II. 7. Atomic Magnetometer toward the Fr EDM Experiment

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A permanent electric dipole moment (EDM) of an elementary particle, which is associated with the spin, is a good observable to probe the physics beyond the standard model (SM) of elementary particles, since the EDM violates the CP symmetry and is sensitive to CP violation in the physics in the SM1). The electron EDM is enhanced in the heavy atom due to the relativistic effect2). The francium (Fr) atom has the largest enhancement factor of the electron EDM in the alkali atom3). We plan to search for the electron EDM by using laser cooled Fr atoms4).

Since the EDM couples with the electric field, it is deduced from a measurement of the energy splitting of the spin with a static electric field. In the actual EDM experiment, we need a static magnetic field in addition to the static electric field due to a tiny energy shift of the EDM. Then, the monitor of the magnetic field, which is applied to the Fr atom, is an important issue. In order to monitor the magnetic field, we are developing a rubidium (Rb) atomic magnetometer based on a nonlinear magneto-optical rotation (NMOR) effect with frequency modulated light5).

The principle of the NMOR effect of the Rb atom is as follows. A laser light with a wavelength tuned to the Rb D1 transition produces the spin alignment state of the Rb atom. The time evolution of the spin alignment under the applied magnetic field occurs and the spin alignment rotates around the magnetic field. Then, the laser light interacts with the rotated spin alignment. As a result, the polarization plane of the laser light is rotated, which has the dispersive shape as a function of the magnetic field. This effect occurs around the zero magnetic field due to the relaxation of the spin alignment in the high field. By using the frequency-modulated (FM) light, the NMOR effect in the finite field can be observed due to a match between the modulation frequency of the laser light and the spin precession frequency of the Rb atom. Thus, we can monitor the magnetic field by measuring the rotation angle of the laser light.

The magnetometer apparatus is shown in Fig. 1. The light source is the DFB laser. The frequency of the laser light is modulated by the modulation of the laser current. The Rb atom is confined to the Paraffin coated glass cell. Paraffin is an anti-relaxation material6). The glass cell is placed inside the magnetic shield which is introduced in order to suppress the effect of the stray magnetic field. The magnetic field is produced by the 3 axis Helmholtz-like coil inside the shield. The laser light transmitted to the cell is divided by using a polarized beam splitter to measure the rotation angle of the polarization plane. The intensities of the divided lights are detected by the balanced photo-detector and its output is sensed in a lock-in amplifier for phase sensitive detection. The output of the lock-in amplifier is monitored by an oscilloscope.

Figure 2 shows the FM-NMOR spectrum. The field sensitivity of the magnetometer is limited by the linewidth and the signal-to-noise ratio of the spectrum. By optimizing the experimental conditions (such as power, frequency or modulation depth of the laser light), the present sensitivity reaches about 20 pT/Hz$^{1/2}$. Then, we performed the actual filed measurement. The result of the measurement is shown in Fig. 3. The rectangle magnetic field is applied along to the incident direction of the laser light by using the 3 axis Helmholtz-like coil. The strength of the applied field is about 300 pT, which is estimated by the interpolation of the calibration using the flux gate magnetometer. The magnetometer responds to the changes in the applied magnetic field as shown in Fig. 3. Frequency component noise of about 50 Hz, which can be derived from the power supply, is also observed. We need to suppress this noise in order to improve the sensitivity of the magnetometer.

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References

1) Kriplovich I.B., Lamoreaux S.K., CP Violation Without Strangeness, Springer, Heidelberg (1997).
2) Ginges J. S. M. and Flambaum V. V., *Phys. Rep* **397** (2004) 63.
3) Mukherjee D., Sahoo B. K., Nataraj H. S. and Das B. P., J. *Phys. Chem A* **113** (2009) 12549.
4) Inoue T., Ando S., Aoki T., Arikawa H., Ezure S., Harada K., Hayamizu T., Ishikawa T., et al., *Hyperne Interact* **231** (2015) 157.
5) Kimball D. F. J., Jacome L. R., Guttikonda S., Bahr E. J. and Chan L. F. J., *Appl. Phys* **106** (2009)

063113.
6) Alexandrov E. B., Balabas M. V., Pazgalev A. S., Vershovskii A. K., Yakobson N. N., *Laser Phys* **6** (1996) 244.

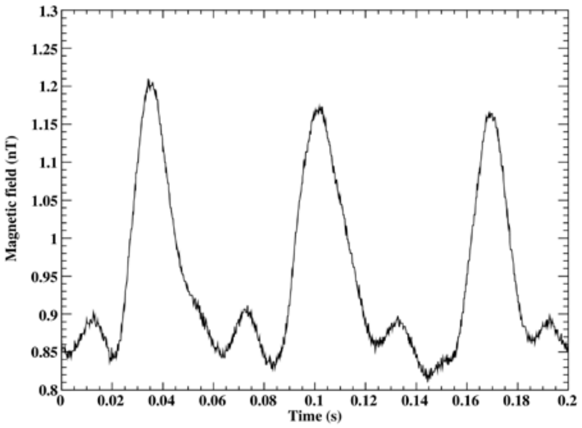

Figure 1. Experimental setup.

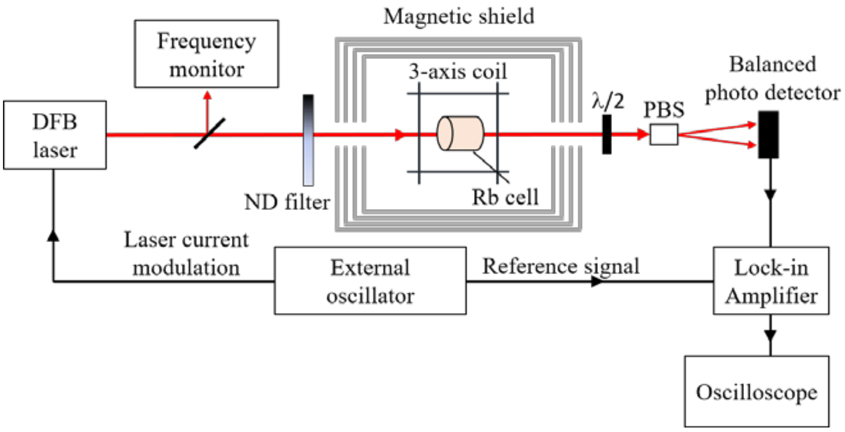

Figure 2. FM-NMOR spectrum.

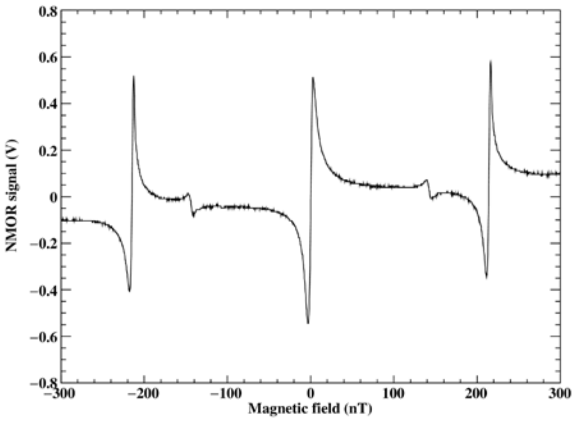

Figure 3. Magnetic field measurement.