# Faraday anomalous dispersion optical filter at $^{133}$Cs weak 459 nm transition

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A 459 nm Faraday anomalous dispersion optical filter (FADOF) working at the side wings of the cesium $6S_{1/2} \rightarrow 7P_{1/2}$ transition with weak oscillator strength is achieved. The transmittance of the higher side wing reaches 98% at a temperature of 179°C and magnetic field above 323 G. The experimental results coincide with the theoretical predictions in 1982 and 1995, which were not realized in experiments for over three decades. Due to its high transmittance, high accuracy, and narrow linewidth, the 459 nm FADOF can be applied in underwater optical communications, the building of active optical clocks, and laser frequency stabilization in active optical clocks. 

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## 1. INTRODUCTION

A Faraday anomalous dispersion optical filter (FADOF) was first proposed and utilized for astrophysical researches [1] and then later as a unique element for frequency locking of lasers [2,3]. In 1982, a complete theory of FADOF was derived [4], in which the cesium 459 nm transition ($6S_{1/2} \rightarrow 7P_{1/2}$) was carefully calculated as an example. Various kinds of FADOFs have been realized using different atomic transitions since then, such as 589 nm in sodium and 766 nm in potassium [5], 780 [6] and 795 nm [7] in rubidium, 455 nm in cesium [8,9], etc. FADOF has many advantages, such as ultranarrow linewidth [10], narrow equivalent noise bandwidth (ENBW) [11], high transmittance and high noise rejection ratio [12,13], and can be used in free-space optical communications [14], lidar remote sensing systems [15–17], underwater optical communications [18], etc. Moreover, the narrow linewidth together with high accuracy makes FADOF an excellent candidate for laser frequency stabilization [2,3,19,20]. The characteristic of ultranarrow bandwidth makes FADOF appropriate for building active Faraday optical clocks [21,22].

In this paper, a 459 nm FADOF working at the side wings with high transmittance is experimentally demonstrated and precisely measured, though the theoretical calculation was first done in 1982 [4] and extended in 1995 [23]. The observation of transmission of Cs 459 nm FADOF is mentioned earlier, which only points out that the transmittance is low, but no experimental data is presented [24]. To our knowledge, this is the first experimental research about 459 nm FADOF with detailed experimental data. To overcome the problem of weak oscillator strength ($2.84 \times 10^{-3}$ [25]), we make the FADOF operate at relatively higher temperature and a larger magnetic field. The transmittance of FADOF can reach as high as 98% at a proper condition (179°C and 323 G in this work) (note that the parameters here are not selected based on theoretical calculations; it is an experimental result when a high transmittance is achieved) at side wings. The highest transmittance, shape of the spectra, and changing tendency of the spectra with temperature and magnetic field coincide with the theoretical predictions (see Fig. 4 in Ref. [23]).

## 2. EXPERIMENTAL SETUP

The experimental setup is shown in Fig. 1. The whole glass cell is 5 cm in length and filled with pure natural Cs atoms. The windows of the glass cell do not induce significant dispersion. The transmitted spectrum is interrogated by an external cavity diode laser with a mode-hop free tuning range of 12 GHz. The power of the incident laser beam is 2 mW with a beam size of 1 mm × 0.6 mm in the horizontal and vertical directions. Two Glan–Taylor prisms (G1 and G2) are set with orthogonal polarization directions. G1 is used to generate linear polarized light, and G2 is used to select the rotated light. A pair of solenoids is used to generate a uniform and tunable steady magnetic field, which can generate 985 G at 5 A. The transmittance of FADOF is defined regardless of the system loss, such as from glass absorption and reflection, and is recorded as the ratio of light power transmitted when G1 is perpendicular to G2 under Faraday rotation with the magnetic field on to that when G1 is parallel to G2 with the magnetic field off, excluding the atomic absorption.

## 3. EXPERIMENTAL RESULTS

The transmitted spectrum is carefully measured under different temperatures (109°C–179°C) and magnetic fields (0–985 G).

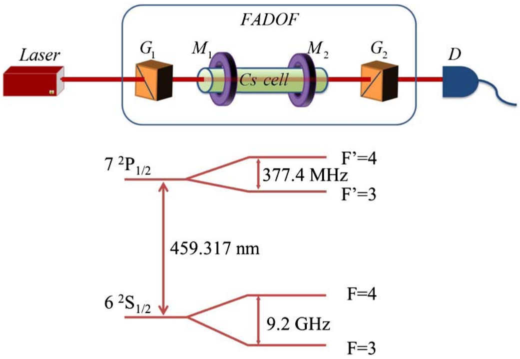


Fig. 1. Experimental setup of the FADOF working at Cs $6S_{1/2} \rightarrow 7P_{1/2}$ transition and related energy levels. An external cavity diode laser is used for transmittance detection. G1 and G2 stand for two Glan–Taylor prisms, of which the polarizations are orthogonal to each other. M1 and M2 stand for a pair of solenoids that can contain the whole glass cell and its package. D stands for photoelectric detector. The Cs cell inside the solenoids is 5 cm long and heated.

Because the Cs ground state $6S_{1/2}$ has two hyperfine structure lines, e.g., $F = 4$ and $F = 3$, they always exhibit two FADOF spectra, in which the central frequencies are separated by 9.2 GHz.

Figure 2 shows the transmittance of the FADOF at 323 G. The Doppler broadening is about 0.8 GHz at our lowest temperature (109°C); thus, the hyperfine splitting of the excited

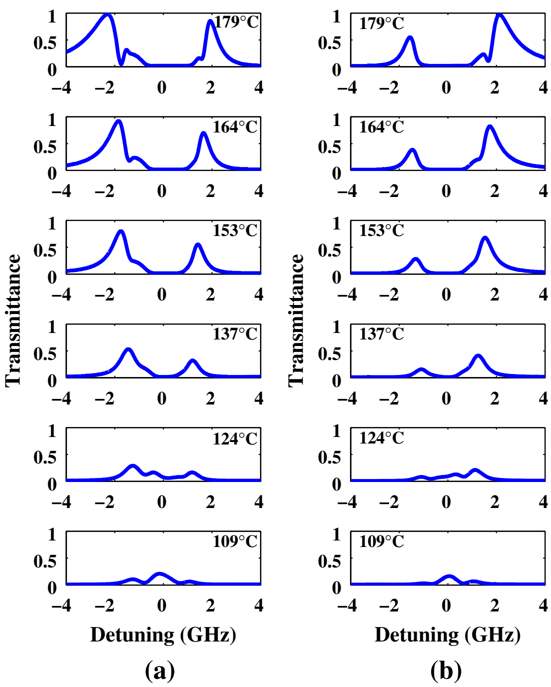


Fig. 2. Transmittance with different temperatures at 323 G. (a) Left column shows the transmitted characteristics from ground state $F = 4$ with temperatures of 179°C, 164°C, 153°C, 137°C, 124°C, and 109°C. (b) Right column shows the transmitted characteristics from ground state $F = 3$ under the same conditions of temperature. Above 137°C, the FADOF works at the side wings. At 179°C and 323 G [corresponding to the first row in (a) and (b)], with frequency increasing, the transmittance of the four peaks is 98%, 82%, 42%, and 92%. The linewidths (full width at half maximum, the same hereinafter) of these four peaks are 1.2, 0.6, 0.5, and 0.8 GHz, respectively.

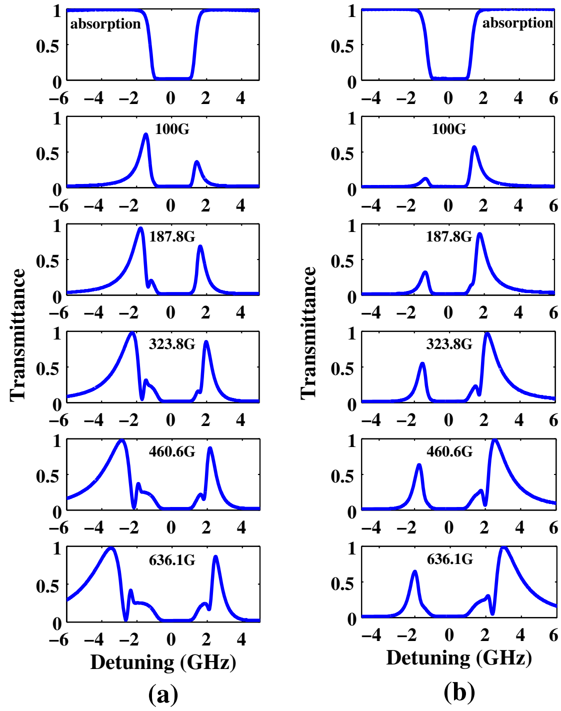


Fig. 3. Cs 459 nm FADOF transmittance with different magnetic fields at the Cs cell temperature of 179°C from different ground states. (a) Transmittance curves from ground state $F = 4$. (b) Transmittance curves from ground state $F = 3$. With the magnetic field increasing, the transmitted signal arises at both wings of the absorption signal. The wavelength of the transition $6S_{1/2}(F = 4) \rightarrow 7P_{1/2}$ is 459.320 nm, which for transition $6S_{1/2}(F = 3) \rightarrow 7P_{1/2}$ is 459.314 nm.

state can be ignored. The FADOF transmittance curves with different magnetic fields at the Cs cell temperature of 179°C (with number density of about $7.8 \times 10^{14}/\text{cm}^3$) from different ground states are shown in Fig. 3. The transmittance of the higher peaks reach to near 100% after 323 G.

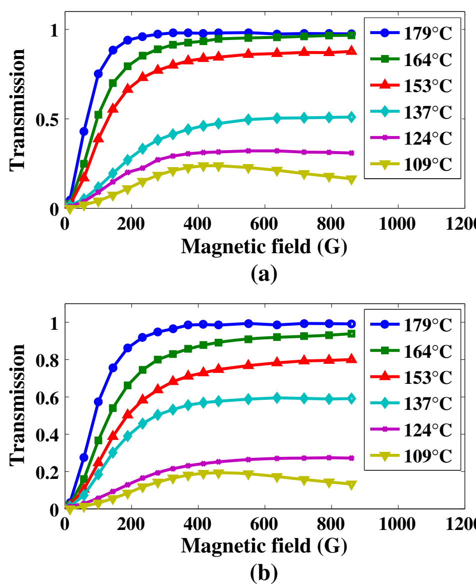


Fig. 4. (a) and (b) Transmittance of the peak transmission of 459 nm FADOF changing with the magnetic field at different temperatures from ground states $F = 4$ and $F = 3$. Symbols are data points; continuous curves are guides to the eye.

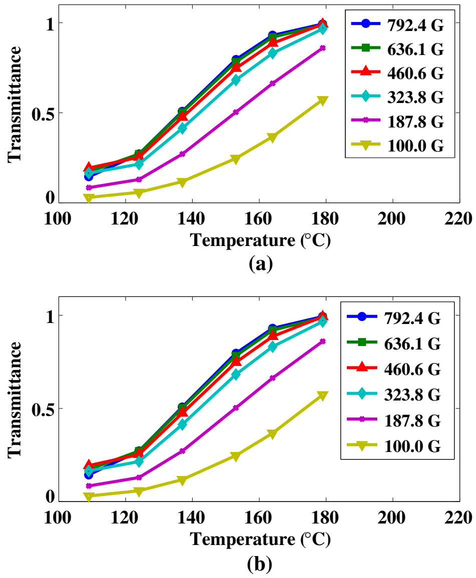


Fig. 5. (a) and (b) Transmittance of the peak transmission 459 nm FADOF changing with temperatures at different magnetic fields from ground states $F = 4$ and $F = 3$. Symbols are data points; continuous curves are guides to the eye.

We measure the transmitted spectra at different magnetic fields and record the transmittance of the higher peak. The transmittance of the peak transmission changing with the cell's magnetic field in detail is shown in Figs. 4(a) and 4(b). When the Cs cell temperature is higher than 120°C, the transmittance rises with the magnetic field increasing as long as the magnetic field is less than 323 G. When the magnetic field is above 323 G, the transmittance becomes gradually stable. The best case in our work is 179°C with a 323 G magnetic field, where the transmittance of the higher peak is about 98% with a bandwidth of about 1.2 GHz. The transmittance of the peak transmission changing with cell temperature at a different magnetic field is shown in Figs. 5(a) and 5(b), where one can see the transmittance increases with the temperature and magnetic field increasing.

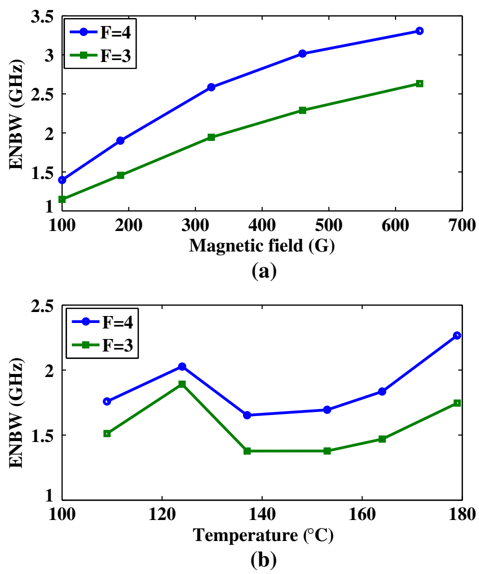


Fig. 6. ENBW of the transmitted spectra changing with (a) magnetic field and (b) temperature. Symbols are data points; continuous curves are guides to the eye.

For practical applications, we may need to consider the ENBW [11]. The ENBW of the spectra changing with temperature and magnetic field is shown in Fig. 6, according to the data in Figs. 2 and 3. At 179°C, with the magnetic field increasing, the ENBW increases. When the magnetic field is fixed at 323 G, the ENBW increases suddenly at about 120°C. This is because, when temperature is near 120°C, the FADOF works neither at the line center nor the side wings. The passband is wide while the transmittance is low. The ENBW for transition from ground state $F = 4$ is larger than that from ground state $F = 3$ because the second transmitted peak is not too small, and the transmitted spectra has a larger tail at the red detuning.

## 4. DISCUSSIONS

It should be noted that the temperature of the Cs cell should only be taken as "indicative" because it is difficult to accurately measure the temperature in the cell. Two thermistors are contacted to the cell wall to measure the temperature. Because the Cs cell is well packaged to maintain the temperature, we evaluate the difference between the measured temperature and the real temperature to be smaller than 3°C. Moreover, the imperfection of the polarization crossing between G1 and G2 may lead to an intensity error of the output signal, which is evaluated to be smaller than 1.5%. The laser frequency drifts of about 26 MHz/ min also lead to an error smaller than 0.25%, which can be ignored. Recently, it is found that the self-broadening [26] becomes significant and affects the spectra of FADOF when the number density is large [27]. It is also an issue to be investigated in regards to how the mechanism works in our experiment.

## 5. CONCLUSION

In conclusion, a 459 nm FADOF working at Cs $6S_{1/2} \rightarrow 7P_{1/2}$ transition with an oscillator strength as weak as $2.84 \times 10^{-3}$ is realized. The transmittance arrives at 98% at a cell temperature of 179°C and a magnetic field of 323 G. The experimental results show consistency with the previous theoretical calculation results. This result can be applied in underwater optical communications, for there is a transmittance window of light at 400–470 nm [18], and the laser frequency stabilization of pumping laser for four-level Cs active optical clocks [28]. An active Faraday optical clock with a much narrower linewidth also can be expected when applied with weak oscillator strength atoms [21,22].

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