Analysis of atom detection via the magnetic optical effect*

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We demonstrated a new method of atom detection by means of the magnetic optical effect. The number density of the atom cloud was measured by detecting the rotation angle of the polarization plane of linearly polarized probe light when propagating inside the atomic cloud. Detuning, the magnetic field and light intensity dependencies of the rotation angle were studied theoretically and experimentally to find the best parameter for atom detection. In this way, we managed to achieve a rotation angle of 0.22 rad with a signal to noise ratio (SNR) of 75 and a contrast of 87.5%.

Keywords: atom detection, magnetic optical effect, Faraday rotation

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1. Introduction

Atom detection is an important task in cold atom experiments. Two of the most popular ways to detect atoms are the absorption and fluorescence methods. They are based on stimulated absorption and spontaneous emission, respectively. However, atoms not only change the intensity of light, but also its phase. Hence, we can detect atoms via the phase shift of probe light. Earlier work such as dispersive imaging done by Andrews *et al.*[1] was an excellent demonstration of atom detection by phase shift measurement. They used an off-resonant light to illuminate an optically dense atom cloud. The atom cloud, which performs as a lens, can deflect light as a result of refraction. With the unscattered light blocked by a thin wire, atom distribution can be revealed by angular distribution of scattered light. The large detuning ensures a low probability for absorption, so the detection is almost nondestructive to internal states. However, the signal is very low (5×10^6 photons scattered by 5×10^6 atoms were detected). Here, we present a simple method that can detect atoms with high contrast by the direct measurement of phase shift of probe light.

It is well known that linearly polarized light can be decomposed into two components with opposing circular polarizations. The change in the difference between their phases results in the rotation of the polarization plane. The best known phenomenon associated with optical rotation is the Faraday effect where the rotational angle is proportional to the magnetic field. In quantum optics, the phase shift of light can be enhanced via atom–photon interaction, known as the magneto–optical effect.[2] With the help of the magneto–optical effect, both the linear and nonlinear Faraday effect have been observed in hot vapors and cold atoms.[3–5] Previous work showed that angles greater than $\pi/2$ can be realized in an optically dense system, and the rotation can be easily switched on or off by turning an external magnetic field on or off. The large rotation angle showed its potential application in a precision magnetometer[6] and vacuum squeezing.[7] Aside from the magnetic field, the rotation angle is proportional to the area number density of the atomic medium, as in the absorption imaging method. In our experiment, we directly measured the rotation angle by detecting its polarization direction. Then, the area number density can be deduced from the detected signal.

In Section 2, we theoretically calculate the magnetic field and light intensity dependences of the coefficient of the rotation angle. In Section 3, our experimental setup and procedure are described. The results are presented and compared with those of numerical calculations in Section 4.

2. Theoretical analysis

The theory of our method can be briefly expressed as follows. When linearly polarized (along the x axis) light propagates along the direction of a magnetic field, it can be characterized by a composition of σ^+ and σ^- light,

$$\begin{aligned}\boldsymbol{E}_0 &= A_0\cos(\omega t+k_0 r)\begin{bmatrix}1\\0\end{bmatrix}\\ &= \frac{A_0}{2}\begin{bmatrix}\cos(\omega t+k_0 r)\\ \mathrm{i}\sin(\omega t+k_0 r)\end{bmatrix}+\frac{A_0}{2}\begin{bmatrix}\cos(\omega t+k_0 r)\\ -\mathrm{i}\sin(\omega t+k_0 r)\end{bmatrix},\end{aligned}\quad(1)$$

where k_0 and ω are the wave number and frequency of the probe light, respectively. When the light propagates inside an atomic medium, the amplitude and phase of the two components will both be changed differently. Then, the output light will be

$$\boldsymbol{E} = \frac{A_0}{2}\exp\left(-\frac{OD_+}{2}\right)\begin{bmatrix}\cos(\omega t+k_0 r+\varphi_+)\\ \mathrm{i}\sin(\omega t+k_0 r+\varphi_+)\end{bmatrix}$$

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$$+\frac{A_0}{2}\exp\left(-\frac{OD_-}{2}\right)\begin{bmatrix}\cos(\omega t+k_0 r+\varphi_-)\\ -\mathrm{i}\sin(\omega t+k_0 r+\varphi_-)\end{bmatrix}, \quad (2)$$

where OD_+ and OD_- are optical thickness of the atomic medium for σ^+ and σ^-, φ_+ and φ_- are the phase shifts of σ^+ and σ^-, respectively. It can be seen that $\boldsymbol{E}$ is elliptically polarized with a major axis of $A_0[\exp(-OD_+/2)+\exp(-OD_-/2)]/2$ and a minor axis of $A_0[\exp(-OD_+/2)-\exp(-OD_-/2)]/2$, and the major axis is tilted by an angle of $\theta=(\varphi_+-\varphi_-)/2$ relative to the x axis.

In our experiment, an atom cloud of ^{87}Rb cooled by mirror-MOT was detected. The frequency of the probe light was set to be resonant with the $F=2\rightarrow F=3$ transition (see Fig. 1(a)). Thus, the internal state Zeeman structure is antisymmetric for σ^+ and σ^- transitions, $OD_+=OD_-=OD$, and $\varphi_+=-\varphi_-=\varphi$. Consequently, equation (2) can be simplified as

$$\boldsymbol{E}=A_0\exp\left(-\frac{OD}{2}\right)\cos(\omega t+k_0 r)\begin{bmatrix}\cos\varphi\\ \mathrm{i}\sin\varphi\end{bmatrix}, \quad (3)$$

which means the output of the probe light is still linearly polarized. The parameters OD and φ are proportional to the real and imaginary parts of susceptibility, respectively. In the stationary regime, they can be written as

$$OD=\frac{2k_0 nl}{\varepsilon_0\hbar}\sum_{e,g}\frac{d_{eg}^2\mathrm{Im}(\rho_{eg})}{\Omega_{eg}}, \quad (4a)$$

and

$$\varphi=\frac{k_0 nl}{\varepsilon_0\hbar}\sum_{e,g}\frac{d_{eg}^2\mathrm{Re}(\rho_{eg})}{\Omega_{eg}}, \quad (4b)$$

where d_{eg} and Ω_{eg} denote, respectively, the dipole matrix element and the Rabi frequency for the $e\rightarrow g$ transition, which follow standard selection rules for σ^+ transition, ρ_{eg} is the related density matrix element, n is the number density of the atom cloud, and l is the length of the atom cloud.

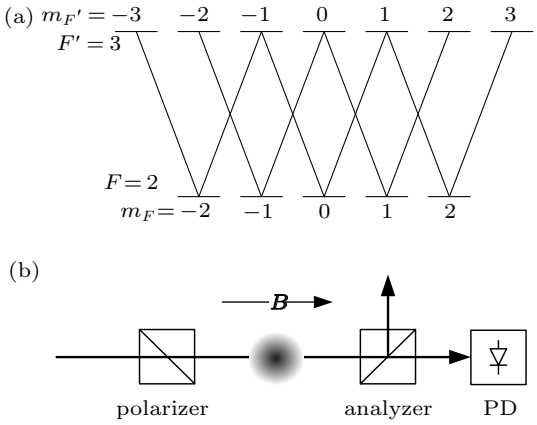


Fig. 1. (a) Energy level structure of Zeeman sublevel of $F=2$ and $F=3$ coupled by a linearly polarized light resonant with the $F=2\rightarrow F=3$ transition. (b) Experiment setup, where PD denotes the photodiode. The polarization planes of the polarizer and analyzer are perpendicular to each other.

To calculate ρ_{eg}, we solve the optical Bloch equation of density matrix operator described as follows:

$$\frac{\mathrm{d}\rho}{\mathrm{d}t}=\frac{1}{\mathrm{i}\hbar}[H_{\mathrm{atom}}+H_{\sigma^+}+H_{\sigma^-},\rho]-\sum_{i,j}\Gamma_{ij}\rho_{ij}|i\rangle\langle j|, \quad (5)$$

where H_{atom} is the atom Hamiltonian, H_{σ^+} and H_{σ^-} are the Hamiltonians of σ^+ and σ^- component of the probe field in the rotating-wave approximation, respectively. The last term in Eq. (5) describes the relaxation of ρ, where the expression of Γ_{ij} is very complicated. It can be briefly stated as: $\Gamma_{ij}=-\Gamma$ if both the i-th and j-th states are excited states; $\Gamma_{ij}=-\Gamma/2$ if one and only one state is the excited state; $\Gamma_{ij}=-\gamma_{ij}$ if $i\neq j$ and they are ground states; $\Gamma_{ij}=\sum_e f_{ei}^2\Gamma-\gamma_{ij}$ if $i=j$ and they are ground states. Here, Γ is the spontaneous decay rate of excited states; γ is the relaxation rate of coherence between ground states, which is negligible for cold atoms; f_{ei} is the Clebsch–Gordan coefficient of the electric dipole transition $e\rightarrow g$. After the steady-state solution of Eq. (5) was acquired numerically, the values of OD and φ were calculated, as shown in Fig. 2.

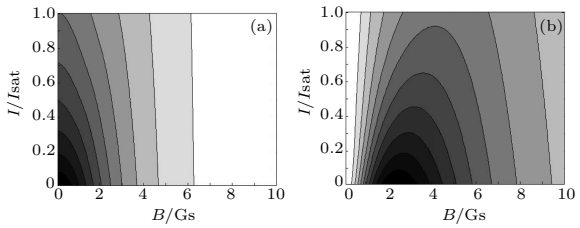


Fig. 2. Contour plot of (a) OD and (b) φ as a function of probe light intensity and magnetic field. The white areas correspond to low absorption and a small rotation angle, the dark areas to large absorption and a big rotation angle. The I_{sat} denotes the saturation intensity.

It can be seen that OD rises when the probe light intensity and magnetic field decrease (see Fig. 2(a)), which is easy to understand: a weaker probe light with lower detuning undergoes greater absorption. Decreasing probe light intensity can also increase the rotation angle (see Fig. 2(b)). However, the maximum of φ appears when B is 2.4 Gs. This value is primarily determined by Γ. Take a two-level system for example, when the Rabi frequency of a probe field is low, the real part of susceptibility can be written as

$$\mathrm{Im}(\chi)=\frac{nd_{eg}^2}{\varepsilon_0\hbar}\frac{4\delta\Gamma^{-2}}{1+4\delta^2\Gamma^{-2}}, \quad (6)$$

where δ is the detuning of the probe field. It can be seen that $\mathrm{Im}(\chi)$ reaches its maximum when $\delta=\Gamma/2$. In this experiment, with the frequency of the probe light fixed, δ was determined by a Zeeman shift. Therefore, a proper magnetic field was required to acquire a high rotation angle.

For most cases, the solution of the optical Bloch equation is considered precisely and reliably. However, it is not easy to acquire an analytical solution when multiple states are taken

into consideration, because optical pumping and coherence between Zeeman states make things complicated. The former can redistribute the population of ground states. The latter results in electromagnetically induced transparency (EIT)[8] and electromagnetically induced absorption (EIA). As a result, a simple analytical solution of Eq. (5) is not available, which makes it inconvenient to deduce information about atoms from the signal. To overcome this difficulty, we neglect optical pumping and coherence between Zeeman states in the situation of low light intensity. If we make a further assumption that the distribution of population among the ground state sublevels is uniform, then the simplified expression can be written as

$$\varphi = \frac{2knl}{5\varepsilon_0\hbar}\sum_{g=-2}^{2} d_{eg}^2 \frac{\delta_{eg}}{\Gamma^2 + 4\delta_{eg}^2}, \tag{7}$$

where $\delta_{eg} = (m_e g_e - m_g g_g)\mu B$ is the Zeeman-shifted detuning of each transition, m_e and m_g is the magnetic number of the excited state and the ground state, respectively; g_e and g_g are Landé factors of them. As depicted in Fig. 3, the result from Eq. (7) coincides well with the numerical solution when light intensity is low. The difference between them is lower than 13%, which means that the simplified expression is available in atom detection.

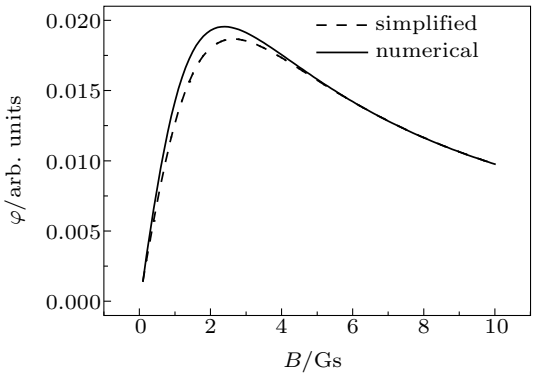


Fig. 3. Solid line: comparison of φ given by the numerical solution of the optical Bloch equation when the light intensity is 0.01 saturation intensity. Dashed line: simplified expression discussed in the text.

3. Experiment

The setup of our experiment is shown in Fig. 1(b), which was described in detail elsewhere.[9] The atom cloud was previously cooled by mirror-MOT. The mirror-MOT was turned on after 5 s, typically more than 2×10^7 atoms with a temperature of about 200 μK and a Gaussian diameter of about 2.2 mm were captured. The probe beam was focused with a Gaussian diameter of about 2 mm. We tuned the position and direction of the probe beam finely until the best absorption spectrum of the atom cloud was acquired, which means that the probe beam and the atom cloud coincided well.

Before the atom cloud was detected, the mirror-MOT was turned off and the internal states of atoms were almost equally distributed among Zeeman sublevel states of the hyperfine ground state $|5^2S_{1/2}, F = 2\rangle$. The anti-Helmholtz coils of the mirror-MOT have a large inductance. It lasted 2 ms until the coils were completely turned off. Too long a shut-down time caused a loss of atoms. We managed to shorten the shut-down time to less than 1 ms. However, an eddy current of the environment resulted in a high residual magnetic field that interfered with the orientation of the quantized axis. Thus, 2 ms was a compromised choice. In the meantime, a bias magnetic field in the direction of the probe light was applied to generate Zeeman shifts.

The probe light was turned on when the current of the anti-Helmholtz coils was completely shut down. To keep background noise at a low level, we used two Glan–Taylor prisms as the polarizer and analyzer. The two prisms were finely adjusted to acquire an extinction ratio higher than 10^5. Transmitted light was received by a photodiode. A Keithley current amplifier was used to convert the photocurrent to a voltage signal which was recorded by an oscilloscope.

The signal was mainly contributed by the component of $\boldsymbol{E}$ along the y axis. For a small OD and φ, light intensity detected by a photodiode can be written as

$$I = \frac{1}{2}A_0^2\varphi^2. \tag{8}$$

As a result, the signal to noise ratio (SNR) equals $10^5\varphi^2$, and the contrast is $(\varphi^2 - 10^{-5})/(\varphi^2 + 10^{-5})$. However, a noise of 5 mV was introduced by the current amplifier when the gain factor was 10^6 V/A, which limited the SNR of the whole detection system. We think a charge coupled device (CCD) camera with a low dark count and high sensitivity would be a good substitution for the photodiode.

4. Results and discussion

The time dependence of the rotational angle is shown in Fig. 4(a), when the intensity of the probe light is 5.3 times the saturation intensity. The signal decays as atoms are constantly heated by the probe light, resulting in their escape from the probe field. During this time, the center of gravity of the atom cloud descends 25 μm. Compared with the dimension of the probing field, its effect on the outcome of detection can be neglected. When the magnetic field is weak, we can see an obvious oscillation of the signal (solid line). This is mainly due to the oscillation of the probe field frequency. When the probe laser is locked, a modulation of the current of the laser diode is needed to acquire a lock-in signal, which results in an oscillation of laser frequency. Comparing the signal derived from the numerical calculation, we managed to determine that the peak-to-peak value of frequency oscillation is about 3.3 MHz. A critical problem caused by this oscillation is an uncertainty as to whether the peak or valley value corresponds to the resonant frequency. To answer this, we calculated the rotation angle as a

function of both detuning and the magnetic field. The numerical solution (see Fig. 4(b)) shows that when the magnetic value is higher than 6.5 Gs, the peak value corresponds to the resonant frequency, and vice versa. To suppress the oscillation, we increased the magnetic field because the oscillation of the laser frequency can be neglected when Zeeman splitting was large. The oscillation could hardly be seen when the magnetic field was higher than 20 Gs (dashed line in Fig. 4(a)).

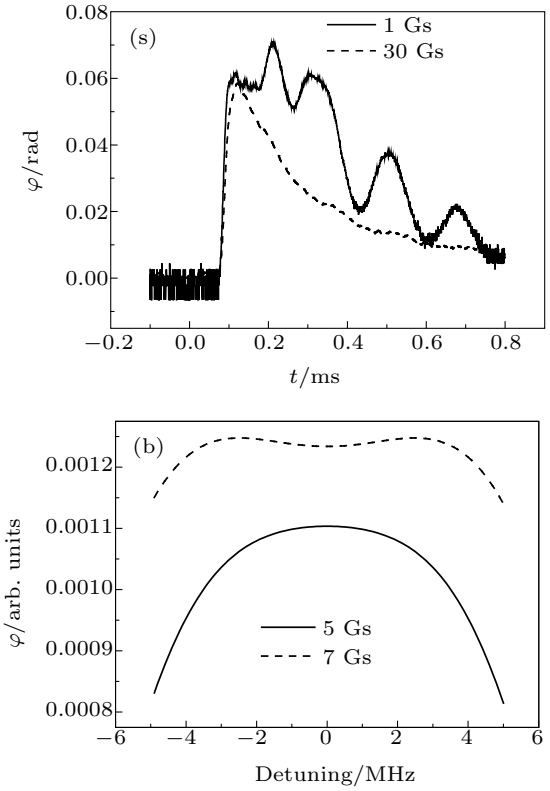


Fig. 4. (a) Rotation angle versus time, when the magnetic field was 1 (solid line) and 30 Gs (dashed line). The intensity of the probe light was 5.3 times saturation intensity. (b) the calculated rotation angle versus detuning, when the magnetic field is 5 (solid line) and 7 Gs (dashed line).

Except for the magnetic field, another parameter that needs to be configured is the probe field intensity. We decreased it from 5.3 times saturation intensity to almost zero, and found that the rotation angle increases as predicted by our theoretical analysis (see Fig. 5). The maximum rotation angle is 0.22 rad, when the magnetic field is 10 Gs. Therefore, the number density of the atom cloud integrated along the probe light direction is about 1.3×10^7 mm^2.

If the only source of noise is the finite extinction ratio, the probe field intensity should be as low as possible. However, noise brought by the signal amplifier could be comparable to the signal, if it is too low. An optimized result was acquired by keeping the probe field intensity higher than the saturation intensity. Additionally, the maximum SNR and contrast was 75 and 87.5%, respectively.

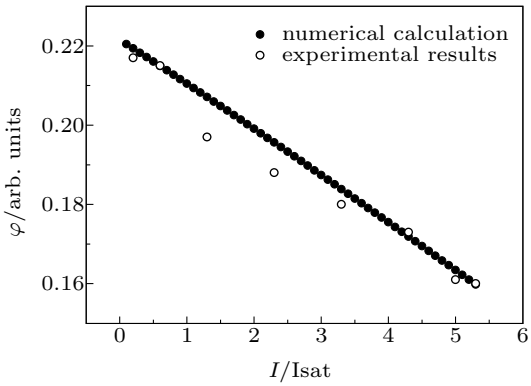


Fig. 5. Rotation angle as a function of probe light intensity with a magnetic field of 10 Gs.

5. Conclusion

In this paper, we report the detection of atoms by means of a magnetic optical effect. Two different models have been used to theoretically study this method. In experiments, we used a mirror-MOT to collect and trap cold atoms. The direction in which the polarization plane of the probe light is rotated by the atom cloud was detected using polarizing technology. With the help of the high extinction ratio of Glan–Taylor prisms, we managed to keep the background noise at a low level, which makes the SNR and contrast of the detection signal high. This method of detection has been applied for precision measurement such as an atomic clock,[10] where the SNR is an important factor of Allan deviation.

References

[1] Andrews M R, Mewes M O, van Druten N J, Durfee D S, Kurn D M and Ketterle W 1996 *Science* **273** 84
[2] Budker D, Gawlik W, Kimball D F, Rochester S M, Yashchuk V V and Weis A 2002 *Rev. Mod. Phys.* **74** 1153
[3] Zigdon T, Wilson-Gordon A D, Guttikonda S, Bahr E J, Neitzke O, Rochester S M and Budker D 2010 *Opt. Express* **18** 25494
[4] Jackson Kimball D F, Jacome L R, Guttikonda S, Bahr E J and Chan L F 2009 *J. Appl. Phys.* **106** 063113
[5] Labeyrie G, Miniatura C and Kaiser R 2001 *Phys. Rev.* A **64** 033402
[6] Wojciechowski A, Corsini E, Zachorowski J and Gawlik W 2010 *Phys. Rev.* A **81** 053420
[7] Matsko A B, Novikova I, Zubairy M S and Welch G R 2003 *Phys. Rev.* A **67** 043805
[8] Fleischhauer M, Imamoglu A and Marangos J P 2005 *Rev. Mod. Phys.* **77** 633
[9] Bo Y, Cheng F, Ke M, Li X L, Tang J Y and Wang Y Z 2009 *Chin. Phys.* B **18** 4259
[10] Lin J D, Deng J L, Ma Y S, He H J and Wang Y Z 2012 *Opt. Lett.* **37** 23