Excited-state Faraday anomalous dispersion optical filter in the reflection configuration

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Abstract: An excited-state Faraday anomalous dispersion optical filter (ES-FADOF) operating in a reflection configuration at a wavelength of 917 nm is experimentally demonstrated based on the cesium (^{133}Cs) $6S_{1/2} \rightarrow 6P_{3/2} \rightarrow 6D_{5/2}$ (852 nm + 917 nm) ladder-type atomic system. The 852 nm laser acts as the pump light populating Cs atoms from the $6S_{1/2}$ ground state to the $6P_{3/2}$ intermediate state, while the frequency of 917 nm laser as the signal light is scanned across the $6P_{3/2} \rightarrow 6D_{5/2}$ transition, so an ES-FADOF spectral signal is obtained. Experimental results show that the performance of ES-FADOF remains nearly identical whether the pump and signal light beams are co-propagating or counter-propagating within the atomic vapor cell. Building on this observation, a reflection-type ES-FADOF is achieved for the first time, which allows signal light to pass through the atomic medium twice round trip, doubling the effective length of the vapor cell, so its peak transmission is obviously improved compared to popular ES-FADOF, where the signal light beam passes through the atomic vapor only once. This technique can be applied to the other FADOF systems, especially suitable for atomic media with high melting points.

1. Introduction

Atomic filters are optical devices widely employed to extract weak optical signals from background noise light fields, applying into the free-space optical communication, remote sensing, laser radar systems, quantum optics experiments and so on [1-3]. They can also be used as frequency-selective elements in the stabilized laser systems [4-5]. Various types of atomic filters have been developed, including the atomic resonance filter (ARF), Faraday anomalous dispersion optical filter (FADOF) [6-8], Voigt anomalous dispersion optical filter (VADOF) [5], laser-induced dispersion optical filter (LIDOF) [9, 10], and ultra-narrowband optical filters based on electromagnetically induced transparency (EIT) effect [11] or cold atoms [12]. Among these, FADOF is particularly favored for its narrow bandwidth, high peak transmission, strong suppression of out-of-band noise, and fast response time. At present, popular FADOFs based on the cesium atom ground state to excited state transitions at wavelengths of 455 nm [13], 459 nm [14], and 852 nm [4] have been realized. FADOFs based on rubidium atoms at 420 nm [15], 780 nm [16-18], and 795 nm [18] have also been presented. To further expand the selectivity of optical filter's working wavelength, researchers have studied optical filters operating on the transitions between two excited states, such as the 532.33 nm ES-FADOF realized based on the potassium excited states $4P_{1/2} \rightarrow 8S_{1/2}$ transition [19], exhibiting a peak transmission of ~3.5% and a bandwidth below ~10 MHz; the 1529 nm ES-FADOF based on the rubidium $5P_{3/2} \rightarrow 4D_{5/2}$ transition [20, 21]; and the 728 nm ES-FADOF based on the rubidium $5D_{5/2} \rightarrow 6F_{7/2}$ transition [22]. Unlike traditional FADOF, ES-FADOF usually requires an additional pump laser to excite atoms from the ground state to an intermediate excited state, and its transmission is relatively low due to limited excitation efficiency. In order to enhance the transmission of FADOF, several methods have been investigated. One approach is to raise the temperature of the atomic vapor cell to increase the number density of atoms, but excessively high temperatures may induce chemical reactions between alkali metal atoms and the inner walls of the vapor cell. Another method is to increase the vapor cell length to extend the interaction region between the atomic medium and the light fields [23]. FADOF often requires a uniform magnetic field parallel to the propagation direction of the signal light beam. To ensure the stability of FADOF signals, the magnetic field is often generated by neodymium-iron-boron permanent magnets. However, it is difficult to ensure the uniformity of magnetic field in a long vapor cell, which may increase the equivalent noise bandwidth (*ENBW*) of the FADOF and also make it not convenient to build a compact FADOF device [5].

Optical filter based on atomic excited-state transition typically involves two optical fields, a pump light and a signal light, which interact with a three-level ladder-type atomic system showing rich and interesting physical phenomena. For example, the transmission and *ENBW* of the circular-induced dichroic excited-state optical filters are significantly different in the two experimental configurations with the co-propagating and counter-propagating pump and signal light beams in the atomic vapor cell [24]. In this work, we compare the performance of an ES-FADOF under the co-propagating and counter-propagating configurations using the ^{133}Cs $6S_{1/2} \rightarrow 6P_{3/2} \rightarrow 6D_{5/2}$ (852 nm + 917 nm) atomic system. Combined with the above comparative results and the unique characteristic of the Faraday effect, in which the rotation direction of the polarization plane of linearly polarized signal light depends only on the magnetic field direction and is independent of the propagation direction of signal light, a reflection-type ES-FADOF is realized.

2. Experimental setup

The relevant hyperfine energy levels of ^{133}Cs atoms are shown in Fig. 1. The frequency interval between the two hyperfine sublevels F=3 and F=4 of the $6S_{1/2}$ ground state is 9192.632 MHz. The natural linewidth of the $6P_{3/2}$ intermediate excited state is 5.2 MHz, with hyperfine sublevels F’=2,3,4,5 have frequency intervals of 151.225 MHz, 201.287 MHz, and 251.092 MHz, respectively. The upper excited state $6D_{5/2}$ has a natural linewidth of 3.1 MHz, and its hyperfine splittings between the F”=1,2,3,4,5,6 are 9.15 MHz, 14.05 MHz, 18.39 MHz, 23.01 MHz, 27.35 MHz, respectively. In the experiment, an 852 nm laser is used as the pump light to excite Cs atoms from the $6S_{1/2}$ state to the $6P_{3/2}$ state, and a 917 nm laser is used as the probe light, with its frequency scanned over the $6P_{3/2} \rightarrow 6D_{5/2}$ transition.

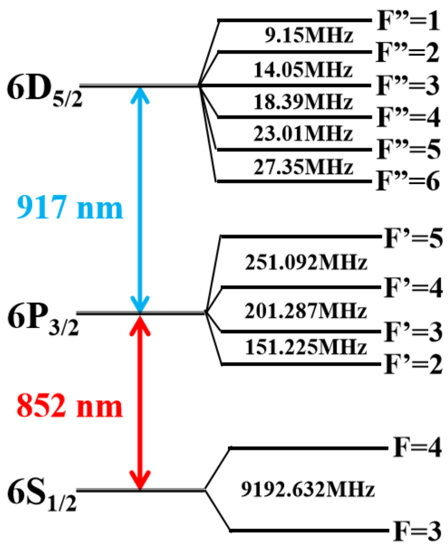

Fig. 1 Relevant hyperfine energy levels of the ^{133}Cs $6S_{1/2} \rightarrow 6P_{3/2} \rightarrow 6D_{5/2}$ ladder-type atomic system

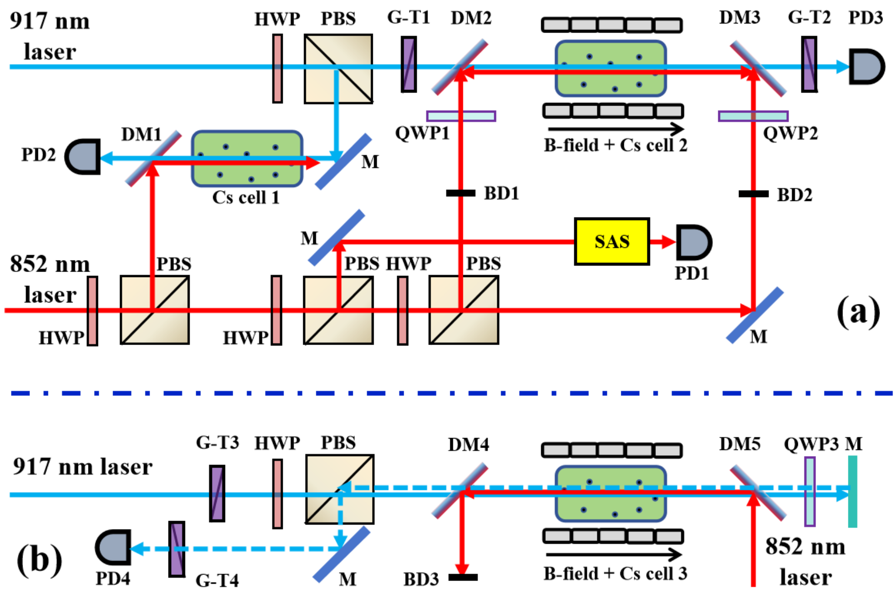

Fig. 2 Schematic of experimental setup for ES-FADOF: (a) the transmitted-type ES-FADOF scheme with both co-propagating and counter-propagating configurations between the pump and signal light beams; (b) experimental design for reflection-type ES-FADOF. (*HWP* half-wave plate, *QWP* quarter-wave plate, *PBS* polarizing beam splitter, *M* mirror, *G-T* Gran-Taylor Prism, *DM* dichroic mirror (transmitting 917 nm laser and reflecting 852 nm laser), *PD* photodetector, *BD* beam dump, *SAS* saturated absorption spectrum, *Cs cell* cesium vapor cell.)

2.1 Transmitted-type ES-FADOF in co-propagating and counter-propagating configurations

The experimental setup of the ES-FADOF for the two configurations with the co-propagating and counter-propagating pump and signal light beams is illustrated in Fig. 2(a). The pump and signal lights are provided by two independent external cavity diode lasers, each with a linewidth of less than 1 MHz. The 852 nm laser is divided into three beams using a combination of a half-wave plate (HWP) and a polarizing beam splitter (PBS). One beam is used for obtaining the saturated absorption spectroscopy (SAS) on photodetector PD1, locking the frequency of the pump light to the $6S_{1/2}F=4 \rightarrow 6P_{3/2}F'=5$ resonance transition, thereby efficiently populating atoms to the $6P_{3/2}$ intermediate state. Another beam at 852 nm is overlapped with the 917 nm laser beam in Cs cell 1 via a dichroic mirror (DM1) to obtain optical-optical double-resonance (OODR) spectroscopy between the $6P_{3/2} \rightarrow 6D_{5/2}$ hyperfine transition by PD2, which serves as a frequency reference. The third beam at 852 nm is used as the pump light in the ES-FADOF experiment, it is further split into two beams: One of the two beams can be selectively blocked by beam dumps BD1 or BD2, enabling the achievement of co-propagating or counter-propagating pumping configuration with the signal light beam in Cs cell 2. To further improve the population efficiency of the $6P_{3/2}$ intermediate state, the 852 nm pump light is circularly polarized. The 917 nm laser with linear polarization serves as signal light in ES-FADOF experiment, and its frequency is tuned to the desired $6P_{3/2} \rightarrow 6D_{5/2}$ transition using OODR signal. The ES-FADOF system consists of a pair of Glan-Taylor prisms (G-T1and G-T2) with an extinction ratio of 10^5:1 and orthogonal polarization directions, a temperature-controlled vapor cell (Cs Cell 2, ~50 mm in length, and ~25 mm in diameter), and an applied axial magnetic field (B-field). The pump and signal light beams have diameters of 2.0 mm and 1.6 mm, respectively. They are overlapped in the Cs cell 2 for the co-propagating (counter-propagating) configuration by DM2 (DM3), and the corresponding ES-FADOF signals are detected by PD3. The transmission of the ES-FADOF is defined as the ratio of the transmitted 917 nm signal light intensity when the polarization directions of G-T1 and G-T2 are orthogonal (with 852 nm pump light and B-field applied) to that when the two polarizers are parallel and both the pump light and B-field are absent [13].

2.2 Reflection-type ES-FADOF

Based on the Faraday magnetic rotation effect, the rotation direction of the polarization plane of linearly polarized signal light is solely determined by the direction of the axial magnetic field and is independent of the signal light's propagation direction within the atomic medium, so a reflection-type ES-FADOF is constructed, as shown in Fig. 2(b). A beam of 852 nm pump light passes into Cs cell 3 through the dichroic mirror DM5, where Cs atoms are excited from the $6S_{1/2}$ ground state to the $6P_{3/2}$ intermediate excited state. A beam of 917 nm linearly polarized signal light is directed through the G-T3, HWP, PBS and DM4 before entering into Cs cell 3 for the first time. The signal light is then reflected by a zero-degree mirror M, allowing it to pass through Cs cell 3 again before finally transmitting through G-T4 and reaching the detector PD4 for obtaining the reflection-type ES-FADOF signal. It can be observed that the 917 nm signal light travels back and forth within the atomic vapor doubling the effective length of the atomic cell 3, thereby enhancing the transmission of ES-FADOF. In the experiment, the polarization directions of G-T3 and G-T4 are consistently perpendicular to each other. With the 852 nm pump light blocked and in the absence of B-field, QWP3 is rotated to maximize the transmission of the 917 nm signal light into PD4, thereby determining the incident signal light intensity of the ES-FADOF. After QWP3 is removed, the intensity of ES-FADOF signal light is measured. The ratio between the latter and former intensities is defined as the transmission of reflection-type ES-FADOF [13].

The transmission and *ENBW* are two crucial parameters for evaluating the performance of optical filters. The *ENBW* of ES-FADOF signal can be theoretically calculated using formula (1) [9]. A smaller *ENBW* value indicates a stronger ability to suppress background noise light.

$$ENBW = \frac{\int_0^\infty S(\nu)d\nu}{S(\nu_m)} \tag{1}$$

In formula (1), $S(v)$ represents the transmission of the ES-FADOF signal, v denotes the frequency of the signal light, and $S(v_m)$ signifies the peak transmission.

3. Experimental results and discussion

3.1 Comparison of ES-FADOF spectra under co-propagating and counter-propagating configurations of pump and signal light beams

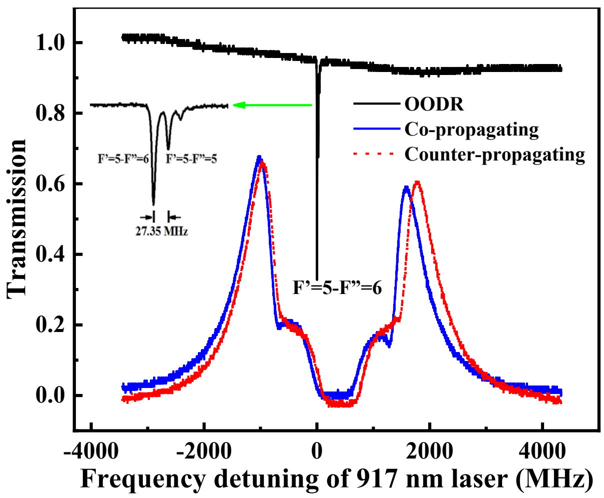

Fig. 3 Typical spectra signals of ES-FADOF under both co-propagating and counter-propagating configurations

Based on the ^{133}Cs $6S_{1/2} \rightarrow 6P_{3/2} \rightarrow 6D_{5/2}$ ladder-type atomic system, the 852 nm pump laser power is ~30 mW, with its frequency tuned to the $6S_{1/2}F=4 \rightarrow 6P_{3/2}F'=5$ hyperfine transition, exciting Cs atoms to the $6P_{3/2}$ intermediate excited state. The frequency of 917 nm signal light with a power of ~50 μW is scanned across the $6P_{3/2} \rightarrow 6D_{5/2}$ transition. Typical experimental results as shown in Fig. 3 are obtained for the ES-FADOF in both co-propagating and counter-propagating configurations at a Cs cell 2 temperature of ~120°C and an axial magnetic field intensity of ~300 G. The upper curve in Fig. 3 represents the OODR spectral signals, where the hyperfine splitting interval of 27.35 MHz between the F”=6 ↔ F”=5 of the $6D_{5/2}$ excited state serves as the frequency scale. The two lower curves in Fig. 3 correspond to the ES-FADOF signals in co-propagating and counter-propagating configurations, showing no essential difference in performance with all other experimental conditions being the same.

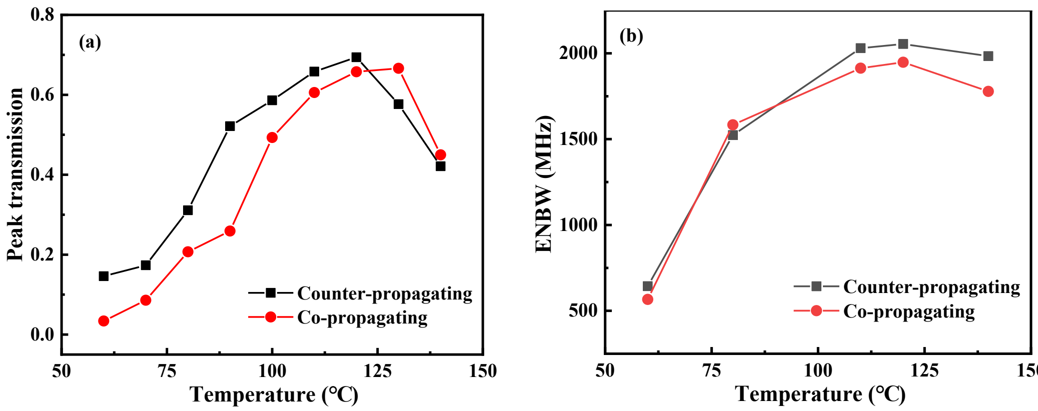

Fig. 4 Changes of peak transmission (a) and *ENBW* (b) of the 917 nm ES-FADOF signal versus the temperature of ^{133}Cs vapor cell under both co-propagating and counter-propagating configurations

When the temperature of Cs vapor cell 2 varies between 40 - 150°C, other experimental parameters remain consistent with those in Fig. 3. The changes of transmission and *ENBW* of the 917 nm ES-FADOF for the two experimental configurations are illustrated in Fig. 4: the increase of temperature results in an increase of atomic number density, facilitating the population transfer of more cesium atoms from the $6S_{1/2}$ ground state to the $6P_{3/2}$ intermediate excited state, so that the transmission of the ES-FADOF gradually increases, reaching a maximum of 67% at 120°C. However, when the temperature further rises within the range of 130 - 150 °C, the absorption of the atomic vapor to the 917 nm signal light significantly intensifies, and so the transmission begins to decrease. The *ENBW* of the 917 nm ES-FADOF, calculated using formula (1), exhibits an upward trend with rising temperature of Cs vapor cell 2, and eventually saturates at ~2000 MHz, indicating its performance as a narrow linewidth optical filter.

At the optimized atomic cell temperature of 120°C, and with all other experimental parameters consistent with those in Fig. 3, the changes of peak transmission and *ENBW* of the 917 nm ES-FADOF are shown in Fig. 5. when the axial magnetic field intensity varies within the range of 20 - 860 G. The peak transmission of ES-FADOF exhibits a rapid and nearly linear increase in the range of 0 - 100 G, gradually transitioning to a saturated state between the 100 - 300 G. When the magnetic field intensity ranges from 300 G to 900 G, there is a substantial increase in splitting distance between Zeeman sub-levels, resulting in multi-peak splitting of optical filter signals, and consequently causing a gradual decline in ES-FADOF transmission. It also should be noted that the *ENBW* of ES-FADOF continues to widen with an increasing magnetic field intensity due to Zeeman effect. Therefore, it can be concluded that an optimal magnetic field strength for the 917 nm ES-FADOF lies ~300 G.

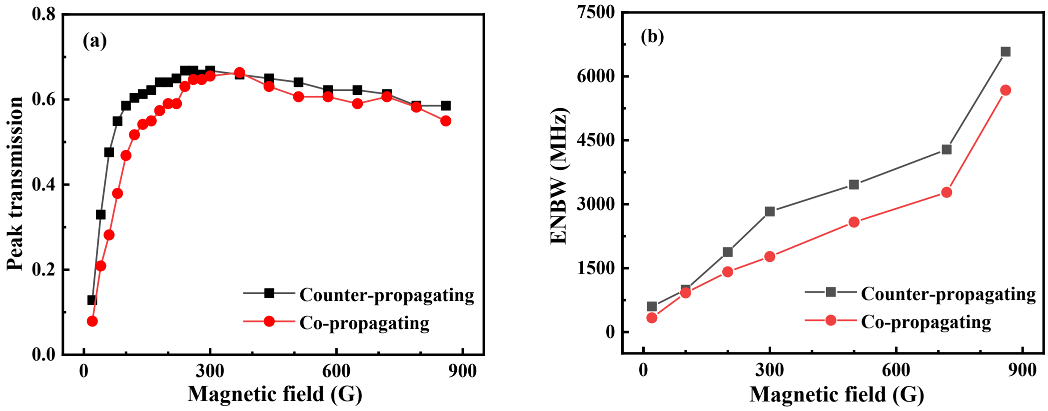

Fig. 5 Changes of peak transmission (a) and *ENBW* (b) of the 917 nm ES-FADOF signal versus the intensity of axial magnetic field under both co-propagating and counter-propagating configurations

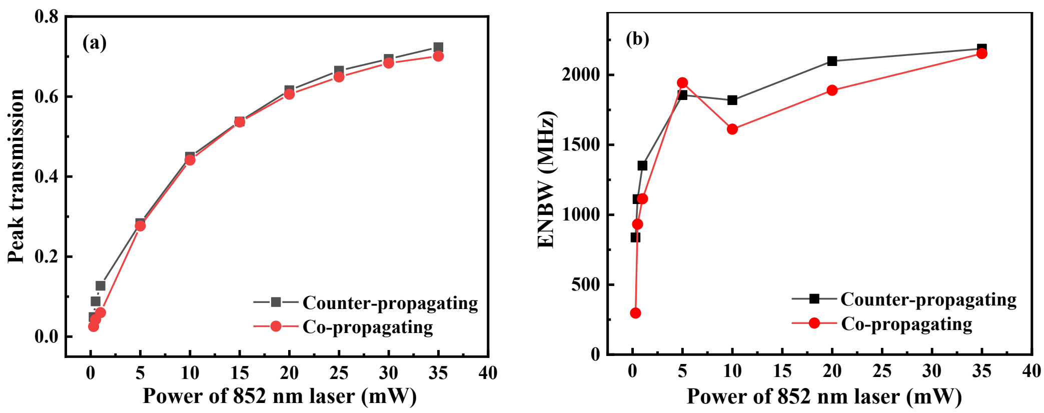

Fig. 6 Changes of peak transmission (a) and *ENBW* (b) of the 917 nm ES-FADOF signal versus the power of 852 nm pump laser under both co-propagating and counter-propagating configurations

Under the optimized temperature of 120°C and an axial magnetic field intensity of 300 G, with other experimental parameters consistent with those shown in Fig. 3, the dependence of ES-FADOF spectral transmission and *ENBW* on 852 nm pump optical power is illustrated in Fig. 6 for both co-propagating and counter-propagating experimental configurations. As the 852 nm pump light power varies from 0 to 35 mW, a stronger pump light will effectively excite more atoms from the $6S_{1/2}$ state to the $6P_{3/2}$ state, resulting in a gradual increase in the peak transmission of ES-FADOF under the two configurations. However, *ENBW* experiences a rapid increase at the pump optical powers below ~5 mW, followed by a slower rise within the range of 5 mW to 35 mW.

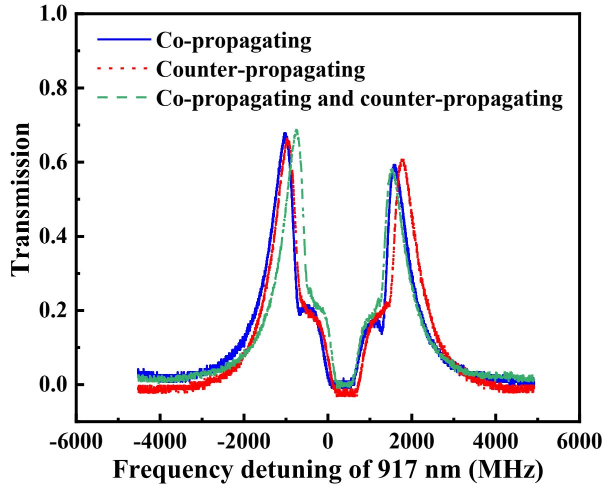

Fig. 7 Spectral signals of ES-FADOF for the three experimental arrangements

It can be clearly seen from Figs. 4 to 6 that the performance of the ES-FADOF in the co-propagating and counter-propagating configurations is almost the same. A direct experimental evidence is as follows: when two beams of 852 nm pump light, each with a power of 15 mW, are simultaneously incident from both ends of the Cs cell 2, or when a beam of 852 nm pump light with a power of 30 mW is incident from either end of the Cs cell 2, the profiles of the ES-FADOF signals under all three experimental arrangements are nearly identical, as shown in Fig. 7.

3.2 Experimental realization of a reflection-type ES-FADOF

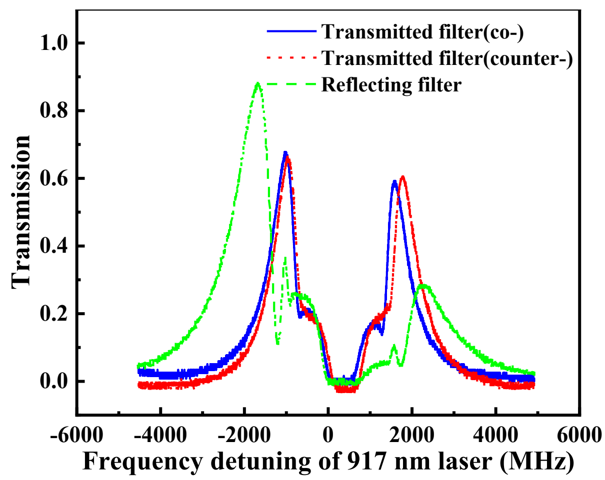

Fig. 8 Reflection-type ES-FADOF and traditional transmitted ES-FADOF with co-propagating and counter-propagating experimental configurations

The rotation direction of polarization plane of linearly polarized signal light is only related to the direction of the axial magnetic field in the experiment of FADOF, so when the signal light propagates back and forth through the atomic cell, the equivalent length of the atomic cell is doubled, which can improve the transmission of the FADOF to a certain extent. This improvement has been confirmed in our previous experiment involving FADOF operating on the transition between a ground state and an excited state [23]. For the ES-FADOF, usually based on a three-level ladder-type atomic system, a pump light populates atoms from the ground state to an intermediate excited state, and then the signal light scans the transition from the intermediate state to a higher excited state to generate ES-FADOF signals. The process involves the interaction between two optical fields and three-level atoms, and pump and signal light beams within the atomic vapor are typically arranged in either co-propagating or counter-propagating configurations, and their significant differences have been observed in other experiments, such as those involving excited-state spectra and LIDOF signals [24]. Fortunately, the experimental results in section 3.1 have shown that the transmission, *ENBW* and spectral profile of the 917 nm ES-FADOF exhibit negligible differences between the co-propagating and counter-propagating configurations under identical experimental conditions. Based on this observation, we built a reflection-type ES-FADOF (see Fig. 2). The relevant experimental parameters are the same as those in Fig. 3, and the typical results are illustrated in Fig. 8. In the reflection-type configuration, the effective length of the Cs cell 3 is increased, resulting that the 852 nm pump light power is fully utilized, and more atoms are excited from the $6S_{1/2}$ ground state to the $6P_{3/2}$ intermediate excited state, so the peak transmission of the reflection-type ES-FADOF is obviously higher than that of the popular transmitted ES-FADOF. Detailed comparisons between the reflection-type and transmitted ES-FADOFs at the different temperature (Fig. 9(a)), axial magnetic field intensity (Fig. 9(b)) and pump power (Fig. 9(c)) are provided. Experimental parameters are as follows: the power of the 852 nm pump and 917 nm signal light is 30 mW and 50 μW, respectively; an optimized temperature of Cs cell 3 is 120°C, and an axial magnetic field strength is 300 G. The peak transmission of the reflection-type ES-FADOF can reach ~88%, whereas that of the transmitted ES-FADOF achieves ~65%. According to formula (1), *ENBW* of reflection-type and transmitted ES-FADOF are calculated, with no obvious difference observed.

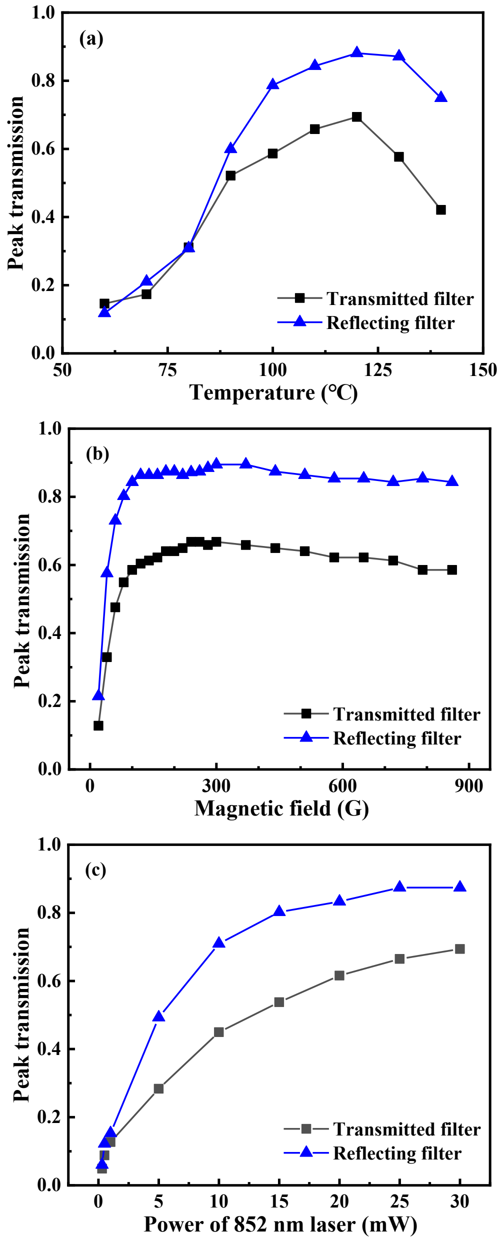

Fig. 9 Peak transmission of reflected ES-FADOF and transmitted ES-FADOF varies with temperature of atomic vapor cell (a), axial magnetic field (b), and 852 nm pump light power

4. Conclusions

Based on the ^{133}Cs $6S_{1/2} \rightarrow 6P_{3/2} \rightarrow 6D_{5/2}$ ladder-type atomic system, with an 852 nm laser as the pump light and a 917 nm laser as the signal light, we experimentally confirm that the ES-FADOF exhibits comparable performance in both co-propagating and counter-propagating experimental configurations. On the basis of the above fact and the unique characteristics of Faraday effect, we demonstrate a reflection-type ES-FADOF. The effects of various factors such as the beam configuration, temperature of atomic vapor cell, axial magnetic field intensity, and pump light power on ES-FADOF performance are measured and compared. Under optimized experimental parameters, the reflection-type ES-FADOF achieves a peak transmission of up to 88% with an *ENBW* of 1.8 GHz, which is higher than the peak transmission of transmitted ES-FADOF. This technique provides a robust method for improving the peak transmission of FADOF. The high-transmission and narrow-band FADOF holds significant value for the detection of weak optical signals in quantum optics experiments and other practical applications.

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Author Contributions

Baodong Yang wrote the manuscript. Keru Zang, Hanshuai Zhao measured and dealt with the experimental data. Junmin Wang, Jun He and Haitao Zhou supervised the study and corrected the manuscript. All authors reviewed the manuscript.

Declarations

Conflict of interest The authors declare no competing interests.

References

[1] T. Haider, A review of magneto-optic effects and its application. Int. J. Electromagn. Appl. **7**(1), 17-24 (2017)

[2] J.X. Tang, Q.J. Wang, Y.M. Li, L. Zhang, J.H. Gan, M.H. Duan, J.K. Kong, L.M. Zheng, Experimental study of a model digital space optical communication system with new quantum devices. Appl. Opt. **34**(15), 2619-2622 (1995)

[3] A. Popescu, T. Walther, On an ESFADOF edge-filter for a range resolved Brillouin-lidar: The high vapor density and high pump intensity regime. Appl. Phys. B **98**(4), 667-675 (2010)

[4] P.Y. Chang, Y.L. Chen, H.S. Shang, X.L. Guan, H. Guo, J.B. Chen, B. Luo, A Faraday laser operating on Cs 852 nm transition, Appl. Phys. B **125**(12), 230 (2019)

[5] Z.J. Liu, X.L. Guan, X.M. Qin, Z.Y. Wang, H.B. Shi, J. Zhang, J.X. Miao, T.T. Shi, A.H. Dang, J.B. Chen, An atomic filter laser with a compact Voigt anomalous dispersion optical filter. Appl. Phys. Lett. **123**, 131103 (2023)

[6] Z.M. Tao, Y.L. Hong, B. Luo, J.B. Chen, H. Guo, Diode laser operating on an atomic transition limited by an isotope ^{87}Rb Faraday filter at 780 nm. Opt. Lett. **40**(18), 4348-4351 (2015)

[7] X.B. Xue, Z.M. Tao, Q.Q. Sun, Y.L. Hong, W. Zhuang, B. Luo, J.B. Chen, H. Guo, Faraday anomalous dispersion optical filter with a single transmission peak using a buffer-gas-filled rubidium cell. Opt. Lett. **37**(12), 2274-2276 (2012)

[8] A. Rudolf, T. Walther, High-transmission excited-state Faraday anomalous dispersion optical filter edge filter based on a Halbach cylinder magnetic-field configuration. Opt. Lett. **37**(21), 4477-4479 (2012)

[9] B. Luo, L.F. Yin, J.Y. Xiong, J.B. Chen, H. Guo, Induced-dichroism-excited atomic line filter at 1529 nm. IEEE Photon. Technol. Lett. **30**(17), 1551-1554 (2018)

[10] Y.F. Wang, S.N. Zhang, D.Y. Wang, Z.M. Tao, Y.L. Hong, J.B. Chen, Nonlinear optical filter with ultranarrow bandwidth approaching the natural linewidth. Opt. Lett. **37**(19), 4059-4061 (2012)

[11] Z. Tan, X.P. Sun, J. Luo, Y. Cheng, X.C. Zhao, X. Zhou, J. Wang, M.S. Zhan, Ultranarrow bandwidth tunable atomic filter via quantum interference-induced polarization rotation in Rb vapor. Chin. Opt. Lett. **12**(12), 121404 (2014)

[12] W. Zhuang, Y. Zhao, S.K. Wang, Z.J. Fang, F. Fang, T.C. Li, Ultranarrow bandwidth Faraday atomic filter approaching natural linewidth based on cold atoms. Chin. Opt. Lett. **19**(3), 030201 (2021)

[13] Y.F. Wang, X.G. Zhang, D.Y. Wang, Z.M. Tao, W. Zhuang, J.B. Chen, Cs Faraday optical filter with a single transmission peak resonant with the atomic transition at 455 nm. Opt. Express **20**(23), 25817-25825 (2012)

[14] X.B. Xue, D. Pan, X.G. Zhang, B. Luo, J.B. Chen, H. Guo, Faraday anomalous dispersion optical filter at ^{133}Cs weak 459 nm transition. Photon. Res. **3**(5), 275-278 (2015)

[15] L. Li, G. Bi, Isotope ^{87}Rb Faraday anomalous dispersion optical filter at 420 nm. Opt. Lett. **39**(11), 3324-3327 (2014)

[16] B. Luo, L.F. Yin, J.Y. Xiong, J.B. Chen, H. Guo, Signal intensity influences on the atomic Faraday filter. Opt. Lett. **43**(11), 2458-2461 (2018)

[17] Z.M. Tao, M.Z. Chen, Z.F. Zhou, B.L. Ye, J.H. Zeng, H.P. Zheng, Isotope ^{87}Rb Faraday filter with a single transmission peak resonant with atomic transition at 780 nm. Opt. Express **27**(9), 13142-13149 (2019)

[18] Y. Yan, J.P. Yuan, L.R. Wang, L.T. Xiao, S.T. Jia, A dual-wavelength bandpass Faraday anomalous dispersion optical filter operating on the D1 and D2 lines of rubidium. Opt. Commun. **509**, 127855 (2022)

[19] R.I. Billmers, S.K. Gayen, M.F. Squicciarini, V.M. Contarino, W.J. Scharpf, D.M. Allocca, Experimental demonstration of an excited-state Faraday filter operating at 532 nm. Opt. Lett. **20**(1), 106-108 (1995)

[20] Q.Q. Sun, Y.L. Hong, W. Zhuang, Z.W. Liu, J.B. Chen, Demonstration of an excited-state Faraday anomalous dispersion optical filter at 1529 nm by use of an electrodeless discharge rubidium vapor lamp. Appl. Phys. Lett. **101**(21), 211102 (2012)

[21] J.Y. Xiong, L.F. Yin, B. Luo, H. Guo, Analysis of excited-state Faraday anomalous dispersion optical filter at 1529 nm. Opt. Express **24**(13), 14925-14933 (2016)

[22] L.F. Yin, B. Luo, Z.J. Chen, L. Zhong, H. Guo, Excited state Faraday anomalous dispersion optical filters based on indirect laser pumping. Opt. Lett. **39**(4), 842-844 (2014)

[23] Y. Liu, B.D. Yang, J.M. Wang, W.Y. Huang, Z.Y. Gou, H.T. Zhou, Demonstration of Faraday

anomalous dispersion optical filter with reflection configuration. Chin. Phys. B **31**(1), 017804 (2022)

[24] H.S. Zhao, B.D. Yang, Z. Xue, L.L. Zheng, Experimental study on ultra-narrow bandwidth optical filters with excited states of cesium atoms. Chin. J. Lasers **51**(5), 0508001 (2024)