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Nonlinear magneto-optical effects in cold atoms of ^{87}Rb*

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With laser-cooled cold ^{87}Rb atoms as a magneto-optical medium, a weak right circularly polarized probe field and frequency modulation technique are used to detect the magnetic distribution of the quadrupole field. A two-peak dispersion-like signal other than that of the usual nonlinear magneto-optical effect mentioned in other papers is obtained.

Keywords: nonlinear magneto-optical rotation, cold atoms, two-peak dispersion-like signal
PACC: 7820L, 4250V, 3280P

1. Introduction

Nonlinear magneto-optical rotation (NMOR), the light power dependent rotation of the polarization plane of light in a magnetic field, known as the Faraday rotation, has been applied for magnetometry (in both longitudinal and transverse fields).[1] Atomic magnetometers based on NMOR may enhance the sensitivity to the magnetic fields by an order of magnitude compared with conventional optical pumping magnetometry. It is shown that through an appropriate parameter choice, the shot noise limit of sensitivity to small magnetic fields can approach $10^{-11}\mathrm{G}/\sqrt{\mathrm{Hz}}$.[2,3] When linearly polarized light resonant with the atomic sample propagates through an atomic sample along the direction of magnetic field, several nested, dispersively shaped features can be observed in the field dependence of the rotation angle. The feature reaching a maximum at several gauss is due to a hole burning effect in the atomic velocity distribution. A number of recent investigations are focused on this subject. Most of the works addressing NMOR are carried out with a linearly polarized beam passing through the hot atoms with density approaching $10^{10}/\mathrm{cm}^3$ along the magnetic field. At different powers of probe beam, NMOR contributes to the formation of Bennett structures in the atomic velocity distribution and coherence of Zeeman states. In the weak field case, the NMOR effects are established through a three-step process: (1) atoms in the medium are optically pumped into an aligned Zeeman state, causing the atomic vapour to acquire linear dichroism; (2) the atomic alignment processes in the magnetic field, rotating the axis of dichroism; (3) the light polarization is rotated by interaction with the dichroism of the atomic medium.[4–8]

In view of the importance of magnetic field distribution around the zero magnetic field in cold atom physics, we need to know clearly the order of magnitude of the magnetic field inside the cold atoms and also the influence from other equipment. But up to now, few works on such subject deal with cold atoms and give accurate description of the order of the magnitude around the zero magnetic field. Recently, a group in France has given an experimental analysis of the laser-cooled ^{85}Rb sample.[2] However, it just discussed an Ioffe-type model. So the quadrupole magnetic field around the zero is still not clear. In this work, we utilize the cold atoms obtained by laser cooling and a trapping technique as the atomic medium, and a σ^+ circularly polarized light propagates through the cold atoms. When the probe beam passes through the cold atoms with its propagating direction parallel to the magnet coils, we got the two-peak dispersion-like feature of cold atoms, from which we can obtain the zero magnetic distribution of the quadrupole field. This offers a new and accurate method to measure

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the weak magnetic field under such special conditions. The reason why we do not use a linearly polarized beam is that after the probe beam propagates in the cold atoms, it can be decomposed into a right circularly polarized and left circularly polarized beam. But when it propagates in this symmetrical quadrupole magnetic field structure, they rotate in the reverse direction and the total contribution to the rotation is zero.

2. Experimental setup

We prepare the cold atom sample using the ordinary laser cooling and trapping method. The experimental setup is shown schematically in Fig.1.

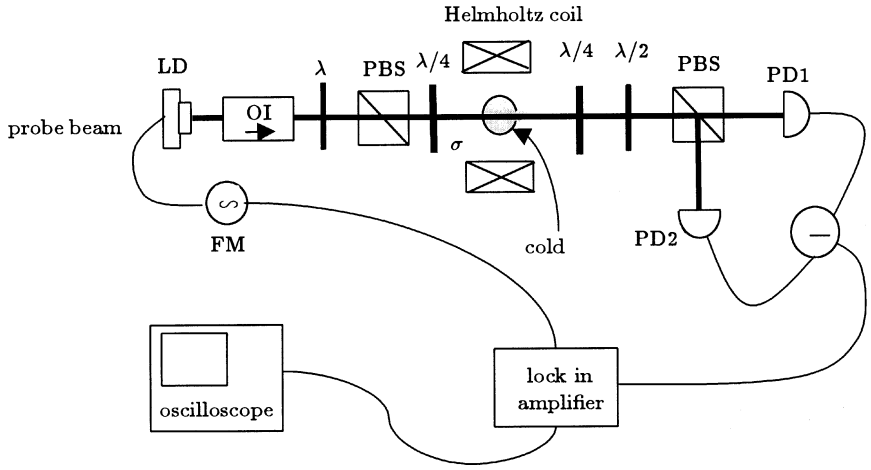


Fig.1. Schematic experimental setup LD: laser diode, OI: optical isolator, PBS: polarization beam splitter, $\lambda/4$: quarter-wave plate, PD: photodiode.

A magneto-optical trap (MOT) is loaded from a chamber with dilute ^{87}Rb and its isotope ^{85}Rb in it. The vacuum of the chamber is maintained at the level of 1×10^{-6}Pa. We use six laser beams with two pairs counter-propagating, and the other pair are obtained by one beam reflection from a high reflection mirror after going through a quarter-wave plate. The laser system is composed of 500mW external grating feedback diode laser with tapered amplifier (product of Toptica) as trapping and cooling beam and a 50mW external grating feedback diode laser (product of Toptica) as a repumping beam. All the trapping and cooling laser beams are red-detuned at the transition of ^{87}Rb $5S_{1/2}F{=}2 \rightarrow 5P_{3/2}F'{=}3$ of D_2 line (wavelength 780nm). These two laser systems are all frequency-locked to their hyperfine structure absorption peaks respectively. For the purpose of a high frequency trap (HFT), we build our setup in the following way. As mentioned above, one of trapping and cooling beams is obtained by retroreflection. The first quarter-wave plate after the cold atoms is used to compensate the cooling beam passing through the small hole into a linearly polarized beam. A half-wave plate before the PBS is used to counteract the influence of a σ^- cooling beam downwards. There are holes in the centre of the quarter-wave plate and the highly reflecting mirror with diameters about 2mm as channels for the cold atoms to pass through and reach the lower chamber (its detail will be described elsewhere). So there is reversed pinnacle in the MOT, which is created by the radiation pressure for the imbalance of the up and down beam in the centre, as shown in Fig.2.

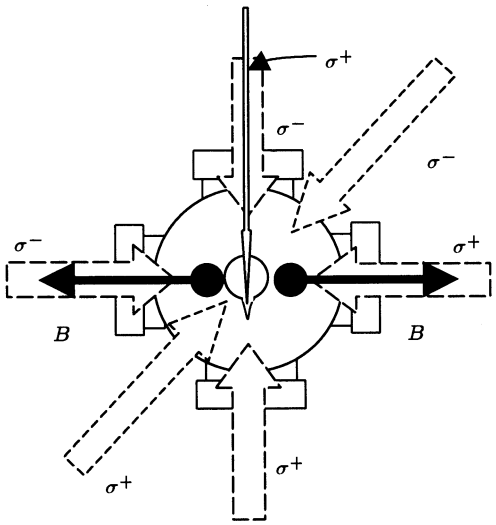


Fig.2. Inner optical structure of the cold atomic system.

Another external grating feedback laser diode is used as a probe beam, which runs at the transition of ^{87}Rb $5S_{1/2}F$=2 $\rightarrow 5P_{3/2}F'$=3. In the experiment, about 10^8 atoms are trapped and with temperature about 300μK. The magnetic gradient is about 6G/cm around the B=0. The probe beam about 35μW with diameter 2mm and with σ^+ polarization propagates through the cold atoms. The Zeeman sublevel distribution of states $5S_{1/2}F$=2 and $5P_{3/2}F'$=3 of ^{87}Rb is shown in Fig.3.

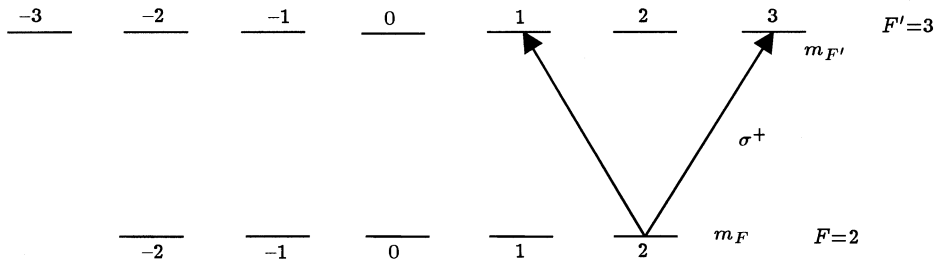


Fig.3. Zeeman sublevel transition of the $5S_{1/2}F$=2 state to $5P_{3/2}F'$=3 of ^{87}Rb.

To guarantee the probe beam to go through the zero magnetic field, several apertures are used to collimate and a common commercial CCD camera is used to monitor the diffusion of the cold atoms when the magnetic field is suddenly turned off. This technique is widely used in laser cooling and trapping experiments. In order to avoid the influence of the low frequency band and ensure the sensitive detection of information of cold atoms, we use the technique of FM (frequency modulation) with modulation frequency 7KHz and amplitude 150mV. We benefit from the FM technique in two respects: (1) low frequency noise can be expelled in small signal detection; (2) when the atomic alignment axis is precessing with Larmor frequency around the direction of external magnetic field, a signal can be detected at the modulation frequency. A balanced detection scheme is designed to single out the NMOR signal, for the balanced polarimeter is insensitive to circular dichroism of the unequal absorption for right-and left-circular polarizations of the sample, making this system appropriate for investigating optical rotation in the general case that the sample probe beam is elliptically polarized. Signals from the two photodiodes are mixed in a subtraction box and then analysed by the lock-in amplifier and oscilloscope, from which we obtain the phase information of the rotation angle. So we can obtain the dispersion-like NMOR signal corresponding to the magnetic field around the zero spot of the quadrupole field.

3. Results and discussion

A two-peak dispersion-like signal is obtained with our cold atomic system. Usually, a dispersion-like signal has only one peak, but for our cold atoms, as a result of the state redistribution effect and difference absorption between right and left circularly polarized beam, there are two peaks, as shown in Fig.4.

We make our cold atomic system a physical model and give a simple analysis of the mechanism of this phenomenon. In our case, cold atoms are established near the zero magnetic field. In fact, the probe beam propagates in a quadrupole magnetic field, and its direction is perpendicular to the longitudinal magnetic field. The cold atoms are prepared in the state of $5S_{1/2}|F=2, m_F=2\rangle$. Due to the transit process, some cold atoms will be collided out of the trap and new atoms will be trapped. As to our system, the σ^+ circularly polarized probe beam induces the transition from $5S_{1/2}|F=2, m_F=2\rangle \rightarrow 5P_{3/2}|F=3, m_F=3\rangle$ when the probe beam passes through the left side of the zero magnetic field. The gradient of quadrupole magnetic field around the zero is 6G/cm. So it introduces a phase $\varphi_1 = \frac{\omega_0 l}{c}\mathrm{Re}[n_+(\omega_0)]$,[8] where l is the path length through the cold atoms, c is the speed of light in vacuum, and ω_0 is the frequency of the sample at resonance. But the probe light passes by the zero magnetic field and reaches the right side of the cold atoms. Now, for the case of the quadrupole field, the magnetic field is changed to the opposite direction. So the probe beam turns to be a left circularly polarized light relative to the magnetic field of this side, i.e. σ^-. In fact, the probe beam rotates in the weak magnetic field in the same direction along the path. However, at this time it introduces another

phase $\varphi_2 = \frac{\omega_0 l}{c}\mathrm{Re}[n_-(\omega_0)]$. So the rotation angle induced by the weak field or imbalance field is

$$\theta = \varphi_1 + \rho\varphi_2 = \frac{\omega_0 l}{c}(1+\rho) + \frac{\alpha}{8\pi}\mathrm{Re}\left[\frac{2(1+\rho)\gamma^2 - \mathrm{i}\gamma(\delta+s) - \mathrm{i}\rho\gamma(\delta-s)}{\gamma^2 - \delta^2 + s^2 + \mathrm{i}2\delta\gamma}\right],$$

where ρ is the ratio of Clebsch–Gordan coefficients of left circularly polarized beam to right circularly polarized beam, α is optical density, $\delta = \omega - \omega_0$ is the detuning of probe beam from the atomic transition frequency, and $s = g_\mathrm{F}\mu_\mathrm{B}B/\hbar$ is the Zeeman splitting space from the Zeeman state $m_{F'}$=2 to other adjacent substates due to the magnetic field of the quadrupole around the zero magnetic field. Taking into account the angle introduced by the $\lambda/4$, the angle in total obtained by the output of lock-in amplifier is the sum of these angles. Also we can get the magnetic magnitude around zero of the quadrupole magnetic trap by means of the Larmor frequency, with $\Omega_m = \Omega_l = g_\mathrm{F}\mu_\mathrm{B}B$. According to this formula, for our cold atomic structure (Ω_m=7kHz, g_F=1/2), the magnetic field near zero is about 1428μG.

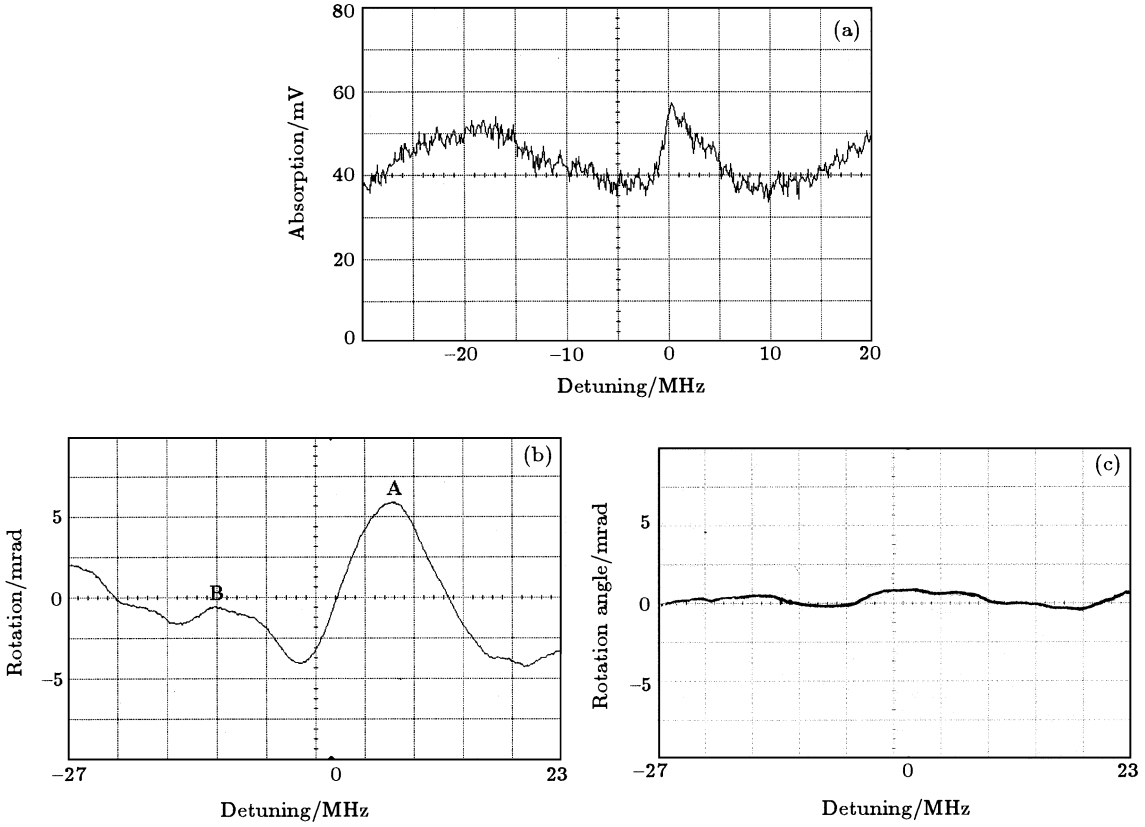


Fig.4. Absorption signal and dispersion signal of the NMOR effect of the cold atomic system. (a) Absorption spectrum of the NMOR effect with cold atoms. (b) Dispersion spectrum of the NMOR effect with cold atoms. (c) Dispersion spectrum without the cold atoms.

In summary, we use a right circularly polarized beam and the frequency modulated technique and get a two-peak dispersion-like NMOR signal. From this signal, we can speculate on the imbalance or the residual weak field of the cold atom systems. In addition, owing to the high sensitivity of atomic energy level to the magnetic field, there is large rotation in cold atoms compared with the Faraday material. Moreover, in the regime of near-resonance excitation, the absorption to the probe beam causes a deformation to the transmitted beam, which becomes elliptical. So φ denotes the deviation from the original polarization to the elliptical polarized beam. In addition, if the probe beam does not go through the zero magnetic field symmetrically, the rotation angle results from two contributions: one is transverse magnetic field rotation, the other is longitudinal magnetic field rotation, which is more complicated.

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