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Optically pumped rubidium atomic magnetometer with elliptically polarized light

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ABSTRACT

Optically pumped rubidium atomic magnetometer with elliptically polarized light is demonstrated theoretically and experimentally. Compared with the conventional optical absorption detection mode, the sensitivity of atomic magnetometer for this detection mode can be improved by an order of magnitude under our experimental condition. Some parameters that influence the performance of this magnetometer is studied, which are the form of elliptically polarized light, the amplitude of exciting magnetic field, and the laser intensity. The sensitivity of 2.5 pT/$\sqrt{}$Hz is obtained when these parameters are optimized.

1. Introduction

In many significant fields, such as fundamental physics [1], biomagnetism [2] and geophysical exploration [3], optically pumped atomic magnetometers play an important role. Atomic magnetometer has been studied for about six decades since the concept of it was proposed by H. Dehmelt in 1957 [4]. Great progresses have been achieved and a variety of atomic magnetometers have been realized [5–7]. The sensitivity of atomic magnetometer can reach subfemtotesla per the square root of Hertz [6,7].

There are two conventional detection modes of atomic magnetometers, which are optical rotation mode and optical absorption mode [8]. Optical rotation mode is based on the polarization rotation of the transmitted linearly polarized probe light, and it needs circularly polarized pump light to polarize the sensory atoms along the direction perpendicular to the probe light. Optical absorption mode is based on the absorption of the transmitted circularly polarized light, and the probe and pump light is the same beam. Compared with the optical absorption mode, the optical rotation mode can suppress common mode noise and possess higher signal-to-noise ratio since it detects the differential intensity of probe light [8,9]. However, the optical absorption mode has a simple configuration and is superior in some particular applications [10,11]. In 2009, a new detection mode for spin-exchange-relaxation-free atomic magnetometer was proposed by V. Shah, which uses elliptically polarized light as probe and pump light simultaneously and detects the differential intensity of the transmitted probe light [12]. Therefore, it combines the advantages of the conventional optical absorption and rotation modes. Nevertheless, it has not been studied whether the sensitivity of atomic magnetometer for this new detection mode is higher than that for the conventional optical absorption mode or not.

In this paper, an optically pumped rubidium atomic magnetometer with elliptically polarized light is realized. Compared with the previous studies, deeper research on some parameters that influence the performance of this kind of atomic magnetometer is done. We demonstrate experimentally that compared with the conventional optical absorption mode, the detection mode of this paper possesses much higher sensitivity.

2. Experimental setup

The experimental setup is shown in Fig. 1. A cubic cell with a volume of 8 cm^3 contains ^{87}Rb atoms and 100 Torr of buffer gas (N_2 and ^{4}He) for slowing atomic diffusion and quenching. The cell is placed inside a five-layer magnetic shield. It is heated with a hot air oven and its temperature is stabilized to 90 °C. A detected constant magnetic field B_0 along the z-axis and an oscillating magnetic field $\vec{B}_1$ exciting the atomic transitions along the x-axis are generated by the surrounding two pairs of Helmholtz coils. The Helmholtz coils along the z-axis are driven by steady current circuit and the Helmholtz coils along the x-axis are driven by a lock-in amplifier.

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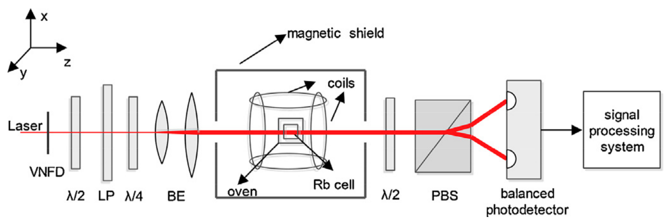

Fig. 1. Schematic diagram of the experimental setup. VNDF: variable neutral density filter, λ/2: half-wave plate, LP: linear polarizer, λ/4: quarter-wave plate, BE: beam expander, PBS: polarized beam splitter.

The laser beam is generated by a distributed feedback diode laser which is turned to near ^{87}Rb D1 transition. It polarizes along the polarization axis of a linear polarizer after passing through this linear polarizer. The laser beam becomes elliptically polarized light after passing through a quarter-wave plate with the fast axis along the y-axis. The intensity of elliptically polarized light is controlled by turning a variable neutral density filter and a half-wave plate before the linear polarizer. And then, it polarizes the ^{87}Rb atoms along the z-axis after expansion and collimation. The magnetic response signal is measured with a half-wave plate, a polarized beam splitter (PBS) and a balanced photodetector by utilizing optical rotation of linearly polarized component of laser beam [13]. The rear half-wave plate is adjusted to make the signal equal to zero in the absence of optical rotation, at first. Finally, the detected signal is acquired and processed by the signal processing system.

3. Theory

If the polarization axis of the linear polarizer is turned and the angle between it and y-axis is θ (Define that θ is positive when the polarization axis of the linear polarizer is in the first and third quadrant of x–y plane, otherwise θ is negative.), then after the laser beam passes through the quarter-wave plate, it becomes elliptically polarized light and its electric field $\vec{E}_1$ is given by

$$\vec{E}_1 = E_0 \begin{pmatrix} 1 & 0 & 0 \\ 0 & -i & 0 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} \sin\theta \\ \cos\theta \\ 0 \end{pmatrix} = E_0 \begin{pmatrix} \sin\theta \\ -i\cos\theta \\ 0 \end{pmatrix}. \tag{1}$$

Here, E_0 is the amplitude of $\vec{E}_1$.

When B_0 along the z-axis is applied, but $\vec{B}_1$ is not applied, by optical pumping with the elliptically polarized light, the polarization of ^{87}Rb atoms along the z-axis P_0 is given by [14]

$$P_0 = s\frac{R_{OP}}{R_{OP} + R_{rel}}, \tag{2}$$

where s is the component of average photon spin along the z-axis, and it can be calculated as

$$s = i\hat{\epsilon}_1 \times \hat{\epsilon}_1^* \cdot \hat{z} = -\sin(2\theta). \tag{3}$$

Here $\hat{\epsilon}_1$ is the unit vector of $\vec{E}_1$, and $\hat{z}$ is the unit vector along the z-axis. R_{OP} is the optical pumping rate for an unpolarized ^{87}Rb atom, which is proportional to the intensity of the elliptically polarized light. R_{rel} is the intrinsic relaxation rate of ^{87}Rb atoms.

Considering the influence of $\vec{B}_1 = 2B_1\cos(\omega_a t)\hat{x}$, the polarization of ^{87}Rb atoms along the z-axis P_z is given by [15]

$$P_z = P_0\frac{1 + [(\gamma B_0 - \omega_a)T_2]^2}{1 + [(\gamma B_0 - \omega_a)T_2]^2 + \omega_1{}^2 T_1 T_2}. \tag{4}$$

Here, $2B_1$ is the amplitude of $\vec{B}_1$, ω_a is the angular frequency of $\vec{B}_1$, $\hat{x}$ is the unit vector along the x-axis, γ is the gyromagnetic ratio of ^{87}Rb atom, T_2 is the transverse relaxation time of ^{87}Rb atoms, T_1 is the longitudinal relaxation time of ^{87}Rb atoms, and $\omega_1 = \gamma B_1$.

Assume that the angle between the optic axis of the rear half-wave plate and y-axis is φ. When there is no ^{87}Rb cell, after the laser beam passes through the rear half-wave plate, its electric field $\vec{E}_2$ is given by

$$\vec{E}_2 = E_0 \begin{pmatrix} -\cos(2\varphi) & \sin(2\varphi) & 0 \\ \sin(2\varphi) & \cos(2\varphi) & 0 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} \sin\theta \\ -i\cos\ \theta \\ 0 \end{pmatrix} = E_0 \begin{pmatrix} -\cos(2\varphi)\sin\theta - i\sin(2\varphi)\cos\theta \\ \sin(2\varphi)\sin\theta - i\cos(2\varphi)\cos\theta \\ 0 \end{pmatrix}. \tag{5}$$

As the PBS splits the laser beam into two beams which polarize along the x-axis and y-axis, respectively, it is easy to obtain that when φ is turned to be equal to $\pi/8$, the intensity of the two beams is the same which is independent of θ.

When the ^{87}Rb cell exists and $\varphi = \pi/8$, the differential signal S_d detected by the balanced photodetector is given by [12]

$$S_d \approx k_d I_0 P_z \cos(2\theta). \tag{6}$$

Here, k_d is a constant number which is related to the operational temperature, the length of the ^{87}Rb cell and the frequency of laser beam. $I_0 = E_0^2$ is the intensity of the elliptically polarized light. Substituting Eqs. (2)–(4) into Eq. (6), we can obtain

$$S_d \approx -\frac{1}{2}\frac{R_{OP}}{R_{OP} + R_{rel}}\frac{1 + [(\gamma B_0 - \omega_a)T_2]^2}{1 + [(\gamma B_0 - \omega_a)T_2]^2 + \omega_1{}^2 T_1 T_2} k_d I_0 \sin(4\theta). \tag{7}$$

We can find from Eq. (7) that the frequency response signal as a function of ω_a exists an extreme value, and the extreme value appears when $\omega_a = \gamma B_0$. Fig. 2 is the frequency response signal obtained by scanning the frequency of $\vec{B}_1$ using the magnetometer of this paper. As γ is a constant number, we can extract the value of B_0 from the frequency response signal by feedback control [16].

For an optically pumped atomic magnetometer, the sensitivity δB can be described by [14]

$$\delta B = \frac{\Delta\omega}{\gamma S_{NR}}. \tag{8}$$

Here, $\Delta\omega$ is the resonance linewidth for magnetometer, which is defined by the full-width at half-maximum of the frequency response signal. S_{NR} is the signal-to-noise ratio for the detected signal. In this paper, the signal intensity is obtained by extract half of the amplitude of the frequency response signal when $\omega_a = \gamma B_0$. For obtaining the noise intensity, the frequency response signal when $\omega_a = \gamma B_0$ passes through a low-pass filter with a cut-off frequency of 200 Hz, and then the filtered signals are continually acquired. By computing the standard deviation of 2000 continual data, the noise intensity with a bandwidth of 200 Hz is obtained.

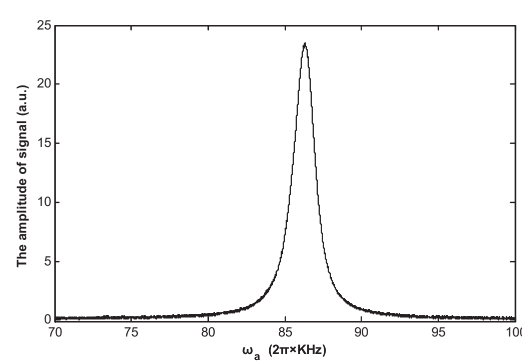

Fig. 2. Frequency response signal for optically pumped rubidium atomic magnetometer.