Development of NMOR magnetometer for spin-maser EDM experiment

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Abstract

We have been developing a high sensitivity atomic magnetometer for atomic EDM experiments using a low-frequency nuclear spin maser. In the developed nuclear spin maser of $^{129}$Xe, suppression of drift and fluctuation in the magnetic field is one of the important issues. The magnetometer being developed for spin maser EDM experiments utilizes the nonlinear magneto optical rotation (NMOR) effect in Rb atomic vapor. The enhancement of the optical rotation in a small magnetic field relies on the long spin-coherence time of Rb atoms in a vapor cell. The NMOR spectrum was measured by using fabricated Rb cells coated with an anti-relaxation material. The NMOR spectrum dependence on laser frequency, cell coating, and laser beam diameter were investigated. The magnetic sensitivity at present is 0.2 $\mu$G/ $\sqrt{Hz}$ from observed NMOR and noise spectra.

Keywords: Electric dipole moment, nuclear spin maser, atomic magnetometer, Nonlinear magneto optical rotation

1. Introduction

The study of permanent electric dipole moment (EDM) has been an important issue in searching for physics beyond the standard model [1, 2, 3]. The non-vanishing EDM associated with spin constitutes clear evidence of the violation of time reversal invariance and space reflection invariance. Recently, not only neutron EDM experiments [4], but also atomic EDM experiments have been performed or proposed [5, 6]. In the experiments, the EDM signal occurs as a frequency shift $\Delta \nu = 4dE/h$ of the spin precession, when the direction of the electric field $E$ is reversed along a static magnetic field $B$. Here $d$ is the non-zero EDM, and $h$ is the Plank constant. Therefore, the precise measurement of spin precession is one of the key issues for EDM experiments. In pursuing a precise measurement of the spin precession frequency in an EDM experiment, one desirable effect is that the continuous observation time of spin precession is prolonged to the greatest extent possible. A nuclear spin maser in which the nuclear spin precession is maintained beyond its transverse relaxation time $T_2$ is an important approach to achieving this goal [7, 8, 9]. We have been developing a $^{129}$Xe nuclear spin maser that is capable of operating at a lower frequency than that of conventional nuclear masers by introducing a feedback system based on optical detection of nuclear spin [9, 10]. The aim of this research is to suppress the fluctuations in the applied static magnetic field, which is one of the main sources of frequency fluctuations in spin masers, by using smaller static fields to operate the maser. A low static field enables us to introduce high sensitivity magnetometers. High sensitivity magnetometers are inevitably important for all EDM experiments because the drift or fluctuation of the magnetic field easily hides the small EDM signal. In order to detect a frequency shift of 1 nHz which would occur with an EDM signal at the $10^{-28}$ em level in the experiment with neutrons or diamagnetic atoms, the magnetic field should be stabilized or monitored with the sensitivity of 1 pG.
Recently optical atomic magnetometers, which utilize the magneto-optical properties of atomic samples, have been studied intensively. Upgrading atomic magnetometers with improved laser technologies, their performance has greatly improved. Their magnetic sensitivities are approaching that of superconducting quantum interference devices (SQUIDs). Magnetometers based on the non-linear magneto-optical rotation (NMOR) effect of alkali-metal atoms are promising for a precise measurement of magnetic fields [11, 12]. Their sensitivities can reach up to $3 \text{ pG/} \sqrt{\text{Hz}}$. Another type of high sensitivity magnetometer, the so-called spin-exchange relaxation-free (SERF) magnetometer, uses high-density alkali metal atoms to cancel the effect of spin relaxation induced from spin-exchange, with a fundamental limited sensitivity of $0.1 \text{ pG/} \sqrt{\text{Hz}} [13, 14]$. In NMOR-based magnetometers, the dynamic range of magnetic field measurement can be extended to above the level of 1 G by using frequency or amplitude modulation in the laser light range [15, 16]. We report in this paper the current status of the development of the NMOR-based magnetometer aimed at operation in our spin-maser EDM experiment performed under a static field of 30 mG.

2. Magnetometer based on the NMOR

The origin of the NMOR magnetometer was the discovery of the Faraday effect of alkali metal atoms in a magnetic field in the vicinity of the resonance absorption frequency of incident light by Macaluso and Corbino [17]. The Macaluso-Corbino effect can be described by a simple transition $F = 1 \rightarrow F' = 0$ as shown in Fig.1 (a). Linearly polarized incident light whose wavelength is tuned to this transition frequency is considered to be a superposition of two coherent circularly-polarized components, $\sigma^\pm$. The non-zero magnetic field $B_0$ induces a difference between two resonance frequencies for $\sigma^+$ and $\sigma^-$ due to the Zeeman shift in the $m = \pm 1$ states. Therefore the refractive index for $\sigma^\pm$ components is given by

$$n_\pm(\omega) \approx 1 + \frac{2\pi\chi_0}{2(\omega - \omega_0) + g_F \mu_B B + i\gamma}$$.

(1)

Here $\omega$ and $\omega_0$ denote the light frequency and resonance absorption frequency, respectively, $\gamma$ is the spectral width of the atom, $g_F$ is the Lande factor of the atom, $\mu_B$ is the Bohr magneton, and $\chi_0$ is the amplitude of the linear optical susceptibility. This difference in the refractive index $n_\pm$ induces the different phase velocities of the $\sigma^\pm$ component so that the polarization plane of incident light tends to rotate after passing the atomic vapor. The rotation angle of light polarization is proportional to $n_+ - n_-$, and can be described using a dispersion-like function:

$$\phi = \frac{2\pi \mu_B B}{h\gamma} \frac{1}{1 + \left(\frac{2\pi \mu_B B}{h\gamma}\right)^2 \frac{1}{l_0}}$$.

(2)
when $\omega$ is tuned to $\omega_0$. Here, $l$ and $l_0$ represent the optical length of the sample and the absorption length. The dispersion curve of the rotation angle on the magnetic field has a typical width of $\gamma \sim 1$ GHz, determined by the Doppler width of the atoms.

The above phenomenon is "linear" magneto-optical rotation. In "nonlinear" magneto-optical rotation (of light intensity), a nonlinear process of light-atom interaction occurs in which a smaller-field optical rotation can be observed than the linear optical rotation. As explained in [11], the NMOR effect is induced by several types of physical processes. In particular, small-field optical rotation occurs as the so-called coherence effect. This process is also described by Eq. (2) but the relaxation rate of atomic alignment precesses around this magnetic field with the Larmor frequency. This phenomenon is clearly explained in the "polarized film" model [11] shown in Fig. 1(b). The rotation of the atomic alignment axis around the $z$-axis produces linearly polarized light at the output of the atomic sample, which is rotated by an angle proportional to $\sin 2\theta$, where $\theta$ is the rotation angle of the atomic alignment axis from the initial light polarization axis ($x$-axis). The rotation angle of this coherence effect is also described by Eq. (2), but the relaxation $\gamma$ in this case corresponds to the relaxation rate of atomic alignment.

According to Eq. (2), a significant change in the rotation angle $\phi$ is observed if the resonance width $\Delta B$ of the spectrum is narrow. The sensitivity to the magnetic field near $B_z = 0$ (within width $\Delta B$) is expressed as

$$\delta B = \left( \frac{\partial \phi}{\partial B_z} \right)^{-1} \delta \phi,$$

where $(\partial \phi/\partial B_z)$ represents the slope of the optical rotation angle to the longitudinal magnetic field $B_z$, and $\delta \phi$ is the measurement sensitivity to the rotation angle. Therefore the magnetic sensitivity becomes higher with a narrower NMOR spectrum and with higher sensitivity to the rotation angle. The spectrum width is determined by the relaxation rate $\gamma$ of the atomic coherence. In recent studies, atomic relaxation rates have become as low as 1 Hz for alkali-metal atoms confined in paraffin coated cells, which corresponds to a magnetic sensitivity of $3 \text{ pG/} \sqrt{\text{Hz}}$. Research into the mechanism of spin relaxation in atom-wall collisions is continuing, and new coating materials and new preparation procedures are expected for prolonging the relaxation time of alkali-metal atoms [18].

3. Development of NMOR magnetometer at RIKEN-TITech

The experimental setup for the development of the NMOR-based magnetometer at RIKEN-TITech is shown in Fig. 2. Rb vapor in a glass cell whose inner surface is coated with paraffin (Parafrint RG) is used for NMOR measurements. The Rb atomic density is $5 \times 10^9 \text{cm}^{-3}$ at room temperature. The Rb cell, having a cylindrical shape ($\phi 25 \text{mm} \times 25 \text{mm}$) is located inside a four layer magnetic shield and irradiated by a laser beam emitted from a Littrow-type external-cavity diode laser (ECDL). A residual magnetic field on the order of 0.1 mG still exists because demagnetization process is not yet optimized. The wavelength of the laser light is tuned to the D1 absorption line of $^{85}\text{Rb} (794.76 \text{ nm})$. The maximum output power is 50 mW, and the line width is 1 MHz. The laser beam is split into two passes, one for NMOR measurements and one for monitoring the laser frequency. The frequency is monitored by observing the laser induced fluorescence (LIF) with a Rb reference cell. The laser beam is linearly polarized by a linear polarizer and then passed through the Rb cell where the polarization plane is rotated due to the NMOR effect. The rotation angle $\phi$ is measured with a linear polarizer, used as a polarization analyzer, located behind the Rb cell; the transmission axis of the analyzer is set at $\pi/4$ from the polarization axis of the incident light. The rotation angle is determined from the observed transmitted intensity using a photo diode. In the measurement of this rotation angle, the direction of the linear polarization is periodically modulated with a photo-elastic modulator ($f_{\text{mod}} = 50 \text{kHz}$) in order to improve the sensitivity to the rotation angle. A three-axis Helmholzt coil is installed inside the magnetic shield to
Figure 2: Experimental setup for the development of NMOR-based magnetometer.

suppress the residual field for future developments. In this experiment, only the z-component coil was used to apply the longitudinal magnetic field to measure the NMOR signal.

The NMOR dependence on the laser frequency was measured by scanning the grating mirror in the ECDL, as shown in Fig. 3, where the longitudinal field was fixed at $B_z = 250 \text{ mG}$. Figure 3(a) shows the energy levels of the $^{85}\text{Rb}$ atom with four hyperfine transitions. To measure the NMOR effect in a $^{85}\text{Rb}$, the transition $\uparrow\downarrow\; (F = 3 \rightarrow F' = 2)$ was used, with the magnetic sublevels shown in Fig.3(b). Figure 3(c) shows the NMOR signal dependence on the relative frequency of the ECDL, along with the simultaneously observed LIF signal for the reference Rb cell. Two NMOR peaks with the Doppler broadening were measured in this frequency region for $F = 3 \rightarrow F' = 2$ in $^{85}\text{Rb}$ and $F = 2 \rightarrow F' = 1$ in $^{87}\text{Rb}$. The magnetic field dependence of NMOR for the laser tuned near the peak of the transition

Figure 3: (a) Energy level of a $^{85}\text{Rb}$ atom. (b) Magnetic sublevels in transition $\uparrow\downarrow$ in $^{85}\text{Rb}$. (c) NMOR dependence on relative laser frequency. The LIF signal of a Rb is shown in the lower panel.

$\uparrow\downarrow$ is shown in Fig. 5. The NMOR spectra observed with a wide-scan range ($B_z = -2.0 \sim +2.0\text{G}$) and a narrow-scan
range \((B_z = -15.0 \sim +15.0 \text{ mG})\) are shown respectively. These spectra fit well with the model equation (2). The characteristic width of 0.2 G in the wide-scan spectrum is controlled by the so-called transit effect, where the width depends on the transit time of atoms through the laser beam region. The estimated relaxation time 20 \(\mu\text{s}\), determined by fitting the wide-scan spectrum using Eq. 2, is consistent with the transit time. In the narrow-scan spectrum, on the other hand, a small-field rotation was observed whose width \((\Delta B \sim 2 \text{ mG})\) was governed by the life-time of atomic alignment through multiple collisions with the inner wall of the glass cell. This is known as the wall-induced Ramsey effect, where an atom aligned by the laser light bounces against the cell many times, while maintaining its atomic coherence and then re-enters the laser beam to be probed for its alignment phase. If the inner wall of the cell is coated with a suitable coating material, the effective coherence time can be prolonged so that the narrow width of the NMOR spectrum can be observed. The estimated relaxation time in the observed narrow-scan spectrum is 8 ms, which is 400 times longer than the transit time. This indicates that the paraffin coating is effective in our preparation procedure of the Rb cell. We also prepared a non-coated Rb cell with which the narrow-width spectrum is not observed. In order to clarify the relation between the NMOR spectrum and the space region of the atom-laser interactions, the NMOR dependence on the diameter of the laser beam was determined. Figure 5 shows the narrow-scan NMOR spectra for three different of diameters. The spectrum width is almost the same for all beam diameters. On the other hand, the signal height (rotation angle) of the spectrum is enhanced for large beam diameters. This enhancement is because the number of Rb atoms to be probed for the spin alignment rotation increases as the beam diameter becomes larger.

Figure 4: Measured NMOR spectrum (a) Magnetic field is scanned from -2.0 G to +2.0 G (wide-scan) (b) Magnetic field is scanned from -15.0 mG to +15.0 mG (narrow-scan).

From the observed detection noise spectrum in the present setup, we determine that the noise level is on the order of \(\delta \phi \sim 4 \times 10^{-4} \text{ mrad/} \sqrt{\text{Hz}}\). The largest observed slope \((\partial \phi/\partial B_z)_{B_z=0}\) in the NMOR spectrum is 5 rad/G. Therefore the sensitivity of the NMOR magnetometer to the magnetic field is, at present, \(\delta B \sim 0.2 \mu\text{G/} \sqrt{\text{Hz}}\).
4. Summary and future plans

We have developed the NMOR-based magnetometer with Rb atoms in order to precisely monitor the field fluctuations in the spin maser EDM experiment being developed. The observed NMOR spectra have a narrow width due to preservation of spin coherence during multiple collisions with the paraﬃn coated wall of the cell. From the observed NMOR spectra for paraﬃn coated Rb cells, the spin coherence time is estimated to be 8 ms, and the magnetic sensitivity at present is $\delta B \sim 0.2 \mu G / \sqrt{Hz}$.

The present performance of the NMOR magnetometer can be improved by investigating the characteristics of the NMOR spectrum. Some topics for further study include: (i) the preparation procedures of the paraﬃn coated cell. (ii) suppression of the residual magnetic field along the transverse axis. (iii) the spectrum dependence on light intensity. (iv) the spectrum dependence on cell size, and (v) suppression of detection noise.

In addition, we are now preparing to operate the NMOR magnetometer with frequency (or amplitude) modulation in order to precisely measure the magnetic field in the range of 30 mG with which the spin maser operates. This scheme has been recently studied [15, 16] and is expected to extend the dynamic range of the NMOR magnetometer to the geophysical- scale (~ 1 G).

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