Controlling Magneto-Optical Rotation via Atomic Coherences

Anil K. Patnaik and G. S. Agarwal

Physical Research Laboratory, Navrangpura, Ahmedabad 380 009, India
e-mail: aanil@prl.ernet.in

Abstract. An isotropic medium, having magnetic sublevels, when subjected to a magnetic field or an electromagnetic field can induce anisotropy in the medium; and as a result the plane of polarization of the probe field can rotate. Therefore the rotation due to the magnetic field alone, can be controlled efficiently with use of a coherent field. We show, using a control field, significant enhancement of the magneto-optical rotation and demonstrate the possibility of realizing magneto-optical switch.

1 Introduction

An isotropic medium having \( m \)-degenerate sublevels when subjected to a magnetic field exhibits birefringence in its response to a polarized optical field. This is due to the fact that Zeeman splitting of magnetic sublevels causes asymmetry in the refractive indices for left and right circular polarization components of the optical field. The result is magneto-optical rotation (MOR); i.e., the plane of polarization of the light emerging out of the medium is rotated with respect to that of the incident. For example consider a \( V \)-scheme (say \( ^{40}Ca \) system) with \( ^4S_0 \) as ground state and \( ^1P_1 \) as its excited states, subjected to a magnetic field \( B \). We probe it by a linearly polarized light propagating along \( B \). Let \( \chi_+ \) and \( \chi_- \) be the susceptibilities corresponding to the right and left circular polarizations. For small absorption the polarization rotation is given by

\[
\theta = \pi k_p l \text{Re}(\chi_- - \chi_+),
\]

where \( k_p \) corresponds to propagation vector of the probe and \( l \) is the length of the medium. We note that \( \chi_\pm \) depend on the number density of atoms and the oscillator strength of the transition.

Production of large magneto optical rotation is important for a number of applications. In a recent experiment, Sautenkov et al [1] have shown enhancement of resonant MOR in an optically dense vapor of \( Rb \) atom by several order of magnitude. Further, a coherent field can manipulate the susceptibilities \( \chi_\pm \) of the medium, and in particular can modify the dispersion properties of the medium [2]. In another recent experiment on coherence induced anisotropy, Wielandy and Gaeta [3] have demonstrated that when a \( Rb \) vapor cell is illuminated by a strong laser beam of a particular polarization,
and is probed by a linearly polarized laser beam, the plane of polarization of the probe is rotated as the control field induces birefringence in the medium.

In this article, we consider the possibility of control of the MOR by using a strong laser beam. We also show that for a chosen configuration, inclusion of Doppler effect in the problem gives significant enhancement in the MOR - that demonstrates the possibility of realizing Magneto-optical switch.

2 The Model Scheme and Determination of $\chi_{\pm}$

![Fig. 1.](image)

(a) The four-level model scheme (say of $^{40}$Ca) having $m$-degenerate sublevels as its intermediate states. The symbols in left hand side denote the energy levels of $^{40}$Ca atom. $2\Gamma_i$ and $2\gamma_i$ are the spontaneous decays, $2g_i$ ($2G_i$) is Rabi frequency of the probe (control) field due to coupling of the intermediate state $|i\rangle$ with $|g\rangle$ ($|e\rangle$). The detuning of probe (control) field from the center of $|1\rangle$ and $|2\rangle$ are represented by $\delta$ ($\Delta$). $2\Omega$ is the Zeeman split between the intermediate states. 

(b) A block diagram that shows the configuration under consideration. $B$ defines the quantization axis $z$. The input probe $E_{in}$ is $x$-polarized and the control field is left circularly polarized. Both the fields propagate along $z$. After passing through the cell, output is observed through a $y$-polarized analyzer.

We consider a model system [see Fig.1] involving say cascade of transitions $|j = 0, m = 0\rangle$ (level $|g\rangle$) $\leftrightarrow$ $|j = 1, m = \pm 1\rangle$ (level $|1\rangle$ and $|2\rangle$) $\leftrightarrow$ $|j = 0, m = 0\rangle$ (level $|e\rangle$). This for example will be relevant for expressing $^{40}$Ca. The probe $E_p$ will act between the levels $|g\rangle$ and $|1\rangle, |2\rangle$. We assume in addition the interaction of a control laser $E_c$ to be nearly resonant with the transition $|e\rangle \leftrightarrow |1\rangle, |2\rangle$. For simplicity we drop the transition $m = 0 \leftrightarrow m = 0$. We thus assume the loss to $m = 0$ state by spontaneous emission could be pumped back by an incoherent pump. We derive the density matrix equation for the system

$$\frac{\partial \rho}{\partial t} = -\frac{i}{\hbar} [\mathcal{H}, \rho] + \text{spontaneous decay terms},$$

(2)
that describes the dynamics of the system. Where $H$ defines the Hamiltonian of the system. We solve Eq.(2) and could obtain complete analytical solutions in the steady state. The susceptibilities of the medium, to different circularly polarization components, are proportional to the off-diagonal density matrix element corresponding to the transition the polarized field couples. However, here we do not present the complete analytical results [4].

For an $x$-polarized input probe beam, after passing through the medium, the transmission at the output through a crossed polarized analyzer (scaled with the input intensity) can be written as

$$T_y = \frac{1}{4} \left| \exp \left( \frac{i \alpha l}{2} \tilde{\chi}_+ \right) - \exp \left( -\frac{i \alpha l}{2} \tilde{\chi}_- \right) \right|^2;$$

where $\tilde{\chi}_\pm$ represent the normalized susceptibilities. In rest of this article, we drop the tilde for brevity. The quantity $\alpha l$ gives resonant absorption of the medium. For a particularly interesting case of a $\sigma^-$ polarized control field (i.e., $E_{c+} = 0$, $E_{c-} \neq 0$), $\chi_\pm$ are found to be

$$\chi_- = \frac{i \gamma}{(\gamma + i(\delta - \Omega))},$$

$$\chi_+ = \frac{i \gamma (G_1 + G_2 + i(\Delta + \delta))}{|G_1|^2 + (\gamma + i(\delta + \Omega))(G_1 + G_2 + i(\Delta + \delta))},$$

where the symbols represent the parameters defined in Fig.1. For simplicity, we have assumed $\gamma_1 = \gamma$. In all the plots, all frequencies are scaled with $\gamma$ ($= G_i$). Clearly, $\chi_-$ is independent of control field parameters, whereas $\chi_+$ depends strongly on the strength and frequency of the control field. For large $|G_1|$, both real and imaginary part of $\chi_+$ will show Autler-Townes splitting and therefore will cause a large asymmetry between the two polarization components.

## 3 Laser Field Induced Enhancement of MOR

From Eq.(4) and (5), we note that, $\chi_+(\Omega = 0) \neq \chi_+(\Omega = 0)$ for $G_c \neq 0$. Therefore the birefringence can be induced in the medium by the laser field even in absence of the magnetic field [3]. Thus one observes a large rotation of the polarization of the probe. There are many reports of laser field induced birefringence [3] which had suffered from large absorption, resulting in a very small rotation signal at the output. Further when magnetic field is present, new frequency regions are created by application of the control field where significant enhancement of MOR signal is obtained particularly in the regions where the MOR, otherwise, is negligible. For example in Fig.2 at $\delta \sim \pm 50$, there is a large enhancement of MOR. For detuned control fields the MOR could be enhanced further and we also analyze the case of an elliptically polarized control field and identify many interesting parameter domains where large MOR is obtained (results not shown here).
4 Realization of a Magneto-Optical Switch

We next consider a Doppler broadened medium where one needs to average $\chi_\pm$ over the atomic velocity distribution function inside the cell. We have identified a configuration that takes advantage of the Doppler broadening to increase the asymmetry between $\chi_\pm$, and hence to obtain significantly large enhancement of the MOR signal.

We consider the same configuration as in Fig. 1 but with control field ($\sigma_-$ polarized) and the probe field ($x$-polarized) counter propagating to each other. The $\sigma_-$ component of the probe is, thus, Doppler broadened as it does not see the control field, but on the other hand $\sigma_+$ component experiences the counter propagating $\sigma_-$ polarized control field and, therefore, is almost Doppler free. That leads to enhancement of the asymmetry between $\chi_+$ and $\chi_-$. We have derived analytical expressions for the Doppler averaged values of $\chi_\pm$ and hence for the rotation spectra. In Fig. 2, at $\delta \sim 0$, MOR enhancement factor is as large as $3.7 \times 10^4$, compared to that of MOR with no control field case. Such an action of control field can be used as a magneto-optical switch that switches the given polarization state of the probe field to its orthogonal component. Several interesting set of parameters are identified where the $y$-polarized signal intensity at the output is as large as $\sim 92\%$ of the $x$-polarized input intensity.

Fig. 2. Large enhancement of MOR for a range of frequencies of the probe beam is shown. The parameters are mentioned above.
5 conclusion

We have shown how a control field can induce birefringence and enhance MOR. We have also shown that it can create new regions where MOR enhances significantly. In an inhomogeneously broadened medium, we have shown that, the control field enhances MOR to a large order of magnitude, and therefore it demonstrates the possibility of realizing a magneto-optical switch.

References

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