A Voigt Anomalous Dispersion Optical Filter Immune to the Cell Temperature Fluctuation

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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); Voigt anomalous dispersion optical filter (VADOF); diode laser; Voigt laser

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 and alkali 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 ^{87}Rb 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.

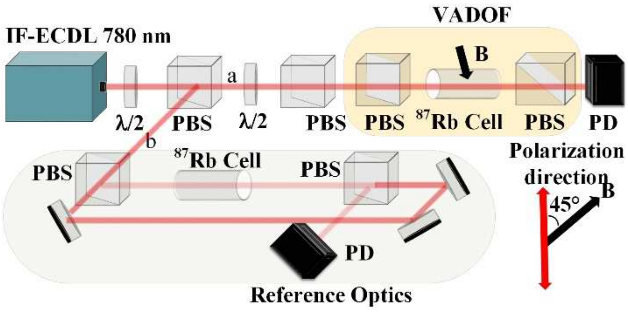

Fig. 1. Schematic of the experimental setup. λ/2, half-wave plate (HWP); PBS, polarization beam splitter; PD, photon detector; The probe laser is split into two laser beams (laser a and laser b) by an HWP and a PBS. Reference optics aims at probing saturated absorption spectroscopy (SAS) of ^{87}Rb as a frequency reference. VADOF is composed of a vapor cell filled with thermal rubidium atoms, and permanent magnets for providing a homogeneous magnetic field. The Angle between the magnetic field direction and the polarization direction of the incident laser is 45°.

VADOF comprises a ^{87}Rb atomic vapor cell with a length of L = 30 mm, a set of permanent magnets, a temperature control system, and two PBSs. The magnet with a smaller volume in VADOF constructs a stronger and more uniform magnetic field than that of FADOF. Thus, the transmission spectrum of VADOF has a narrower bandwidth. Importantly, the transmission spectrum of VADOF is insensitive to the cell temperature variation. That makes VADOF immune to the fluctuations of the cell temperature, and therefore the Voigt laser could be immune to external temperature fluctuation and realize long-term free-running.

We also assemble a ^{87}Rb FADOF as a comparison of VADOF. The magnet placement is the main difference between FADOF and VADOF, and the other packages are the same. The transmission spectrum of FADOF can be probed by replacing the VADOF with FADOF in Fig.1.

III. DISCUSSION

We first analyze the transmission spectrum of FADOF and VADOF in simulation, using a theoretical analysis tool [12]. The magnetic field of VADOF and FADOF are both set as 300 G and the length of ^{87}Rb atomic vapor cell is set as 3 cm. 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, as presented in Fig.2. In this case, the highest peak of the FADOF obtains a transmittance of 97%, when the cell temperature is around 75℃, as shown in Fig. 2(a). However, another transmission peak with an equal transmittance exists in the transmission spectrum. If this FADOF is applied to a Faraday laser, a dual-mode output might occur, which is not desirable except for specialized studies. The bandwidth of FADOF is 1.225 GHz and the thermal frequency drift rate is 157 MHz/℃, seeing Fig. 2(d). For comparison, the VADOF obtains a single highest peak with a transmittance of 48%, when the cell temperature is around 75℃. Therefore, the Voigt laser could output a single-mode laser with the above VADOF as a frequency-selective element. Besides, the bandwidth of this highest peak is 400 MHz and the frequency drift rate of the highest transmission point with the cell temperature variation is 14 MHz/℃, seeing Fig. 2(c) and (d). Considering that the bandwidth and thermal drift rate have important contributions to the frequency stability, the Voigt laser is expected to achieve better frequency stability than the Faraday laser.

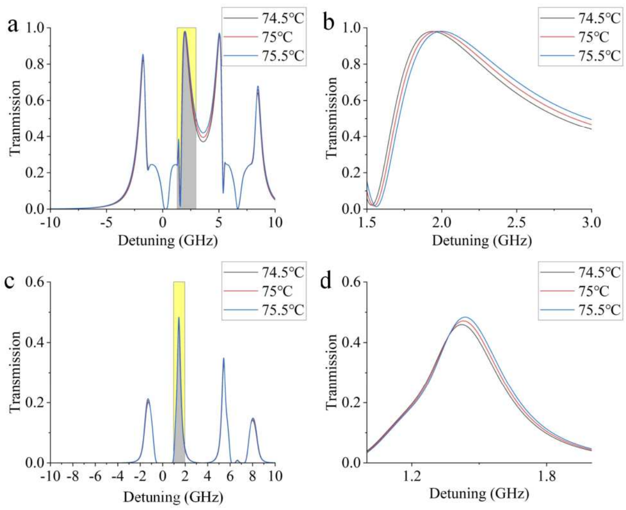

Fig. 2. The theoretical transmission spectrum of FADOF (a) and VADOF (c) at 74.5℃, 75℃, and 75.5℃, respectively. (b) and (d) are enlargements of (a) and (c), respectively. The magnetic field is 300 Gs.

Then, we experimentally probe the transmission of FADOF and VADOF. For a ^{87}Rb atomic vapor cell with a diameter of 10 mm, two permanent magnets with a volume of 8 cm^3 can generate a 300 G magnetic field with a homogeneity better than 99%. The temperature of the ^{87}Rb cell is controlled by an electric heating element that allows for maintaining the cell temperature variation within 0.1℃. 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 experiment results are presented in Fig.3.

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, as presented in Fig.3. As predicted in the simulation results, the transmission spectrum contains two peaks with an equal transmittance, which is no desirable for a single-mode output Faraday laser, seeing Fig. 3(a). Besides, the thermal frequency drift of the FADOF is discussed in Fig. 3(c). The frequency of the highest point shifts by 0.75 GHz with the temperature variation from 75°C to 85°C, and the linear fit indicates that the frequency drift rate is 75 MHz/°C. Typically, the frequency drift rate can reach 116 MHz/°C within the temperature range of 80 – 85°C. In contrast, the transmission spectrum obtains a single highest peak, conductive for a single-mode output Voigt laser. Besides, the frequency of the highest point shifts by 0.44 GHz with the temperature variation from 75°C to 85°C, and the linear fit indicates that the frequency drift rate is 44 MHz/°C.

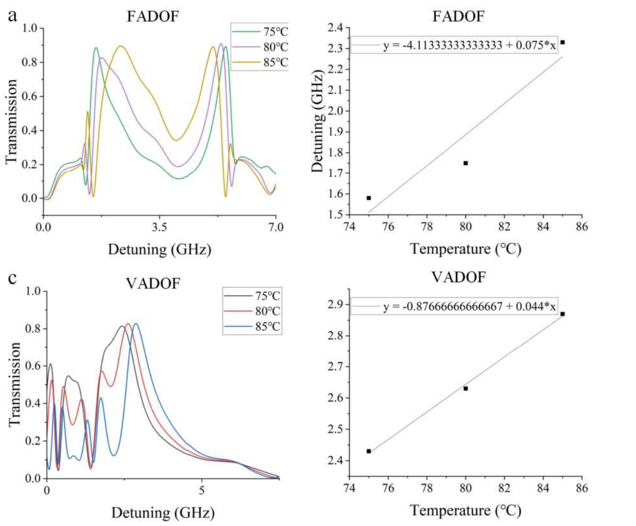

Fig. 3. The experimental transmission spectrum of FADOF (a) and VADOF (c) at 74.5°C, 75°C, and 75.5°C, respectively. The thermal frequency drift of FADOF (b) and VADOF (d) are calculated according to the transmission spectrum, respectively. The magnetic field is 300 Gs.

IV. Conclusions

Here, we investigate the effect of the cell temperature towards the transmission spectrum of FADOF and VADOF in simulations and experiments. The results indicate that the transmission spectrum of this VADOF obtains a single peak with a bandwidth of 400 MHz. Furthermore, the thermal frequency drift rate of the highest transmission point is 44 MHz/°C, while that of a FADOF with the same parameters could reach 116 MHz/°C. That suggests that the VADOF realizes a stronger immunity to the temperature fluctuation of vapor cell. Therefore the Voigt laser, utilizing a VADOF as a frequency-selective element, could output a single-mode output with narrow linewidth, which has a higher tolerance to cell temperature fluctuation.

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