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ScienceDirect

Physics Procedia 17 (2011) 245–250

Physics Procedia

Physics of Fundamental Symmetries and Interactions - PSI2010

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 μG/$\sqrt{\text{Hz}}$ 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} $e$cm level in the experiment with neutrons or diamagnetic atoms, the magnetic field should be stabilized or monitored with the sensitivity of 1 pG.

doi:10.1016/j.phpro.2011.06.043

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 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 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 σ^+ and σ^- due to the Zeeman shift in the $m = \pm 1$ states. Therefore the refractive index for $\sigma^{\pm}$ components is given by

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

Here ω and ω_0 denote the light frequency and resonance absorption frequency, respectively, γ is the spectral width of the atom, g_F is the Lande factor of the atom, μ_B is the Bohr magneton, and χ_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

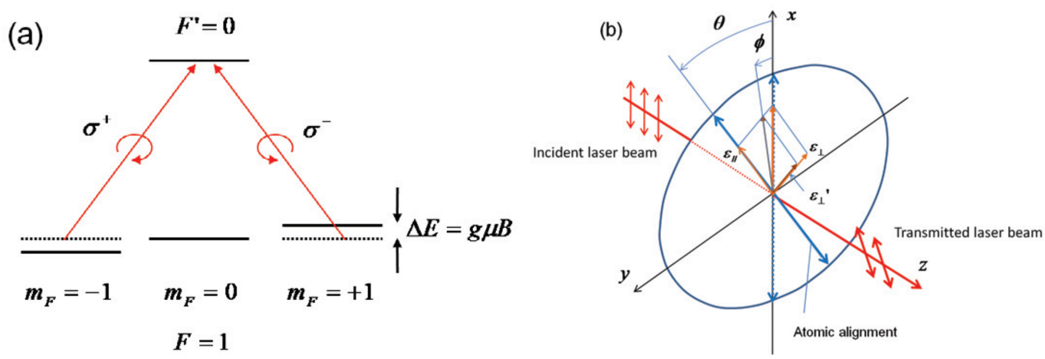

Figure 1: (a) Atomic transition for $F = 1 \rightarrow F' = 0$. (b) Schematic model of the NMOR process. Aligned atoms precessing in a magnetic field are thought of as a rotating polarized film, which is transparent to light polarized along the axis $\epsilon_{\parallel}$ and slightly absorbent for the orthogonal polarization $\epsilon_{\perp}$.

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:

$$\phi = \frac{\frac{2g_F\mu_B B}{\hbar\gamma}}{1 + \left(\frac{2g_F\mu_B B}{\hbar\gamma}\right)^2} \frac{l}{l_0}, \quad (2)$$