of 455 nm SAS in the resonance spectrum.

Next, the 1470 nm laser power as a function of 455 nm pumping power is analyzed. We measured the laser slope efficiency for the gain medium with several different vapor temperatures in the range 138-195°C. As depicted in Fig. 4, with the increase of atomic density, the laser slope efficient increases first and then reduces. The maximum laser power can reach 67 μW with pumping power of 6 mW. The laser power can be further improved with a higher pumping power.

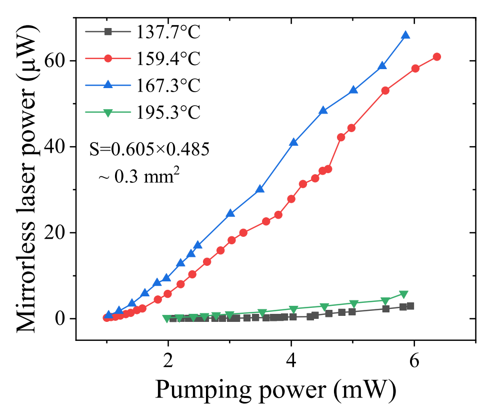


Fig. 4. The power of cw mirrorless laser as a function of 455 nm pumping power at different vapor temperatures. The spot-light size of pumping laser is 0.605×0.485 mm^2.

IV. Conclusion

In conclusion, this work explored a cw mirrorless lasing without the use of feedback from optical resonator. The threshold characteristic of mirrorless lasing with the change of pumping frequency detuning, vapor temperature and the pumping power is analyzed. According to Ref. [3], the stimulated emission in a number of other wavelengths, such as $7P_{3/2} - 7S_{1/2}$ 2.932 μm, $7S_{1/2} - 6P_{1/2}$ 1.359 μm and $7P_{3/2} - 5D_{5/2}$ 1.361 μm transitions can be also realized with the 455 nm laser as the pumping laser. Among these possible transitions, the strength of 2.932 μm and the 1.470 μm lasing are relatively high. As an optical frequency standard, high transition frequency is easier to achieve better frequency stability. Therefore, the mirrorless lasing at 1.470 μm transition is studied in this paper. Next, we will study the laser characteristic of 1.359 μm. Moreover, further research on the linewidth characteristics of the cw mirrorless laser is necessary. By adding another cavity mirror with ultralow reflectivity, such as 1%, to enhance the feedback from optical resonator on atoms, the mirrorless laser can be developed to the bad-cavity laser [8], [15]. This structure can be used to analyze the differences between the cw mirrorless lasing and the bad-cavity laser, which is aimed at to realize an active optical frequency standard with narrower linewidth.

ACKNOWLEDGMENT

This work was supported by National Natural Science Foundation of China under Grant No. 91436210, China Postdoctoral Science Foundation under Grant No. BX2021020, and Wenzhou Major Science & Technology Innovation Key Project under Grant No. ZG2020046.

REFERENCES

[1] S. Jacobs, G. Gould, and P. Rabinowitz, "Coherent Light Amplification in Optically Pumped Cs Vapor," Phys. Rev. Lett. **17**, 415-417 (1961).

[2] P. P. Sorokin, and J. R. Lankard, "Infrared Lasers Resulting from Photodissociation of Cs2 and Rb2," J. Chem. Phys. **51**, 2929-2931 (1969).

[3] A. Sharma, N. D. Bhaskar, Y. Q. Lu, et al., "Continuous-wave mirrorless lasing in optically pumped atomic Cs and Rb vapors," Appl. Phys. Lett. **39**, 209-211 (1981).

[4] B. V. Zhdanov, T. Ehrenreich, and R. J. Knize, "Highly efficient optically pumped cesium vapor laser," Opt. Commun. **260**, 696-698 (2006).

[5] K. C. Brown, and G. P. Perram, "Cesium laser operating in the blue by direct optical excitation of the 7P3/2 state," In High Energy/Average Power Lasers and Intense Beam Applications V **7915**, 68-75 (2011).

[6] X. Xue, D. Pan, and J. Chen, "A cavityless laser using cesium cell with 459 nm laser pumping," In 2015 Joint Conference of the IEEE International Frequency Control Symposium the European Frequency and Time Forum, pp. 614-617 (2015).

[7] D. Antypas, O. Tretiak, D. Budker, et al., "Polychromatic, continuous-wave mirrorless lasing from monochromatic pumping of cesium vapor," Opt. Lett. **44**, 3657-3660 (2019).

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

[9] G. A. Kazakov, J. Bohnet, and T. Schumm, "Prospects for a bad-cavity laser using a large ion crystal," Phys. Rev. A **96**, 023412 (2017).

[10] 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).

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

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

[13] 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).

[14] 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.

[15] S. J. M. Kuppens, M. P. Van Exter, and J. P. Woerdman, "Quantum-limited linewidth of a bad-cavity laser," Phys. Rev. Lett. **24**, 3815-3818 (1994).