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A tunable atomic line filter without sacrificing transmission based on the combination of selective pump and magnetic field

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ABSTRACT

This paper presents a theoretical model of an atomic line filter based on optical anisotropy which is induced by the combination of the selective pump and an external magnetic field. By analyzing the pumping process, we carefully elucidated the influence of the selective pump and magnetic field on the pumping process, and furthermore on the tunability and peak transmission of the filter. Different from the previously reported filter, our numerical results suggest that this type of filter has a large-scale tunability at the transmission peak position without sacrificing transmission, which is very important in free-space optical communication and lidar systems subjected to large Doppler shift.

1. Introduction

Atomic line filters (ALF), which feature high transmission, narrow bandwidth, and excellent out-of-band rejection [1], are crucial components in laser system [2], free-space optical communication [3], lidar system operation [4–6], space remote sensing [7], narrowband quantum light generation [8–10], laser frequency stabilization [11–13], and quantum key distribution [14]. There have been many previous studies on the Faraday anomalous dispersion optical filter (FADOF) [15–17] and excited state FADOF (ESFADOF) [18–20], which is based on the anomalous dispersion of the Faraday rotation near the resonance lines of certain atomic vapors in a longitudinal magnetic field. These two devices are also commonly utilized in a variety of applications.

The selective pumping is a very useful way to obtain optical anisotropic media and is commonly utilized in magnetometry [21], atomic clocks [22], slow light [23], and laser spectroscopy [24]. A traditional laser induced anisotropy optical filter (LIAOF) consists of an alkali vapor between two crossed Glan-Tomson prisms, plus a circularly polarized pump that populates the atoms on hyperfine levels. If the light is far from the resonance of its working frequency, it does not interact with the alkali vapor and is blocked by the crossed analyzer due to unchanged polarization. For light near the resonance, the first Glan-Tomson prism changes the probe to a linearly polarized probe; the medium then exhibits an anisotropy experienced by the

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linearly polarized probe field according to the selection rules for electric-dipole transition. The optical anisotropy consists of circular dichroism and birefringence, which contains different absorption coefficients and refractive indexes between the right and left circularly polarized probe components. These differences allow this wavelength of light to partially pass through the second Glan-Tomson prism, which is the working principle of the kind filter.

Many atomic line filters based on laser-induced anisotropy have been proposed in recent years [25–28]. Most of the extant research centers around fast response speeds, narrow filter bandwidths, tunable transmission peaks, and rich wavelength selection ranges. The operating wavelength of the filter must be changed often during practical application, and pump detuning is frequently necessary to shift the transmission peak position though this decreases the transmission. This drawback limits the tunability of the filter to only a few gigahertz. This paper proposes a novel theoretical LIAOF model assisted by a longitudinal magnetic field, and the numerical results suggest that this type of filter has a large-scale tunability without sacrificing transmission.

2. The selective pumping process under magnetic field

For the sake of simplicity, we use the same three-level ladder system of ^{87}Rb atoms as Ref. [29]. A σ^+ polarized field (780 nm) drives the $5S_{1/2}(F=2)$ to $5P_{3/2}(F=3)$ transition in the pumping process while a linearly polarized field (775.9 nm) probes $5P_{3/2}(F'=3)$ to $5D_{3/2}(F''=3)$ and $5D_{3/2}(F''=2)$ transition. In the absence of magnetic fields, the hyperfine sub-levels are degenerated and the system can be treated as an ideal four-level ladder system. When a longitudinal static magnetic field acts on the atoms, the energy levels shift and the degeneracy of all the three involved hyperfine levels is broken; this makes the system is more complicated to the point where it can no longer be regarded as a simple three-level system. For convenience, we tab the sublevels $5S_{1/2}(F=2, m_F=+2)$, $5P_{3/2}(F'=3, m_{F'}=+3)$, $5D_{3/2}(F''=3, m_{F''}=+3)$, and $5D_{3/2}(F''=2, m_{F''}=+2)$ as $|1\rangle$, $|2\rangle$, $|3\rangle$ and $|4\rangle$, respectively. In this section, the influence of the magnetic field on the pumping process is carefully evaluated.

It is assumed that the magnetic field is homogeneous within the atomic vapor. B. Yin and T. M. Shay elucidated the effects of a magnetic field on atomic energies in 1991 [30]. The Zeeman energy levels shift under magnetic field can be obtained from the eigenvalues of the Hamiltonian matrix (F, F') for each value of m_F, where F and F' are the total angular momentum of the ground and excited state, respectively, and m_F is the projection of the total angular momentum along the direction of the external magnetic field. As an example, Fig. 2 shows the energy levels relevant to the filter system in the magnetic field. The Zeeman shifts of the four energy levels are all linear and their values are positive throughout the entire range. The sublevel $5P_{3/2}(F'=3, m_{F'}=+3)$ seems more sensitive to the magnetic field than the others, that is because its magnetic dipole constant and electric quadrupole constant are the largest among them [31]. The different responses of these levels to the magnetic field create an interesting phenomenon that is discussed in detail below.

A diagram of the pumping process is shown in Fig. 3. The ground state $5S_{1/2}$ has two hyperfine states denoted by $F=1$, 2, while the excited state $5P_{3/2}(F'=3)$ has four hyperfine states denoted by $F'=0$, 1, 2, 3. The circularly polarized pump with Rabi frequency Ω_c features detuning Δ_c from the transition $5S_{1/2}(F=2)$ to $5P_{3/2}(F=3)$. Each hyperfine level consists of multiple Zeeman magnetic sublevels which degenerate in the absence of magnetic fields. When a magnetic field is applied, the degeneracy of all three hyperfine levels is broken so that the Rb atoms form a complicated system with twenty-four non-degenerate magnetic sublevels. The energy shift for each magnetic sublevel can be obtained by solving the equations written by B. Yin and T. M. Shay [30]; they are defined as Δ_{Bpi} for the sixteen different sublevels of the excited state $5P_{3/2}$ and Δ_{Bgj} for the eight different sublevels of the ground state $5S_{1/2}$, respectively.

There are three possible polarizations and three possible transition levels in the multi-sublevel system, so according to the selection rule, each ground state can be pumped to three different excited states while each excited state can decay into nine different ground states at most. To simplify the notation, we write the population of a ground (excited) state sublevel as $P_{F,m_F}(Q_{F',m_{F'}})$, which is equal to the diagonal density-matrix element $\rho_{F,m_F;F,m_F}(\rho_{F',m_{F'};F',m_{F'}})$. Considering optical pumping with high intensity, the general rate equations of the ground state and excited state sublevels can be expressed as follows [32]:

$$\begin{aligned}\frac{dP_{F,m_F}}{dt} = &-\sum_{F'=F-1}^{F'=F+1} C_{F,m_F}^{F',m_F+1}\frac{\Gamma}{2}\frac{I}{I_{\rm sat}}\frac{P_{F,m_F}}{1+4\Delta'^2/\Gamma^2} + \sum_{F'=F-1}^{F'=F+1} C_{F,m_F}^{F',m_F+1}\frac{\Gamma}{2}\frac{I}{I_{\rm sat}}\frac{Q_{F',m_F+1}}{1+4\Delta'^2/\Gamma^2}\\ &+\sum_{m_{F'}=m_F-1}^{m_{F'}=m_F+1}\sum_{F'=F-1}^{F'=F+1} C_{F,m_F}^{F',m_F+1}\Gamma Q_{F',m_{F'}}\end{aligned} \tag{1}$$

$$\begin{aligned}\frac{dQ_{F',m_{F'}}}{dt} = &\sum_{F=F'-1}^{F=F'+1} C_{F,m_{F'}-1}^{F',m_{F'}}\frac{\Gamma}{2}\frac{I}{I_{\rm sat}}\frac{P_{F,m_{F'}-1}}{1+4\Delta'^2/\Gamma^2} - \sum_{F=F'-1}^{F=F'+1} C_{F,m_{F'}-1}^{F',m_{F'}}\frac{\Gamma}{2}\frac{I}{I_{\rm sat}}\frac{Q_{F',m_{F'}}}{1+4\Delta'^2/\Gamma^2}\\ &-\sum_{m_F=m_{F'}-1}^{m_F=m_{F'}+1}\sum_{F=F'-1}^{F=F'+1} C_{F,m_F}^{F',m_F'}\Gamma Q_{F',m_{F'}}\end{aligned} \tag{2}$$