Frequency Stabilization For The Faraday Laser Operating on Rb 780 nm Transition

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***Summary*—Compared with Faraday anomalous dispersion optical filter, the atom optical filter based on the Voigt effect can generate a stronger and more uniform magnetic field with a compact size of the magnet. The transmission characteristics of the Voigt anomalous dispersion optical filter (VADOF) are further investigated, and a transmission spectrum with ultra-low bandwidth immune to the cell temperature is constructed. Therefore, this optical filter has the potential to perform well in a complex environment, such as outdoor and out space. Importantly, the VADOF could be applied to a diode laser as a frequency-selective element, named "Voigt laser", contributing to better frequency stability.**

Keywords—Faraday anomalous dispersion optical filter (FADOF); Faraday laser; modulation transfer spectroscopy; frequency standard

I. INTRODUCTION

Magneto-optical effects play an important role in matter detection, optical communication, and precision measurement. An atomic line filter is an advantageous magneto-optical bandpass technique owing to its high transmission, narrow bandwidth, and high signal-to-noise ratio [1-6]. Applications vary widely including weak signal detection [7], free-space optical communication [8], quantum key distribution [9], and self-stabilizing laser systems [10].

The Faraday anomalous dispersion optical filter (FADOF) is a kind of atomic line filter that uses the anomalous dispersion effect near the resonant frequency of atoms to achieve ultranarrow bandwidth filtering, where a magnetic field is parallel to the k-vector of the light [1-6]. Since the 1990s, the FADOF has gradually become the focus of research on atomic filters due to its potential roles. FADOFs have been composed of different structures andalkali metals, greatly expanding their performance and application range. Since 2011, FADOF is applied as a frequency-selective element, revealing a stable "Faraday laser" immune to the diode current and temperature, paving the way for compact optical frequency standards [10].

Compared with FADOF, the Voigt anomalous dispersion optical filter (VADOF), where a magnetic field perpendicular to the k vector of the light, is less explored. Unlike the Faraday effect, the Voigt effect rotates the polarization direction of the passing laser by applying a magnetic field, where the k vector of the light and the direction of the magnetic field are perpendicular [11]. Therefore, VADOF could construct a stronger and more homogeneous magnetic field, with less volume than FADOF. In addition, the VADOF obtains a spectrum with a narrower bandwidth, which is insensitive to the temperature fluctuation of the vapor cell compared with FADOF. In this case, A diode laser named Voigt laser, with VADOF as a frequency-selective element, has the potential to obtain better frequency stability and stronger immunity to disturbances from outside or laser diode.

II. METHODS

In this work, we use a homemade 780 nm interference-filter external cavity diode laser (IF-ECDL) to probe the transmission spectrum of VADOF, of which the laser beam diameter is 2 mm. The probe laser is split into two laser beams (laser a and laser b) by a half-wavelength plate (HWP) and a polarizing beam splitter (PBS). We probe the saturated absorption spectroscopy (SAS) of 87Rb as a frequency reference using laser a, which is shown as the green dash in Fig.1. Laser b goes through an HWP and a PBS to control its intensity before probing the transmission spectrum of VADOF. The SAS and transmission spectrum are detected by two photodetectors respectively.

length of L = 30 mm, a set of permanent magnets, and two polarized beam splitters (PBSs). The Faraday laser passes through the optical isolator (ISO) to block optical feedback and then is divided into two beams by a half-wave plate (HW) and a (PBS). The reflected beam is used as the pump laser, and the transmitted beam is the probe laser. The electro-optic modulator (EOM) placed in the pump path is utilized to modulate the phase of the pump laser. The ^{87}Rb cell temperature is kept at 25℃. The probe signal detected by the photodetector (PD) is filtered, amplified, and then used as the residual error signal of MTS after a frequency mixer. This residual error signal is sent to a proportion-integral-derivative (PID) controller and then feedback to the driver of the Faraday laser and PZT as the feedback signal. Once the two cells in Fig. 1 switch position, the setup stands for the frequency stabilization of the Faraday laser operating on the ^{87}Rb 780 nm transition.

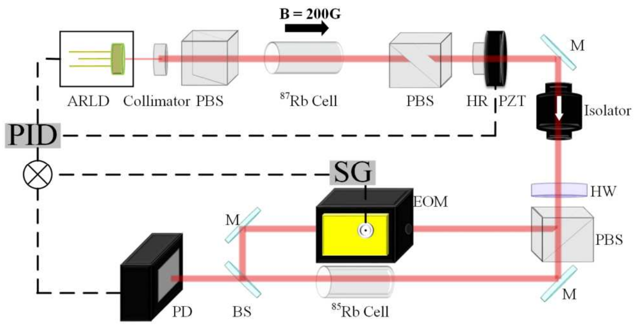

Fig. 1. Schematic of the experimental setup. ARLD, anti-reflection coated laser diode; PBS, polarization beam splitter; R, reflection mirror; PZT, piezoelectric transducer; PD, photon detector; HW, half-wave plate; EOM, electro-optic modulator; BS, beam splitter; SG, signal generator; PID, proportional integral derivative controller.

III. DISCUSSION

We first propose the novel frequency stabilization method in simulation analysis, as shown in Fig.2. When the magnetic field is 50 G and the temperature of ^{85}Rb FADOF is 92 ℃, the FADOF transmission spectrum shows a "wing" spectral profile and the highest transmission peak could refer to the ^{87}Rb F = 2 to F' = 3 transition, seeing Fig. 2(a). Therefore, the Faraday laser with an ^{85}Rb FADOF in the above parameters could be locked to the ^{87}Rb cyclic transition using MTS technology. Besides, the spectral profile of ^{87}Rb FADOF is "line center" and the highest transmission could refer to the ^{85}Rb F = 3 to F' = 4 transition when the magnetic field is 200 G and the temperature of ^{87}Rb FADOF is 70.5 ℃, seeing Fig. 2(b). In this case, the Faraday laser with an ^{87}Rb FADOF could be locked to the ^{85}Rb cyclic transition. Comparing these two frequency stabilization methods, ^{87}Rb FADOF requires a higher magnetic field and lower temperature, and therefore is not convenient for miniaturization but obtains lower power consumption.

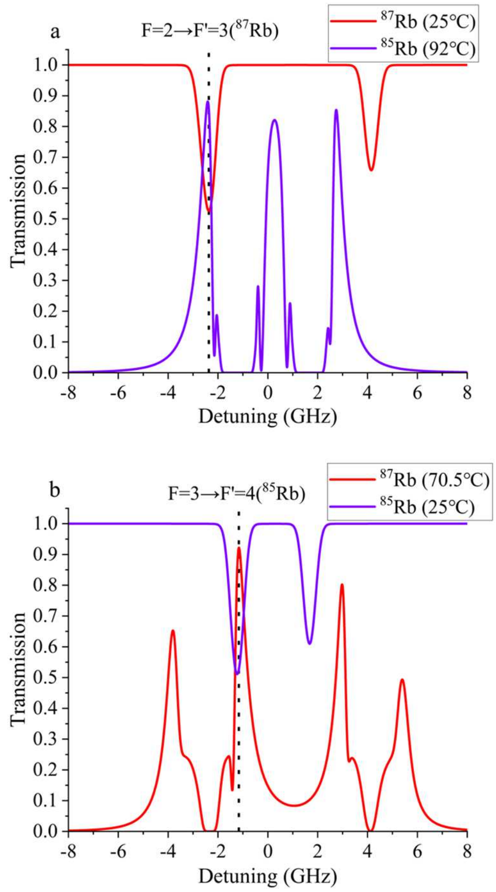

Fig. 2. (a) Transmission spectrum of ^{87}Rb FADOF and transmission spectrum of ^{85}Rb cell. (b) Transmission spectrum of ^{85}Rb FADOF and transmission spectrum of ^{87}Rb cell.

The experiment proof or the above proposal is then constructed, utilizing an ^{87}Rb FADOF with a magnetic field of 200 G, seeing Fig.3. The input intensity is in the order of magnitude of the saturation intensity of ^{87}Rb in the above simulation analysis. However, the application in the laser system requires the input intensity to be much larger. Therefore, we probe the transmission spectrum with an input intensity of 10 mW/mm^2, which is 3 orders of magnitude higher than the saturation intensity of ^{87}Rb. The saturated absorption spectroscopy of a natural Rb atomic cell is obtained as a reference, where the transition of ^{87}Rb and ^{85}Rb can both be observed, presented in Fig. 3(a). Then, the transmission spectrums of a ^{87}Rb atomic cell at different temperatures are probed, where the zero point of the transmission spectrums refers to the atomic transition of $5^2S_{1/2}F = 2 \rightarrow 5^2P_{3/2}F = 3$ of ^{87}Rb, seeing Fig. 3(b) and Fig. 3(c). When the temperature T is less than 50℃, the highest peak of the transmission spectrum refers to the atomic transition of $5^2S_{1/2}F = 2 \rightarrow 5^2P_{3/2}F = 3$ of ^{87}Rb. However, the highest transmittance is lower than 0.3, which is too low for a Faraday laser to emit. Once the temperature is within the temperature range of 50 – 60℃, the highest peak refers to the atomic transition of $5^2S_{1/2}F = 1 \rightarrow 5^2P_{3/2}F = 0$ of ^{87}Rb. This might be a potential approach for a Faraday laser operating at this atomic transition, which has not been reported yet. When the temperature exceeds 60℃, the highest peak starts to approach the transition frequency and refers to ^{85}Rb $5^2S_{1/2}F = 3 \rightarrow 5^2P_{3/2}F' = 4$ transition at the temperature of 70℃. The transmittance of the highest peak reaches 0.75 and the bandwidth is 460 MHz when the temperature is 70℃. In this case, the Faraday laser will be limited within the 460 MHz bandwidth regardless of the variation of the diode temperature and current, and can refer to the atomic transition for the next step of frequency stabilization. Once the temperature exceeds 75℃, the highest peak shift away from the atomic transition and the bandwidth will expand, which is out of our interest.

IV. Conclusions

In conclusion, we put forward a novel frequency stabilization method for the Faraday laser operating on Rb 780 nm transition. Theoretical analysis shows the ^{87}Rb Faraday laser can be locked to the ^{85}Rb cyclic transition and the ^{85}Rb Faraday laser can be locked to the ^{87}Rb cyclic transition. The advantages and disadvantages of these two methods were discussed. Then, the feasibility of locking the ^{87}Rb Faraday laser to the ^{85}Rb cyclic transition is verified by preliminary experiments. This study could greatly promote the development of optical frequency standards. Moreover, other promising research related to atomic filtering operating in large laser intensity may also benefit from the study completed here.

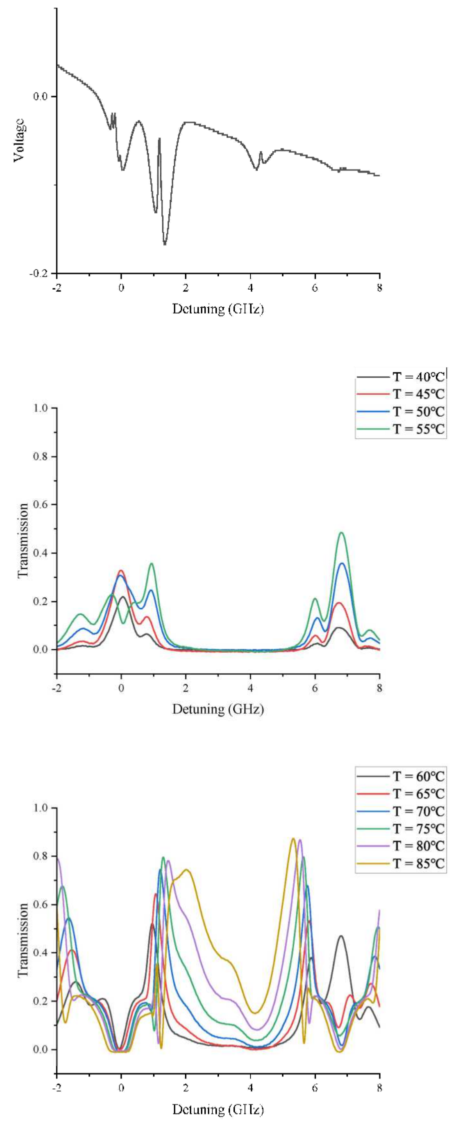

Fig. 3. (a) The saturated absorption spectroscopy (SAS) of Rb. (b) Transmission spectrum of ^{87}Rb FADOF within the temperature range from 40℃ to 55℃. (c) Transmission spectrum of ^{87}Rb FADOF within the temperature range from 60℃ to 85℃.

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