Abstract. Present status of the development of a nuclear spin maser for a $^{129}$Xe atomic EDM search is reported. We studied the frequency behavior of the spin maser presently under operation, and found that the drift in the frequency is correlated with the maser amplitude drift. Also, a high-voltage application system for the $^{129}$Xe precession cell was constructed. The leakage current measured is at present on the level of nA when a high voltage of 10 kV was applied, and is a subject of improvement to be achieved in near future.

1. Introduction

A permanent electric dipole moment (EDM) of a particle or an atom violates the time reversal symmetry, and signifies CP violation because of the CPT theorem. Detection of a finite value of EDM should provide a clear evidence of physics beyond the standard model (SM) of elementary particles, because EDMs predicted in the SM are extremely small, being practically undetectable [1]. Theories beyond the SM, on the other hand, contain a variety of new CP violating phases allowing for EDM to acquire values within the experimental reach [2]. Thus, an experimental search for EDM should constitute a crucial test discriminating between the SM and theories beyond it. An EDM of diamagnetic atom such as $^{199}$Hg and $^{129}$Xe is considered to stem from $P, T$-violating components of nucleon-nucleon interaction, and poses on theoretical models a constraint which is different from those from EDMs of neutron and paramagnetic atoms [3, 4]. The latest experimental upper limits for EDMs of neutron [5], $^{129}$Xe atom [6], and $^{199}$Hg atom [7] are, $|d_n| < 2.6 \times 10^{-26}$ ecm, $|d(129\text{Xe})| < 4.0 \times 10^{-27}$ ecm, and $|d(199\text{Hg})| < 3.1 \times 10^{-29}$ ecm, respectively. So far, the experimental $d(199\text{Hg})$ poses the most stringent constraint on the theories. However, the $^{129}$Xe atomic EDM has a potential of significantly improving the experimental limit by a means of nuclear spin maser technique.

The EDM $d$ is deduced from a frequency shift observed upon the reversal of the electric field $E_0$ relative to the magnetic field $B_0$, namely

$$d = \frac{h (\nu_+ - \nu_-)}{4E_0},$$

where $\nu_+$ ($\nu_-$) represents the frequency of $^{129}$Xe spin precession measured with $E_0$ parallel (antiparallel) to $B_0$. For example, for $E_0 = 10$ kV/cm, an EDM of a size $|d| = 10^{-29}$ ecm gives
a frequency shift as small as $\Delta \nu = \nu_+ - \nu_- = 10^{-10}$ Hz. Thus, high precision of frequency determination, and hence long measurement time of the spin precession, is essential for EDM searches. We are now developing a nuclear spin maser which is a mechanism to sustain the nuclear spin precession for unlimitedly long duration and thereby realize long measurement times [8].

The principle of the spin maser is summarized as follows. The nuclear spin precession is optically detected by using a probe laser light. A feedback field is generated according to the detected signal, with its phase arranged such that the feedback field is always orthogonal to the transverse component of the spin polarization vector. The feedback field is applied with a coil wound around a Xe containing cell. The detection sensitivity for spin precession using probe light is higher than that with a pick-up coil, and consequently the present spin maser can operate even at considerably low static fields. In this way, the absolute size of field fluctuation become smaller and consequently the fluctuation in the precession frequency is substantially suppressed. At present, the spin maser is operated under $B_0 = 30.6$ mG, and the frequency precision of 9.3 nHz has been obtained [9]. Detailed studies of maser operation have revealed that the main factors limiting the present frequency precision are drifts in the solenoid current for the static field and the temperature of the Xe cell [10].

2. Correlation between the maser frequency and amplitude
The frequency property of the spin maser was studied with the currently operating spin maser, in which we recently introduced a fiber-coupled high-power laser, in place of the previous array type laser, as an optical pumping light source for Rb polarization. The maser oscillation amplitude was deduced from two output signals $V_x$ and $V_y$ of a lock-in amplifier. A significant correlation between the maser frequency and amplitude (the correlation coefficient $r = 0.826$) was observed, as shown as Fig. 1. The maser amplitude $V = \sqrt{V_x^2 + V_y^2}$ is proportional to the transverse component of the spin polarization vector. It is noted that the amplitude $V$ is the quantity that determines the feedback strength, and hence should critically influence the behavior of the maser operation. One of the origins of the amplitude drift would therefore be the fluctuation in Xe nuclear polarization, which in turn may be caused by insufficient power of the optical pumping. Scattering of the incident pumping light at the surface of the spherical Xe gas cell may also deteriorate the pumping efficiency. We are now preparing a cubic glass cell to reduce
scattering of the pumping light, and a high power laser with reduced linewidth is also being installed.

3. Construction of high voltage application system
A high voltage system to apply an electric field $E$ to the Xe cell is under development. The setup for the measurement of leakage current between the electrodes is shown in Fig. 2 (a). The electrode is a layer of indium tin oxide (ITO) whose transmittance is measured to be about 85% at a wavelength of the Rb D1 line. A size of electrode is $30 \text{ mm} \times 30 \text{ mm} \times 1.75 \text{ mm}$. Since the gas cell needs to be irradiated by the pumping light to polarize the $^{129}$Xe nuclear spins for the maser operation, we employ ITO as the transparent material for electrodes. The electrodes are attached to a cubic cell made of Pyrex glass whose size is $20 \text{ mm} \times 20 \text{ mm} \times 20 \text{ mm}$. The cubic cell contains air (instead of Xe gas and Rb vapor). The leakage current across the cubic cell was measured with a picoammeter. The picoammeter was protected against sudden sparks by inserting a low-pass filter.

In Fig. 2 (b), the leakage current measured with the electrodes covered with insulator rubbers is shown by triangle dots. The current with the electrodes not covered is indicated by circular dots. A typical leakage current with the electrodes covered with insulator rubbers was about 6.4 nA at a high voltage of 10 kV. An abrupt jump of the leakage current was observed at around 15 kV, using the bare electrodes. This sudden jump was suppressed by covering the electrodes with the insulator rubbers. This phenomenon suggests that a discharge might occur between the electrodes when the high voltage beyond 15 kV is applied and the insulator covering the electrodes may help in suppressing the discharge. We are now producing Xe and Rb containing cells with the transparent electrodes.

4. Summary and future
We studied the frequency behavior of the spin maser with recently introduced fiber-coupled laser as a pumping laser, and found that the observed frequency drift is significantly correlated with the amplitude drift. In order to improve the optical pumping efficiency, the cubic cell and a high power laser with reduced linewidth are being introduced. Also, an electric field application system was constructed. The leakage current was about 6.4 nA, when the high voltage of 10
kV was applied. Cells containing Xe gas and Rb vapor and with transparent electrodes are now being produced.

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