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Cs 728 nm excited state Faraday anomalous dispersion optical filter with indirect pump

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ABSTRACT

We demonstrate a Cs excited state Faraday anomalous dispersion optical filter (ESFADOF) operating at 728 nm using a novel pump method, by which the pump beam and the probe beam in the ESFADOF realized here have no a common energy level. Using this method, the ESFADOF achieves a transmission of 2.39% with a bandwidth of 22.52 MHz, which can be applied to both laser frequency stabilization and future four-level active optical clocks. Under the 455 nm laser pump, in addition to $5^2D_{5/2}$, other states such as $7^2S_{1/2}$, $7^2P_{3/2}$, $6^2P_{3/2}$, $6^2P_{1/2}$ and $5^2D_{3/2}$ have also been populated effectively. Meanwhile, multiple wavelength filters exploiting atomic transitions to these states can be realized.

1. Introduction

In 1956 [1], Ohman found that the Faraday anomalous dispersion optical filter (FADOF) based on the principle of selective magnetic rotation had important applications in astrophysical research. Soon after that, it was used to lock the frequency of a continuous-wave laser to atomic resonance lines [2,3]. In 1982, the transmission characteristics of FADOF were analyzed based on the quantum theory of optical dispersion [4]. In 1991, a model for a FADOF was presented to predict its performance under arbitrary operating temperature conditions and magnetic fields [5]. In 1992, a FADOF operating on 455 nm based on Cs atoms shows that it can provide high transmission, ultranarrow bandwidth, and low equivalent noise bandwidth (ENBW) [6]. Since then, FADOFs composed of different kinds of elements such as sodium [7,8], potassium [9–12], rubidium [13–24], cesium [25,26], calcium [27], magnesium [28], and strontium [29] have been studied theoretically and experimentally. Due to the excellent properties, such as narrow bandwidth [21,30], high transmission [1–6], and high noise rejection [7–10], FADOFs have been applied to many fields such as free space optical communication [31], lidar remote sensing systems [32,33], and hybrid continuous variable/discrete-variable quantum optics [34]. FADOFs have also been used in laser frequency stabilization to make the laser frequency immune to the fluctuation of injection current and temperature [35–37]. A Cs FADOF operating at 894 nm achieves a peak transmission of 77%, with an equivalent noise bandwidth less than 1 GHz [38], which can be used for quantum hybrid systems [39]. Effect of line broadening on the performance of FADOFs shows that wing-type filters in particular are deleteriously affected by homogeneous broadening, while line-centre filters are less affected [40].

FADOFs have many excellent advantages, but their working frequency is limited by ground state transition. Therefore, excited state FADOFs (ESFADOFs) were proposed to extend operating wavelengths. Typically, an ESFADOF requires a pump laser that pumps atoms from the ground state to a lower excited state [14]. The ESFADOFs can also be realized using an electrodeless discharge lamp instead of a pump laser [15,16]. ESFADOFs provide the flexibility to choose alternative wavelengths for different applications [14–16,41,42]. In the Reference [23], authors realize excited state Faraday anomalous dispersion optical filters based on indirect laser pumping. Compared with the commonly used direct pump method, this indirect pump method can reach the same performance using lasers at very different wavelengths. Yet, an ESFADOF at 728 nm has not been reported. Here, we demonstrate an ESFADOF at 728 nm and investigate the transmission as a function of the magnetic field, temperature, and pump power. The ESFADOF at 728 nm achieves a peak transmission of 2.39% with a bandwidth of 22.52 MHz. The ESFADOF at 728 nm can be used for laser frequency stabilization [35,36], as well as active optical clocks at

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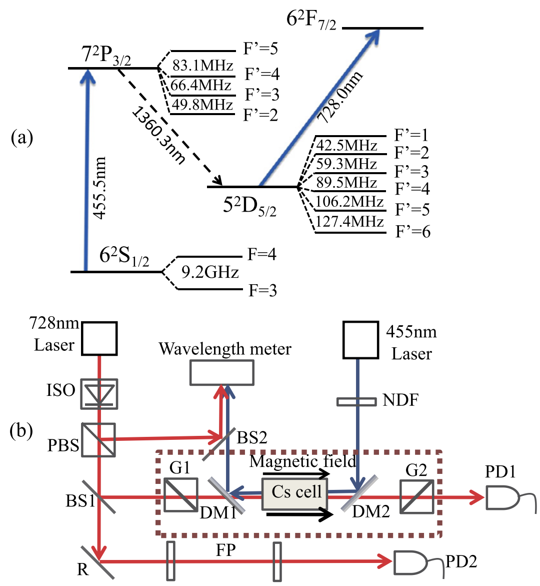

Fig. 1. (a) Relevant Cs energy levels. The 455 nm laser is used as a pump laser and the 728 nm laser is used as a probe laser. (b) Schematics of ESFADOF experimental system. ISO, isolator; PBS, polarization beam splitter; G, Glan–Taylor prism; BS, beam splitter; R, high reflection mirror; NDF, neutral density filter; DM, dichroic mirror (high reflection for 455 nm, high transmission for 728 nm); F-P, Fabry–Perot cavity; PD, photodetector.

728 nm [43,44], including four level active optical clock configuration [45–47], and future Faraday active optical clock [48].

2. Experimental section

The relevant energy level of Cs is shown in Fig. 1(a). A 455 nm laser pumps atoms from the ground state $6^2S_{1/2}$ to the excited state $7^2P_{3/2}$. Then, atoms transit from the higher excited state $7^2P_{3/2}$ to the lower excited states $5^2D_{5/2}$, $7^2S_{1/2}$, and $5^2D_{3/2}$ by spontaneous emission. Therefore, any wavelength filter related to these states can also be realized. In this Letter, a 728 nm probe laser interacts with the atoms through the transition between the $5^2D_{5/2}$ and the $6^2F_{7/2}$.

The experimental setup is shown in Fig. 1(b). G1 and G2 are a pair of crossed Glan–Taylor prisms with an extinction ratio of 1×10^{-5}. The Fabry–Perot cavity is used to calibrate the frequency detuning of the probe laser at 728 nm. The temperature of a 5 cm long Cs cell is controlled by a heating wire with a precision of 0.2 °C. The magnetic field is produced by a pair of ring-shaped permanent magnets along the Cs cell axis. In the experiment, the inhomogeneity of the magnetic field is less than 10%, therefore, it can be ignored. The laser beam at 728 nm is divided into two parts by a PBS. One of the beams is measured by the wavelength meter and the other is divided into two parts by BS1. One beam which passes through the Fabry–Perot cavity is measured by PD2. The other beam which overlaps with the laser beam at 455 nm in Cs cell is measured by PD1. Type of two lasers is single-mode Littrow ECDL grating laser. The 455 nm pump laser power is 11.2 mW and the 728 nm probe laser power is 5.0 mW. The linewidth of two lasers is less than 1 MHz. The laser beam waist diameters at 455 nm and 728 nm are 2.9 mm and 1.8 mm, respectively. The ESFADOF consists of G1, G2, Cs cell, and the magnetic field, which are shown in the dotted box. In the experiment, the system loss is not taken into account when the transmission of ESFADOF is calculated.

3. Results and discussion

In our experiment, various parameters are tuned to obtain higher transmission of the ESFADOF. It can be found that when

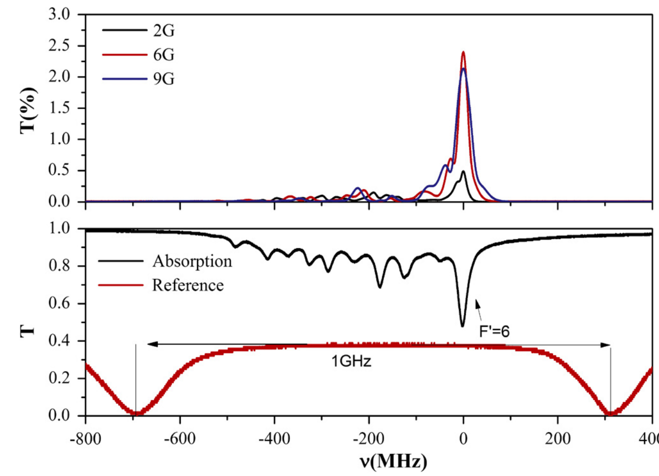

Fig. 2. (Color online.) Lines in the upper frame are transmission spectra of Cs ES-FADOF at 130 °C working at 728 nm, which is working at 130 °C with different magnetic fields. The black line in the bottom frame is the absorption spectrum of Cs atom at 728 nm and the red line is the reference spectrum of Fabry–Perot cavity. T in the vertical axes denotes transmission.

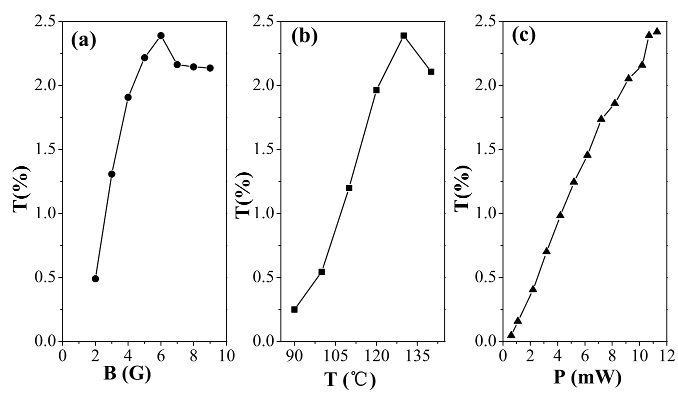

Fig. 3. (a) Transmission T as a function of magnetic field of Cs cell at 130 °C and 10.7 mW. (b) Transmission T as a function of temperature of Cs cell at 6 G and 10.7 mW. (c) Transmission T as a function of 455 nm pump laser power at 6 G and 130 °C.

the pump laser power is 10.7 mW, the temperature of Cs cell is 130 °C, and the magnetic field is 6 G, the transmitted spectra of Cs ESFADOF at 728 nm exhibit multi-peaks as shown in Fig. 2. The maximum peak transmission is 2.39% and the bandwidth is 22.52 MHz, indicating that there are sufficient populations on the lower excited state $5^2D_{5/2}$.

We have also investigated the dependence of the peak transmission on the magnetic field, cell temperature, and pump laser power. Fig. 3(a) shows the transmission T as a function of magnetic field of Cs cell when the temperature is 130 °C and the pump laser power is 10.7 mW. Initially, the peak transmission increases as the magnetic field is increased. When the magnetic field is 6 G, the transmission achieves a maximum of 2.39%. Then, the transmission starts to decrease with further increase of the magnetic field.

Theoretically, we analyze transmission as a function of magnetic field of Cs cell. For a FADOF, $T(Transmission) = \frac{I_{out}}{I_{in}} = \sin\varphi^2$. When $\varphi \ll 90°$, $T = \frac{I_{out}}{I_{in}} = \sin\varphi^2 \approx \varphi^2$. The rotation angle is given by

$$\varphi = \frac{\pi l}{\lambda}(n_+ - n_-) = \frac{3N\Gamma\lambda^2 l}{8\pi}\frac{m_F g\mu B/_{\hbar}}{(m_F g\mu B/_{\hbar})^2 + (2\Omega)^2 + (\frac{\Gamma}{2})^2}$$

$$= \frac{3N\Gamma\lambda^2 l}{8\pi}\frac{m_F g\mu B/_{\hbar}}{(m_F g\mu B/_{\hbar})^2 + 2I_{in}\Gamma^2/I_S + (\frac{\Gamma}{2})^2}$$

$$\Omega^2 = {I_{in}\Gamma^2}/{2I_S}$$