Laser Power Stabilization with a Cesium FADOF

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***Summary*—We achieve the stabilization of the laser power using a cesium Faraday anomalous dispersion optical filter (FADOF). We measured the transmission spectrum of the FADOF. In the transition line of $6s^2S_{1/2}$ *F*=4→$6p^2P_{3/2}$ for cesium at the wavelength of 852 nm, when the laser frequency is constant, the transmission of FADOF increases rapidly and then decreases as the probe laser intensity increases. The negative correlation between FADOF transmission and laser intensity can be used to stabilize the laser power. Therefore, we tune the laser frequency to the cesium $6s^2S_{1/2}$ *F*=4→$6p^2P_{3/2}$ transition line, then the power of the laser passing through the FADOF is expected to be stabilized. This work can be applied to the precision measurement field, such as atomic clocks, atomic gravimeters, atomic magnetometers, etc.**

Keywords—power stabilization；FADOF

I. INTRODUCTION

Laser power need to be stabilized in practical applications, such as atomic clocks [1], atomic gravimeters [2] and atomic magnetometers [3,4].

The main reason for making the laser power unstable is the driving current fluctuations and temperature fluctuations of the laser diodes and mechanical vibration. There are already a lot feedback methods to suppress these factors, which can be divided into internal and external power stabilization methods. The internal stabilization methods mainly control the current and the temperature of the laser diode to stabilize the laser power [5-7]. For external power stabilization, acousto-optic modulation [8-10], electro-optic modulation [11-13], and the liquid crystal phase method [14,15] are usually used to stabilize the laser power. Although these methods are well established, they have to use drivers and feedback circuits, which make the structure complex and expensive.

Faraday anomalous dispersion optical filter (FADOF) was first reported in 1956 [16], which has narrow bandwidth, high transmission, and high noise rejection ratio. Therefore, FADOFs are widely used in laser stabilization and optical communication systems [17-20].

The key to stabilize laser power is to establish a feedback mechanism to suppress the fluctuations in laser power. And a FADOF has different transmission for lasers of different laser intensities. In a certain laser intensity range, the higher the laser intensity, the lower the transmission. Therefore, the FADOF can be used to stabilize the laser intensity, which is simpler than using a phase-locked loop to stabilize the laser power.

Here, we propose a method to stabilize the laser power using a cesium FADOF. Near the atomic transition line of $6s^2S_{1/2}$ *F*=4→$6p^2P_{3/2}$, the transmission of cesium FADOF decreases with the increasing power of the incident laser over a power range. We use the negative correlation between transmission and probe laser intensity to stabilize the laser power.

II. METHODS

As shown in Fig. 1, we use a grating laser as the local oscillation laser. The laser is divided into two paths through the polarization beam splitter (PBS), one into the photodetector and the other into the FADOF for power stabilization. And the laser frequency is tuned to the cesium $6s^2S_{1/2}$ *F*=4→$6p^2P_{3/2}$ transition line (see Fig. 2). FADOF consists of three parts, namely two PBSs, a cesium vapor cell, and NdFeB magnets. The cesium vapor cell in the FADOF, with a length of 3 cm and a diameter of 1.5 cm, is filled with cesium and 10 torr Ar buffer gas. The buffer gas can make the full width at half maximum (FWHM) wider, which can broaden the frequency range of power stabilization. The magnets surrounding the vapor cell can provide an axial magnetic field of 900 G. The vapor cell is surrounded by a heating wire for temperature control, and the cell temperature is fixed at 62°C. To inhibit heat transfer, we fix the vapor cell in Teflon box. The Teflon box is fixed in an aluminum box and secured with screws. Two PBSs is fixed at both ends of the box to select the laser. The polarization directions of the two PBSs are perpendicular to each other. The advantages of using aluminum for a housing are, first, the high hardness of the metal compared to non-metals, and second, the low density and light weight of aluminum compared to other metals. The photograph of FADOF is shown in Fig. 3.

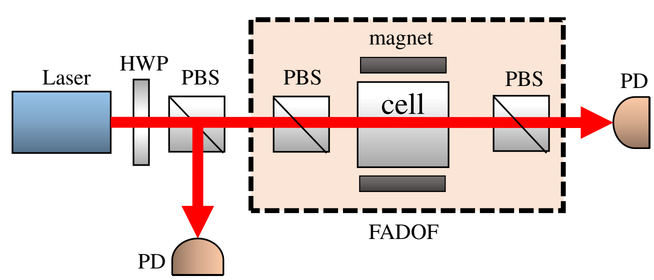

Fig. 1. Schematic of the experimental setup. PBS: polarization beam splitter, PD: photoelectric detector, HWP: half wave plate.

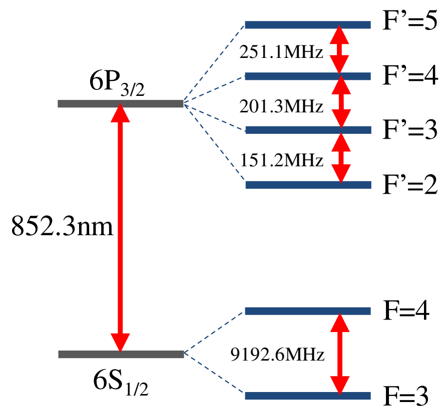

Fig. 2 Cesium energy level diagram.

The laser passing through the first PBS of FADOF is linearly polarized. The linearly polarized laser can be decomposed into left and right circularly polarized laser. And the energy level of the cesium atom splits because of the Seeman effect, which makes the dispersive and absorption lines of the left and right circularly polarized laser split, resulting in the Faraday effect. Therefore, when the laser passes through the cesium atomic vapor cell, the polarization direction is rotated. The absorption and energy level splitting of the cesium atoms differ when the frequency or intensity of the incident laser is different, so the transmission differs after the laser passes through the second PBS. The transmission spectrum is shown in Fig. 4 when the incident laser power is 1.3 mW and the laser intensity is 0.35 mW/mm^2.

Fig. 3 Photograph of the FADOF. The housing of the PBS is made of aluminum. The PBS is fixed to the front and back of the FADOF and is used to select the laser with a specific polarization. The cesium vapor cell is wrapped with a heating wire for temperature control and placed in a Teflon insulation layer with a tight fit between them for better insulation. The Teflon layer is placed in an aluminum housing and secured with screws. The cesium vapor cell is made of glass, with a length of 3 cm and a diameter of 1.5 cm, and is filled with 10 torr Ar as buffer gas. The Teflon insulation layer has holes to place magnets in it. The magnet provides a longitudinal magnetic field of 900 G, which is used to bring about the Zeeman effect.

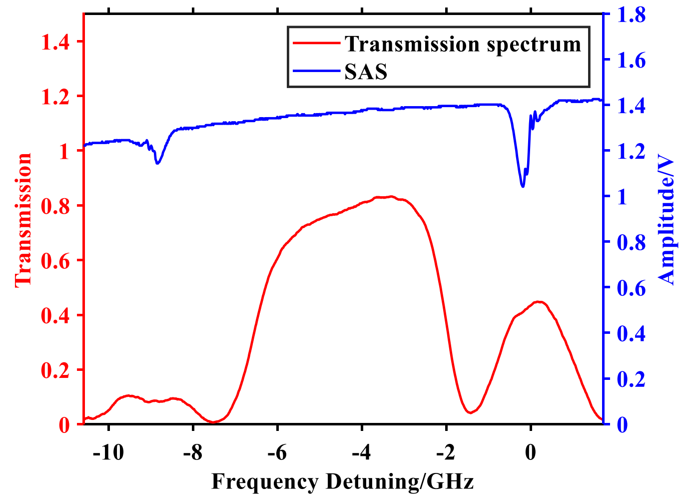

Fig. 4 The transmission spectrum (solid red line) and the corresponding saturation absorption spectroscopy (SAS, solid blue line). 0 GHz of the horizontal ordinate is corresponding to $6s^2S_{1/2}$ F=4→$6p^2P_{3/2}$ F'=5.

As shown in Fig. 5, the influence of the power of the incident laser on the FADOF transmission is measured by varying the laser power using an optical attenuator when the frequency of the grating laser is aligned to the top of the transmission peak at the transition line of $6s^2S_{1/2}$ F=4→$6p^2P_{3/2}$. There is a negative correlation between FADOF transmittance and incident laser power, which can be used to stabilize the laser power. When the optical power is greater than 0.7 mW, the transmission of FADOF decreases continuously with the increase of laser power. When the optical power is between 0.7 mW and 3 mW, the transmission and laser power are approximately linear. When the optical power is greater than 3 mW, the transmission decreases more and more slowly as the laser power increases. We fixed the laser intensity at 0.54 mW/mm^2 to lock the laser power (The laser power is 2 mW, and the spot size of laser is 3.68 mm^2). Because when the laser power fluctuates to less than 2 mW, that is, the laser intensity is less than 0.54 mW/mm^2, the transmission of FADOF decreases; when the laser power fluctuates to more than 2 mW, the transmission of FADOF increases. When the slope of the curve is suitable, the power of the laser can be well stabilized. Because the transmission at the transition line of $6s^2S_{1/2}$ F=4→$6p^2P_{3/2}$ only changes significantly at small laser intensities, the laser spot should be expanded before entering the FADOF and scaled down before entering the detector if the laser power is large.

The PZT was adjusted to align the frequency of the grating laser to the $6s^2S_{1/2}$ F=4→$6p^2P_{3/2}$ transition line for power stabilization. We convert the voltage detected by the detector to laser intensity and then calculate the stabilization of the laser power before and after stabilization. The result will show in the full text.

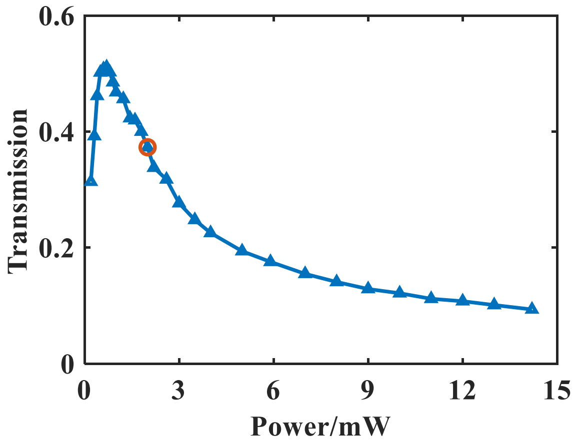

Fig. 5 The influence of the incident laser power on the FADOF transmission when the frequency of the grating laser is aligned to the top of the transmission peak of the transition line $6s^2S_{1/2}$ F=4→$6p^2P_{3/2}$. We fix the laser power at 2 mW, shown with the red circle. The spot size of laser is 3.68 mm².

III. Discussion

To stabilize the laser power using the FADOF, only a FADOF and a temperature-control circuit are required. This is much simpler than other methods in terms of structure and usage, which can also achieve good power stability. Moreover, the cost of this method is very low. This method can be extended to other frequency bands, using FADOF based on other atoms.

Although Fig. 2 only shows the transmission curve at the peak of the transition line $6s^2S_{1/2}$ F=4 → $6p^2P_{3/2}$, it is experimentally demonstrated that the relationship between FADOF transmission and laser power at frequencies near the transition line is similar to that in Fig. 2. Therefore, the power of lasers with frequencies near the transition lines can be well stabilized. At present the long-term power stability achieves good results, and the short one needs further improvement. We need to further explore better FADOF parameters to improve the power stability.

IV. Conclusions

The laser power stabilization is realized with a cesium FADOF. We study the influence of laser intensity on the FADOF transmission, and then fix the laser intensity at optimal value. The negative correlation between FADOF transmission and laser intensity is used to improve the laser power stability. This method can stabilize the laser power without a feedback loop, which can reduce the complexity, cost, and size of the system. In the future, we will try to stabilize the laser power with FADOF working at other wavelengths.

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References

[1] K. Bongs, Y. Singh, L. Smith, W. He, O. Kock, D. wierad, J. Hughes, S. Schiller, S. Alighanbari, S. Origlia, et al., “Development of a strontium optical lattice clock for the SOC mission on the ISS,” C.R. Phys., vol. 16, pp. 553-564, 2015.

[2] Z. Hu, B. Sun, X. Duan, M. Zhou, L. Chen, S. Zhan, Q. Zhang, and J. Luo, “Demonstration of an ultrahigh-sensitivity atom-interferometry absolute gravimeter,” Phys. Rev. A, vol. 88, 2013.

[3] N. Behbood, F. Martin Ciurana, G. Colangelo, M. Napolitano, M. W. Mitchell, and R. J. Sewell, “Real-time vector field tracking with a coldatom magnetometer,” Appl. Phys. Lett., vol. 102, 2013.

[4] D. Budker and M. Romalis, “Optical magnetometry,” Nat. phys, vol. 3, pp. 227–234, 2007.

[5] S. M. Curry, R. Cubeddu, and T. W. Hänsch, "Intensity stabilization of dye laser radiation by saturated amplification," Appl. Phys., vol. 1, pp. 153–159, 1973.

[6] J. Rollins, D, Ottaway, M. Zucker, R. Weiss, and R. Abbott, "Solid-state laser intensity stabilization at the 10^{-8} level," Opt. Lett., vol. 29, pp.1876-1878, 2004.

[7] B W Barr, K A Strain and C J Killow, “Laser amplitude stabilization for advanced interferometric gravitational wave detectors,” Class. Quantum Grav., vol. 22 pp. 4279–4283, 2005.

[8] P. Kwee, C. Bogan, K. Danzmann, M. Frede, H. Kim, P. King, J. Pold, O. Puncken, R. L. Savage, F. Seifert, P. Wessels, L. Winkelmann, and B. Willke, “Stabilized high-power laser system for the gravitational wave detector advanced LIGO,” Opt. Express, vol. 20, pp. 10617-10634, 2012.

[9] J. Junker, P. Oppermman, and B. Willke, “Shot-noise limited laser power stabilization for the AEI 10 m prototype interferometer,” Opt. Lett. vol. 42, pp. 755-758, 2017.

[10] F. Tricot, D. H. Phung, M. Lours, S. Guérandel, and E. de Clercq, “Power stabilization of a diode laser with an acousto-optic modulator,” Rev. Sci. Instrum., vol. 89, 2018.

[11] N. A. Robertson, S. Hoggan, J. B. Mangan, and J. Hough, “Intensity stabilisation of an argon laser using an electro-optic modulator – Performance and limitations,” Appl. Phys. B, vol. 39, pp.149-153, 1986.

[12] C. D. Tran and R. J. Furlan, “Indirect Amplitude Stabilization of a Tunable Laser Through Control of the Intensity of a Pump Laser by an Electro-Optic Modulator,” vol. 47, pp. 235-238, 1993.

[13] F. Liu, C. Wang, L. Li, and L. Chen, “Long-term and wideband laser intensity stabilization with an electro-optic amplitude modulator,” Opt. Laser Technol., vol. 45, pp. 775–781, 2013.

[14] B. Zhou, G. Lei, L. Chen, W. Wu, Z. Wang, X. Meng, and J. Fang, Chin., “Noise suppression for the detection laser of a nuclear magnetic resonance gyroscope based on a liquid crystal variable retarder,” Opt. Lett., vol. 15, 2017.

[15] X. Wang, L. Wu, X. He, X. Huang, and Q. Tan, “Theoretical analysis on power stability and switch time of the non-mechanical beam steering using liquid crystal optical phased array,” Liq. Cryst., vol. 45, pp. 1477–1486, 2018.

[16] Y. Ohman, “On some new auxiliary instruments in astrophysical research VI. A tentative monochromator for solar work based on the principle of selective magnetic rotation,” Stockholms Obs. Ann, vol. 19, pp. 9-11, 1956.

[17] P. P. Sorokin, J. R. Lankard, V. L. Moruzzi, and A. Lurio, “Frequency-locking of organic dye lasers to atomic resonance lines,” Appl. Phys. Lett., vol. 15, pp. 179–181, 1969.

[18] X. Miao, L. Yin, W. Zhuang, B. Luo, A. Dang, J. Chen, and H. Guo, “Note: Demonstration of an external-cavity diode laser system immune to current and temperature fluctuations,” Rev. Sci. Instrum., vol. 82, 2011.

[19] J. Tang, Q. Wang, Y. Li, L. Zhang, J. Gan, M. Duan, J. Kong, and L. Zheng, “Experimental study of a model digital space optical communication system with new quantum devices,” Appl. Opt., vol. 34, pp. 2619–2622, 1995.

[20] H. Shi, P. Chang, Z. Wang, Z. Liu, T. Shi and J. Chen, "Frequency Stabilization of a Cesium Faraday Laser With a Double-Layer Vapor Cell as Frequency Reference," IEEE Photonics J., vol. 14, pp. 1-6, 2022.