Diode laser using narrow bandwidth interference filter at 852 nm and its application in Faraday anomalous dispersion optical filter*

Zhaojie Jiang(蒋招杰)[1], Qi Zhou(周琦)[2], Zhiming Tao(陶智明)[1,3], Xiaogang Zhang(张晓刚)[1], Shengnan Zhang(张盛楠)[1], Chuanwen Zhu(祝传文)[1], Pingwei Lin(林平卫)[4], and Jingbiao Chen(陈景标)[1,†]

[1] *State Key Laboratory of Advanced Optical Communication Systems and Networks, School of Electronics Engineering and Computer Science, and Center for Quantum Information Technology, Peking University, Beijing* 100871, *China*

[2] *School of Photoelectric Information, University of Electronic Science and Technology, Chengdu* 611731, *China*

[3] *College of Science, Guizhou University of Engineering Science, Bijie* 551700, *China*

[4] *National Institute of Metrology, Beijing* 100029, *China*

(Received 19 January 2016; revised manuscript received 9 March 2016; published online 25 June 2016)

We demonstrate an 852-nm external cavity diode laser (ECDL) system whose wavelength is mainly determined by an interference filter instead of other wavelength selective elements. The Lorentzian linewidth measured by the heterodyne beating between two identical lasers is 28.3 kHz. Moreover, we test the application of the ECDL in the Faraday atomic filter. Besides saturated absorption spectrum, the transmission spectrum of the Faraday atomic filter at 852 nm is measured by using the ECDL. This interference filter ECDL method can also be extended to other wavelengths and widen the application range of diode laser.

Keywords: filters, diode lasers, Faraday effect

PACS: 32.30.–r, 42.55.Px, 42.79.Ci **DOI:** 10.1088/1674-1056/25/8/083201

1. Introduction

An external cavity diode laser (ECDL) is widely used in various fields such as atomic physics, metrology, and telecommunication due to its compactness and reliability. The ECDL is usually designed to use a diffraction grating for wavelength discriminator.[1,2] The second solution is to use a Fabry–Perot etalon instead of a diffraction grating for wavelength discriminator.[3,4] However, the two designs mentioned above make laser frequency of the ECDL sensitive to the ambient pressure and to optical misalignment caused by mechanical vibration and noise environment.

The third solution is to use a Faraday anomalous dispersion optical filter (FADOF) as the wavelength selective device.[5–7] The laser wavelength is stably limited at the highest transmission peak of FADOF and nearly immune to the fluctuations of injection current and temperature. However, compared with the traditional ECDL, this ECDL needs an extra FADOF, which greatly increases the cost, the size, and the complexity of the system.

Another solution is to use an interference filter as wavelength-selective element to build the ECDL.[8–15] Its performance is similar to those of other designs, but it is cheap and easy to build. This ECDL with the interference filter is insensitive to misalignment induced by mechanical vibration and thermal noise.

In this work, we use the interference filter with a passband width of 0.45 nm and peak transmission of 92.9% as wavelength selective element to build the ECDL at 852 nm. Then, compared with saturated absorption spectrum, the transmission spectrum of FADOF at 852 nm is measured by using the ECDL.

2. Diode laser using narrow bandwidth interference filter at 852 nm

By changing the filter incidence angle relative to the optical axis, the laser wavelength can be coarsely adjusted. Figure 1 shows the transmission of the interference filter as a function of laser wavelength at incidence angle of 6° by changing an ECDL probe laser. It can be seen that the transmission of laser wavelength of 852.358 nm achieves a maximum of 92.9%. The passband width of the interference filter is 0.45 nm according to the Lorentzian fit.

The energy level diagram of Cs and the experimental setup of the external cavity diode laser are shown in Figs. 2 and 3, respectively. L1 and L2 are two identical lenses (C280TME-B, THORLABS) each with a focal length of 18.4 mm and a numeric aperture of 0.15. L1 is the lens forming a "cat eye" and L2 is the lens providing a collimated output beam. The interference filter with a passband width of 0.45 nm and transmission of 92.9%, which is inserted between two lenses, is used as an intra-cavity wavelength discriminator. The out-coupler is glued onto a piezoelectric transducer

*Project supported by the National Natural Science Foundation of China (Grant No. 91436210) and the International Science and Technology Cooperation Program of China (Grant No. 2010DFR10900).

†Corresponding author. E-mail: jbchen@pku.edu.cn

© 2016 Chinese Physical Society and IOP Publishing Ltd

(PZT). The inner surface of the out-coupler is coated with the partially reflective material and its outer surface is coated with an anti-reflective material. The overall length of the external cavity formed by the out-coupler and the back facet of the diode is 73 mm. The position of the out-coupler is adjusted by PZT in order to change the cavity length. The out-coupler injects the feedback laser beam into the diode. After being collimated by collimating lens (LC C330TME-B, THORLABS) with a focal length of 3.1 mm and a numeric aperture of 0.68, light from laser diode (EYP-RWE-0860-06010-1500-SOT02-0000, EAGLEYARD) arrives at the interference filter. Then, the out-coupled light is collimated by a second identical lens (L2). The advantage of this setup is that the wavelength discrimination and the optical feedback are implemented by two independent elements, i.e., the interference filter and the out-coupler.

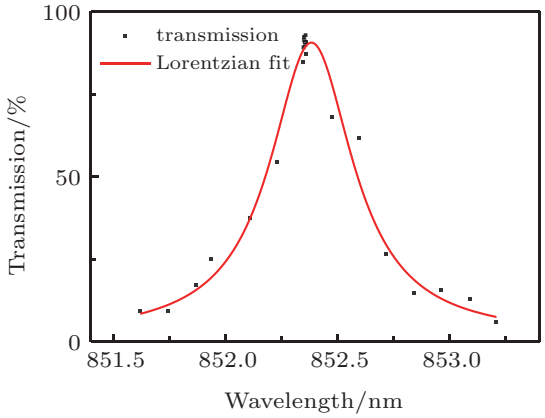


Fig. 1. (color online) Transmission of the interference filter as a function of laser wavelength at an incidence angle of 6°.

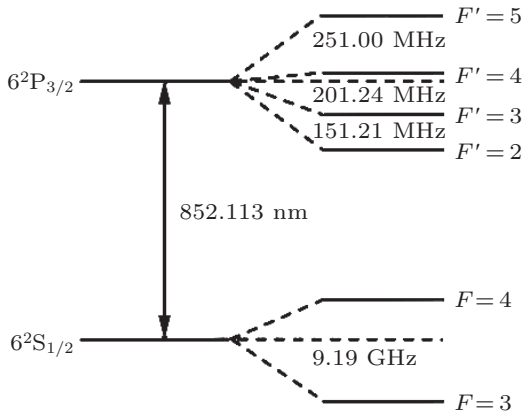


Fig. 2. Energy level diagram of Cs.

Figure 4 shows the laser output wavelength as a function of diode temperature. When the diode temperature is less than 21.95 °C, the value of the output wavelength is almost within 852.3268 nm. Then, the output wavelength increases with the diode temperature increasing and their relationship is almost proportional. This is because the higher the temperature, the longer the cavity length is. The relation between the cavity length and wavelength can be expressed using the formula $L = n(\lambda/2)$, where L is the cavity length, λ is the laser output wavelength, and n is the number of wavelength. When the diode temperature is more than 22.85 °C, the value of the output wavelength almost remains unchanged at 852.3657 nm.

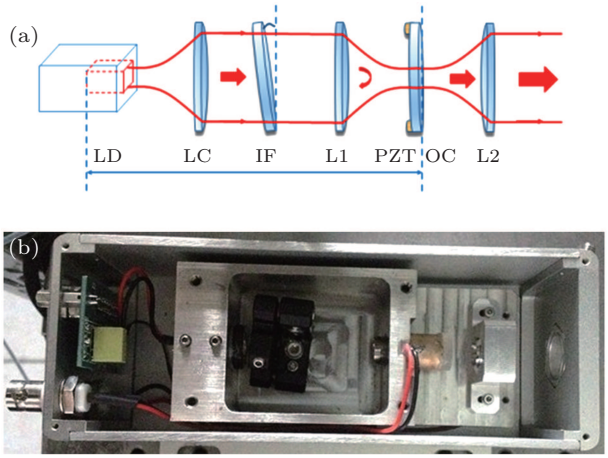


Fig. 3. (color online) (a) Experimental setup of the external cavity diode laser. LD: laser diode; LC: collimating lens; IF: interference filter; L: lens; OC: out-coupler whose transmission is 60%; PZT: piezoelectric transducer. (b) Photograph of the external cavity diode laser.

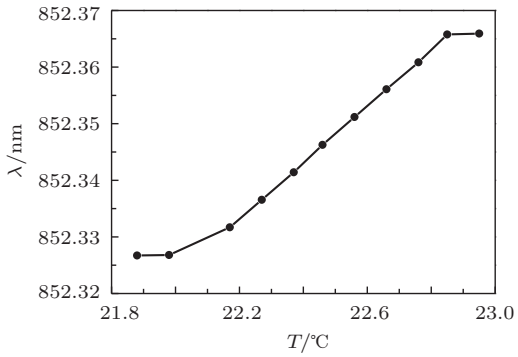


Fig. 4. Laser output wavelength as a function of diode temperature.

Figure 5 shows the laser output wavelength as a function of PZT voltage. The output wavelength decreases with the PZT voltage increasing. When the PZT voltage is between 0 V and 100 V, their relationship is almost inversely proportional. This is because the larger the PZT voltage, the shorter the cavity length is.

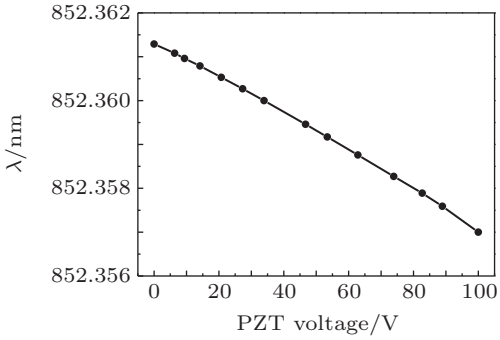


Fig. 5. Laser output wavelength as a function of PZT voltage.

Figure 6 shows that the threshold current is 33 mA and the diode current shifts the laser output power by 0.58 W/mA.

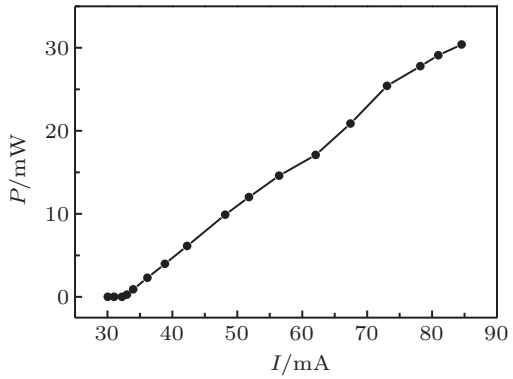


Fig. 6. Laser output power as a function of diode current at 23 °C.

To measure the linewidth of the external cavity diode laser, a heterodyne beating experiment is carried out by using two identical lasers. The result of the heterodyne measurement is shown in Fig. 7. The FWHM of the Lorentzian fit and the Gaussian fit are 40 kHz and 48.9 kHz, respectively. The laser linewidth is $1/\sqrt{2}$ of the FWHM of the beat note. Therefore, the Lorentzian linewidth of each laser is calculated to be 28.3 kHz, and the Gaussian linewidth is 34.6 kHz based on the above fits.

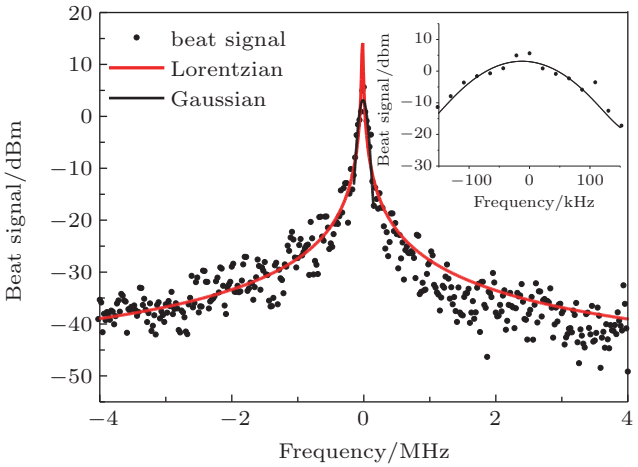


Fig. 7. (color online) Beat signal between two identical external cavity lasers. The sweep time of spectrum analyzer is 10 ms, the resolution bandwidth is 30 kHz, and the video bandwidth is 30 kHz. The FWHM of Lorentzian fit is 40 kHz, and the Gaussian fit is 48.9 kHz. The inset shows the magnified Gaussian fits curve.

3. Application of diode laser in Faraday anomalous dispersion optical filter

Figure 8 shows experimental schematic of FADOF and saturated absorption spectroscopy (SAS). The laser beam from ECDL is split into two parts by BS1. One of them is used for saturated absorption spectrum which is measured by PD2. The other is used for transmission spectrum of FADOF, which is measured by PD1. Two PDs are made in our laboratory. The transmissions of BS1 and BS3 are both 50% and the transmission of BS2 is 20%. G1 and G2 are a pair of crossed polarizers with an extinction ratio of 1×10^{-5} and their transmissions are both 85%. Both Cs cells are 5-cm long and their transmissions are both 82%. The magnetic field is produced by a pair of permanent magnets. The laser wavelength is measured by a wavelength meter (model 621-A-VIS laser wavelength meter from Bristol instruments), which has a resolution of 0.1 pm and an accuracy of $\pm0.2\times$ ppm. In our experiment, the magnetic field is 12 G (1 Gs = 10^{-4} T). The inhomogeneity of the magnetic field is less than 10% and can be ignored. We make use of a magnetic shield to reduce the influence of the external magnetic field.

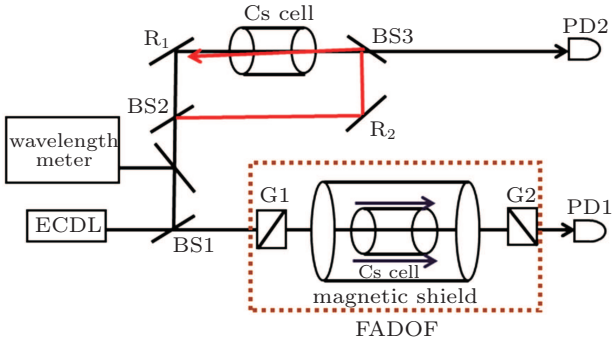


Fig. 8. (color online) Experimental schematics of FADOF and saturated absorption spectroscopy (SAS). ECDL: 852-nm external cavity diode laser using an interference filter; BS: beam splitter; G: Glan–Taylor prism; R: high reflection mirror for 852 nm; PD: photodetector; Wavelength meter, model 621-A-VIS.

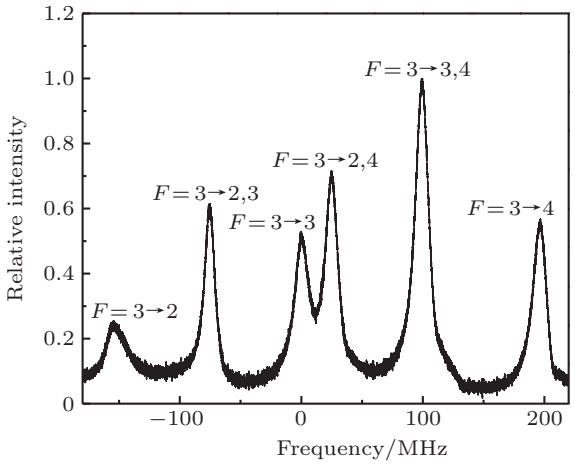


Fig. 9. Saturated absorption spectrum (SAS) at 852 nm corresponding to crossover transition $6^2S_{1/2}$, $F=3\rightarrow6^2P_{3/2}$, $F'=2,3,4$.

The experimental data above indicate that the laser with using the interference filter for wavelength selective element is insensitive to the ambient pressure and to optical misalignment induced by mechanical or thermal deformation.[8] To further check its performance, the laser is used to measure SAS and the transmission spectrum of Cs FADOF. Figures 9 and 10 show the SASs corresponding to crossover transitions $6^2S_{1/2}$, $F=3,4\rightarrow6^2P_{3/2}$, $F'=2,3,4,5$ at 852 nm. These data of SASs indicate that the laser output frequency realized here is stabilized at 852 nm. Figure 11 shows experimental results of FADOF with using the 852 nm ECDL in Fig. 8. The upper

line represents the SAS at 852 nm crossover transition $6^2S_{1/2}$, $F = 4 \rightarrow 6^2P_{3/2}$, $F' = 3,4,5$ which is used for frequency reference. The lower line refers to the transmission spectrum of Cs FADOF. The transmission achieves 52.9% when the temperature of Cs cell is 23 °C and the magnetic field is 12 Gs, indicating that the laser achieved here can be used in Faraday anomalous dispersion optical filter.

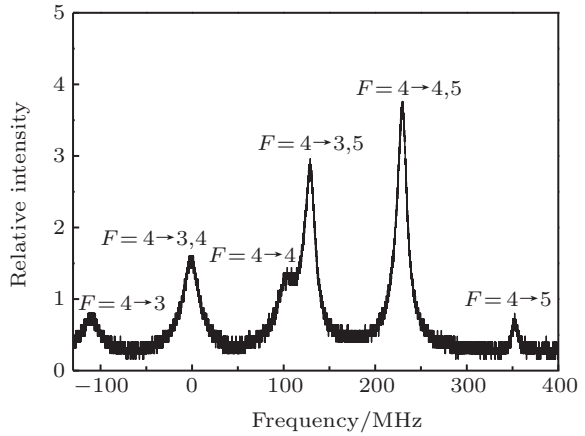


Fig. 10. Saturated absorption spectrum (SAS) at 852 nm corresponding to crossover transition $6^2S_{1/2}$, $F = 4 \rightarrow 6^2P_{3/2}$, $F' = 3,4,5$.

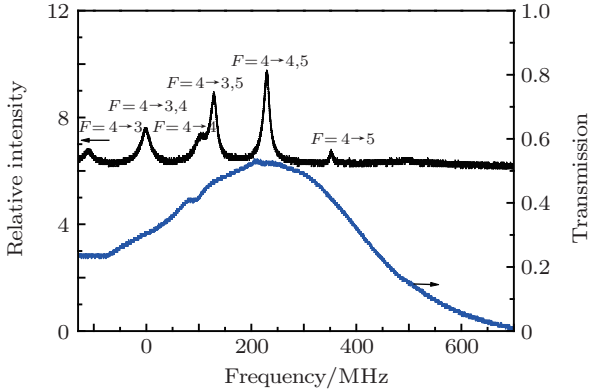


Fig. 11. (color online) Upper line represents the SAS at 852 nm corresponding to crossover transition $6^2S_{1/2}$, $F = 4 \rightarrow 6^2P_{3/2}$, $F' = 3,4,5$. The lower line refers to the transmission spectrum of Cs FADOF. The magnetic field is 12 Gs and the cell temperature is 23 °C.

4. Conclusions

In this work, we use the interference filter as a wavelength-selective element instead of diffraction grating to build an external cavity diode laser at 852 nm. A heterodyne beating experiment is made by using two identical lasers. The Lorentzian linewidth of the laser is 28.3 kHz. In Ref. [15], Ruan *et al*. used the interference filter at 852 nm to build a laser with high frequency which has been used in atomic clock.[16,17] The laser has a linewidth of 72 kHz. In comparison, the laser realized here has a lesser linewidth of 28.3 kHz, which can be used in Faraday anomalous dispersion optical filter, and the experimental results of FADOF are obtained. Our laser can be used not only in an atomic clock, but also as the pump laser in active Faraday optical clock[5,18] and four-level active optical clock.[19–22] At the same time, we demonstrate a Cs FADOF operating at 852 nm by using the laser realized by us. The transmission will increase further if the cell temperature and the magnetic field are optimized. This method can also be extended to other wavelengths and widen the application range of laser.

References

[1] Ricci L, Weidemüller M, Esslinger T, Hemmerich A, Zimmermann C, Vuletic V, König W and Hänsch T W 1995 *Opt. Commun.* **117** 541
[2] Führer T, Stang D and Walther T 2009 *Opt. Express* **17** 4991
[3] Kim H D, Kang S G and Lee C H 2000 *Technol. Lett.* **12** 1067
[4] Allard F, Maksimovic I, Abgral M and Laurent P 2004 *Rev. Sci. Instrum.* **75** 54
[5] Zhang X, Tao Z, Zhu C, Hong Y, Zhuang W and Chen J 2013 *Opt. Express* **212** 8010
[6] Miao X, Yin L, Zhuang W, Luo B, Dang A, Chen J and Guo H 2011 *Rev. Sci. Instrum.* **82** 086106
[7] Tao Z, Hong Y, Luo B, Chen J and Guo H 2015 *Opt. Lett.* **40** 4348
[8] Baillard X, Gauguet A, Bize S, Lemonde P, Laurent P, Clairon A and Rosenbusch P 2006 *Opt. Commun.* **266** 609
[9] Gilowski M, Schubert C, Zaiser M, Herr W, Wubbena T, Wendrich T, Muller T, Rasel E M and Ertmer W 2007 *Opt. Commun.* **280** 443
[10] Wang Z, Lv X and Chen J 2010 *Chin. Opt. Lett.* **8** 496
[11] Bennetts S, Mcdonald G D, Hardman K S, Debs J E, Kuhn C C N, Close J D and Robins N P 2014 *Opt. Express* **22** 10642
[12] Wang N, Feng M, Feng Z, Lam M Y, Gao L, Chen B, Liu A Q, Tsang Y H and Zhang X 2012 *IEEE Photon. Technol. Lett.* **24** 1591
[13] Zorabedian P and Trutna W R 1988 *Opt. Lett.* **13** 826
[14] Thompson D J and Scholten R E 2012 *Rev. Sci. Instrum.* **83** 023107
[15] Ruan J, Liu J, Ma J, Du Z, Wu C and Zhang S 2010 *Chin. Opt. Lett.* **8** 300
[16] Cheng B, Wang Z, Wu B, Xu A, Wang Q, Xu Y and Lin Q 2014 *Chin. Phys. B* **23** 104222
[17] Tian Y, Tan B, Yang J, Zhang Y and Gu S 2015 *Chin. Phys. B* **24** 063302
[18] Zhuang W and Chen J 2014 *Opt. Lett.* **39** 6339
[19] Wang Y, Zhang X, Wang D, Tao Z, Zhuang W and Chen J 2012 *Opt. Express* **202** 5817
[20] Zhang S, Wang Y, Zhang T, Zhuang W and Chen J 2013 *Chin. Phys. Lett.* **30** 040601
[21] Wang Y, Wang D, Zhang T, Hong Y, Zhang S, Tao Z, Xie X and Chen J 2013 *Sci. China-Phys. Mech. Astron.* **56** 1107
[22] Zhang T, Wang Y, Zang X, Zhuang W and Chen J 2013 *Chin. Sci. Bull.* **58** 2033