Optik 125 (2014) 5993–5997

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

The filtering characteristics of potassium Faraday anomalous dispersion optical filter in a strong magnetic field

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ARTICLE INFO

Article history:
Received 29 October 2013
Accepted 1 June 2014

Keywords:
Potassium
Line-centre operation
Optimal transmission
Faraday anomalous dispersion optical filter

ABSTRACT

This paper discusses in detail the effect of magnetic field on the filtering behaviour of potassium D_2 line Faraday anomalous dispersion optical filter (FADOF) when the working temperature and the length of the cell are fixed. The transmission spectra were measured in different magnetic fields and line-centre operation transmission spectrum was obtained under the predicted optimal working condition.

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1. Introduction

As the development of open laser communications, using an ultra-narrow pass-band optical filter to filter the background becomes an important way to improve the signal-to-noise. Since Faraday anomalous dispersion optical filter [FADOF] has the advantages of high transmission, fast response, large field of view, high noise rejecting capability and imageable, it has been considered as the ideal filter and widely applied in various fields [1–16].

A FADOF consists of an atomic vapour cell between two crossed polariers subject to a dc magnetic field. Up to now, a lot of theoretical and experimental researches on the FADOF have been published [1–13,16]. However, most of them discussed the filtering behaviour of the FADOF in relatively weak magnetic field [1–7,10–13], only references [8,9,11,12,16] showed FADOFs operating in strong magnetic field.

Theoretical and experimental studies about FADOF show that FADOF has multiple transmission peaks in relatively weak magnetic field [1–4,7,10,11]. We called it line-wing operation FADOF. When one of the transmission peaks acts as the signal channel, the rest of the transmission peaks inevitably become noisy channels. The usual solution is to use a cascade FADOF to achieve single peak transmission [14,15], i.e. adopting two FADOF tandem structure and employing frequency shift between the transmission peaks of the two FADOF to eliminate the redundant transmission peaks. But increased a FADOF, making the whole filter system structure becomes complicated, and increases the size and cost of the filter. At the same time, the element surfaces of the second FADOF inevitably lead to the loss of the incident light, the filter's overall transmission will decreases.

In a relatively strong magnetic field, FADOF has the same advantages of ultra-narrow bandwidth and high transmission as those in a weak magnetic field. When the operating parameters are selected appropriately, FADOF will show a single peak transmission, we called it line-centre operation FADOF. The central peak of the line-centre operation FADOF has 1–2 GHz ultra-narrow bandwidth and high transmission, and the equivalent noise bandwidth is significantly smaller than the line-wing operation FADOF. Therefore, a line-centre operation FADOF has many advantages as single peak transmission, high transmission and high noise rejection ratio. Furthermore, it overcomes some of the negative factors, such as cumbersome structures and complex theoretical model inherent in the cascade FADOF.

In this paper we investigated potassium Faraday filter [K-FADOF] at D_2 line ($4s_{1/2} \rightarrow 4p_{3/2}$) theoretically and experimentally. The filtering behaviour of the filter has been studied in different magnetic fields. Under the theoretical predicted working conditions, we observed the transmission spectra of the line-centre operation FADOF experimentally. Our theoretical and experimental results are conformed very well.

2. Theoretical consideration

In view of the theoretical model of FADOF have been reported in many articles [1–3,7,12,16], especially in Ref. [16], a complete theory describing the transmission of atomic Faraday filters is

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http://dx.doi.org/10.1016/j.ijleo.2014.06.102
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Table 1
The hyperfine splitting moments of the potassium atoms and distinguish between weak and strong magnetic field.

States of postassium atoms	Hyperfine splitting moments	The intensity of the magnetic field		
		$B < 0.00196\,T$	$0.00196\,T < B < 0.0165\,T$	$B > 0.0165\,T$
$4s_{1/2}$	461.70 MHz	Weak	Weak	Strong
$4p_{3/2}$	18.27 MHz	Weak	Strong	Strong

developed, here it will not be discussed in detail. The expressions of the line strength, polarisability tensor and transmittance of the FADOF in the relative strong magnetic field will be given briefly.

When the interaction energy between the magnetic momentum of the atom and magnetic field is greater than the $\hat{I}\cdot\hat{J}$ coupling energy of the atom, the magnetic field is considered as strong field. In the strong magnetic field, the total angular momentum and its magnetic quantum number F and m_F, respectively, are no longer good quantum numbers. For the purpose of this study, the quantum state may be most simply expressed in eigenstates $\left|J, I, m_J, m_I\right\rangle$.

In which atomic angular momentum and nuclear spin are independently conserved.

The Zeeman line strength for each transition is [7,12,16]:

$$S_q(\gamma M, \gamma' M') = \left|\left\langle IJ\gamma M\left|d_q\right| I'J'\gamma' M'\right\rangle\right|^2$$

$$= \left\{\sum_{Fm_F}\sum_{F'm_{F'}} Y_{\gamma M}^{Jm_J}\left\langle IJm_Im_J\left|d_q\right| I'J'm_I'm_J'\right\rangle Y_{\gamma' M'}^{J'm_J'}\right\}^2 \quad (1)$$

where

$$\left\langle IJm_Im_J\left|d_q\right| I'J'm_I'm_J'\right\rangle = (-1)^{J-m_J}\begin{pmatrix} J & 1 & J' \\ -m_J & q & m' \end{pmatrix}\left\langle J\left\|d\right\| J'\right\rangle \quad (2)$$

$q = \pm 1$ stand for left and right circular polarised components respectively. The atomic polarisibility tensor per unit volume can be written as [7,16]:

$$\chi_q = \frac{iB_{\gamma M}N_0 2\sqrt{\ln 2}\sqrt{\pi}}{\varepsilon_0 h\,\Delta\nu_D}\sum_{\gamma M\gamma' M'} S_q(\gamma M, \gamma' M')\,W[\delta\nu - \delta\nu_{\gamma M\gamma' M'} + i\alpha] \quad (3)$$

where

$$\delta\nu_0 = 2\sqrt{\ln\ 2}\,\frac{\nu - \nu_0}{\Delta\nu_D} \quad (4)$$

$$\delta\nu_{\gamma M\gamma' M'} = 2\sqrt{\ln\ 2}\,\frac{\Delta\nu_{\gamma M\gamma' M'}}{\Delta\nu_D} \quad (5)$$

$$\alpha = 2\sqrt{\ln\ 2}\,\frac{\Gamma}{4\pi\Delta\nu_D} \quad (6)$$

$W(z)$ is Plasma dispersion function, N_0 is the number of the atoms per unit volume, $B_{\gamma M}$ is Boltzmann distribution function.The transmission of the FADOF can be described as [2,3,7]:

$$T_r = \frac{1}{2}\exp(-\bar{\alpha}L)[\cosh(\Delta\alpha L) - \cos(2\rho L)] \quad (7)$$

where L, $\hat{\alpha}$, $\Delta\alpha$ and ρ are the length of vapour cell, mean absorption coefficient, circular dichroism and rotatory power respectively. They can be written as:

$$\bar{\alpha} = \frac{1}{2}(\alpha_+ + \alpha_-) = \frac{\omega}{2c}Im(\chi_+ + \chi_-) \quad (8)$$

$$\Delta\alpha = \frac{1}{2}(\alpha_+ - \alpha_-) = \frac{\omega}{2c}Im(\chi_+ - \chi_-) \quad (9)$$

$$\rho = \frac{\omega}{2c}(n_\pm - n_-) = \frac{\omega}{4c}Re(\chi_+ - \chi_-) \quad (10)$$

For the potassium atoms, the hyperfine splitting moments of the $4s_{1/2}$ and $4p_{3/2}$ states as well as distinguish between weak and strong magnetic field are given in Table 1.

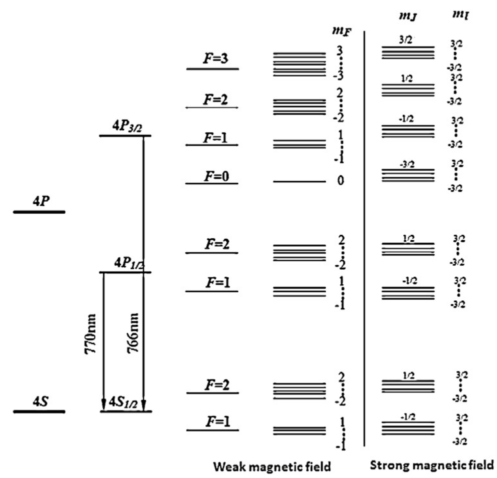

Fig. 1. Hyperfine structure of K 766,770 nm relevant.

In the external magnetic field, the Zeeman effect makes the position of the hyperfine sublevels changed. The hyperfine structure of K 766, 770 nm relevant energy level and the hyperfine Zeeman splitting of $4p_{3/2}$ state of potassium under different magnetic fields were given in Figs. 1 and 2 respectively. As shown in Fig. 2, when the intensity of the external magnetic field is relatively strong, the overlaps between the hyperfine sublevels will appear. Since the hyperfine splitting moment of the $4p_{3/2}$ state is relatively small, the frequency shift of the hyperfine sublevels is about 50 MHz when the intensity of magnetic field is 20×10^{-4} T. The overlaps between the hyperfine sublevels appeared but limited to those have small m_F. With the further enhancement of the magnetic field the overlaps between the hyperfine sublevels increased. The overlaps of the sublevels lead to the reduction of the number of the transitions between the ground state and the excited state alone with the enhancement of the line intensities for each transition. Moreover, as the enhancement of the magnetic field, the distance between the sublevels with positive m_F and negative m_F will increase, the frequency difference between the left and right circular polarised components will increase and away from the centre frequency ν_0. Therefore, as for the FADOF system in the strong magnetic field,

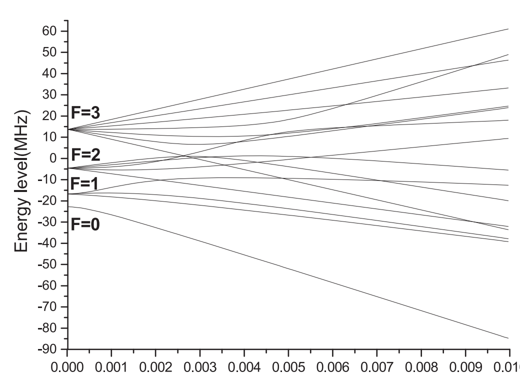

Fig. 2. Hyperfine Zeeman splittings of $4P_{3/2}$ state of Potassium under different magnetic fields.

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