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DEVELOPMENT OF ATOMIC MAGNETOMETER SYSTEM APPROACHING TO THE SPIN EXCHANGE RELAXATION FREE REGIME

Hyun Joon Lee[1,2], *Kiwoong Kim*[2*], *Seong-Joo Lee*[2], *Chan-Seok Kang*[2], *Kwon Kyu Yu*[2], *Yong-Ho Lee*[2], *and Han Seb Moon*[1]

[1]Pusan National University, Korea
[2] Korea Research Institute of Standards and Science (KRISS), Korea, *kwkim@kriss.re.kr

Abstract: We describe a potassium atomic magnetometer based on the spin exchange relaxation free regime. The optical rotation signal was optimized under the condition of temperature of 200 ^{o}C and width was about 0.15 mG when the pump laser power was 55 mW. Signal-to-noise measurements yield a sensitivity of 120 fT/Hz$^{1/2}$ at 10 Hz.

Keywords: magneto-optical rotation, SERF regime, atomic magnetometer.

1. INTRODUCTION

Atomic coherence between ground states generated by the interaction of laser with atoms have been applied to interesting topics such as an atomic magnetometer, frequency standards, light storage, quantum memory, and quantum cryptography [1-10]. Detection of a magnetic field with an atomic magnetometer is performed by monitoring the spin precession due to the external field as observing the optical rotation signal. The principal mechanism of an atomic magnetometer can be described by Faraday rotation classically. Magneto-optical rotation is an optical effect that makes the polarization plane of linearly-polarized light rotated during its propagation through a medium placed in the magnetic field. When the magnetic field is applied along the light propagation direction, we can see this magneto-optical rotation, known as the Faraday's effect. The linearly-polarized light can be decomposed into left (σ^-) and right (σ^+) circularly-polarized lights. In the presence of a longitudinal magnetic field, the Zeeman sublevels are shifted and two circular polarized light beams are resonant on the transitions with different resonance frequencies, satisfying the selection rules. The Zeeman spitting leads the different dispersion of two circularly-polarized components of the linearly-polarized light. Consequently, the phase difference between two components drives the rotation of its polarization plane [8]. By using this phenomenon, Budker group has achieved the NMOE signal with effective resonance width of $\gamma \approx 2\pi$ x1.3 Hz [9].

In recent reports, the most sensitive atomic magnetometers are the spin exchange relaxation free (SERF) magnetometer. In the SERF regime, relaxation due to spin-exchange collisions is eliminated where the spin exchange rate is much greater than the rate of Larmor precession. In Ref. [10] with SERF magnetometer, operating potassium (K) vapour cell at 190 ^{o}C, sensitivity of 0.54 fT/Hz$^{1/2}$ was achieved.

In this paper, we demonstrate the operation of a K magnetometer approaching to the SERF regime. The achieved sensitivity based on optical rotation measurements were about 120 fT/Hz$^{1/2}$ in the experiment. This value is almost two orders worse than Ref. [10]. This is because the residual fields in the magnetic shields is too strong to reach the SERF regime. In the SERF regime rate of Larmor precession depends on the absolute DC magnetic fields, and our condition may not satisfy the SERF conditions. The optical rotation spectra were estimated in the D_1 line of K atoms with light sources for an orthogonal pumping and probing light beams as a function of the wavelength of the probe laser and the intensity of the pump laser.

2. EXPERIMENTAL SETUP

In order to investigate the optical rotation under SERF regime in the D1 line of K atomic vapour, the experimental apparatus shown as Fig. 1 is needed .

Experiment was performed with a glass cell containing K vapour, 600-Torr He buffer gas to reduce the rate that atom in the cell diffuse to the wall of cell, and 15-Torr N_2 to

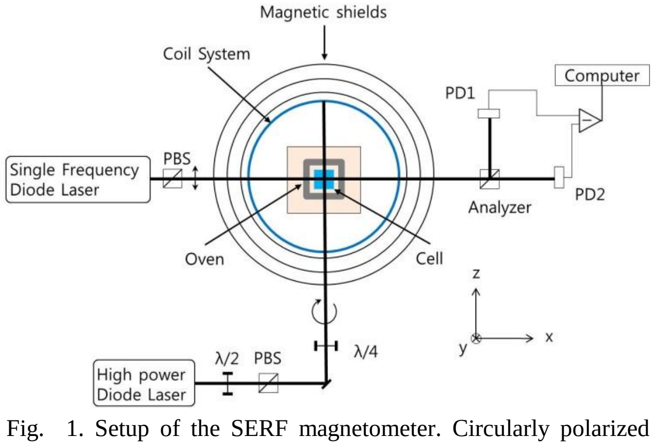

Fig. 1. Setup of the SERF magnetometer. Circularly polarized light tuned to the D1 line, propagating in the *z*-direction produces ground state orientation in the *z*-direction. Optical rotation of the probe beam is detected using a polarimetric method (PBS: Polarizing beam splitter, PD: Photo diode).

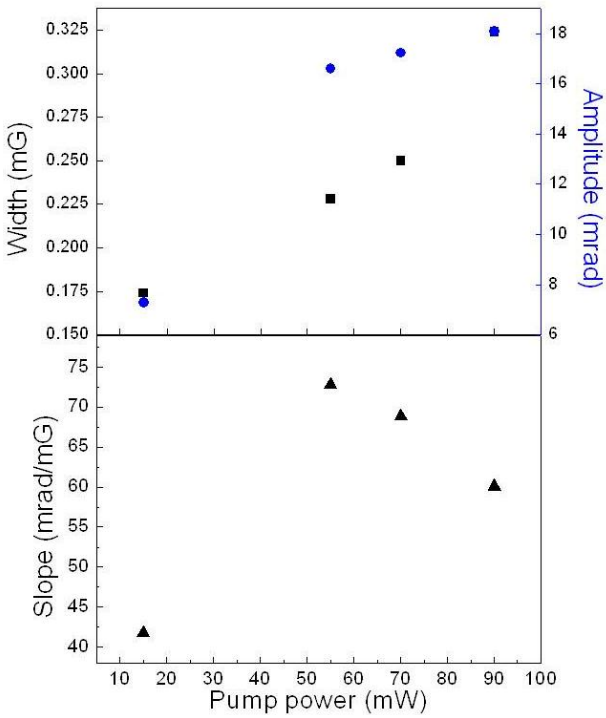

Fig. 2. Half width at half maximum and peak-to-peak amplitude of the observed in the zero-field resonance, as a function of the pump power.

improve optical pumping by quenching. The cell is placed inside a three-layer set of mu-metal chamber. The cell is roughly cubic about 1 inch on a side. The cell was heated to 200 °C by ohmic heater using modulated current source of the frequency of 25 kHz. The saturated K vapour is about $1.4x10^{15}$ cm^{-3}. The ohmic heater is insulated by the insulation panel.

The coil system in Fig. 1 is consisted of 16 square coils and Helmholtz coil, which eliminate the residual field or generate arbitrary homogeneous fields and gradient fields. When a magnetic field is applied to the K vapor cell perpendicular to pump light propagation, SERF condition is satisfied at near the zero magnetic field.

The laser used in our experiment is the distributed feedback (DFB) laser. Optical pumping was accomplished by circularly polarized laser light propagating in the *z*-direction tuned to the center of the K D1 line exactly by monitoring the shape of the signal. The pump beam was amplified from 15 mW to 150 mW by a tapered amplifier. The wavelength of the pump laser was monitored by wavemeter and stabilized on the K D1 line. To prevent the optical feedback we used an optical isolator. We adjust the laser power by using a polarization beam splitter (PBS) and a half wave plate (HWP). The linearly-polarized probe beam, propagating in the *x*-direction, was detuned from K D1 line about several nanometers. The probe beam was generated by a single mode DFB laser and monitored by a Fabry-Perot interferometer. After passing through the HWP and K vapor cell, the laser beam goes through an analyzer which divides the laser beam into same amplitude. The difference of signal between photodiode PD1 and PD2 is measured. The vapour cell is inside a three layer μ-metal shield that can minimize the effects of the external magnetic field including the Earth's magnetic field.

3. EXPERIMENTAL RESULTS

The sensitivity of the magnetometer to magnetic fields depends on the signal-to-noise ratio (S/N) of the Zeeman resonance signal and on the linewidth of the resonance. It can be written mathematically by $\delta B = \frac{\Delta B}{(S/N)}$, where ΔB is the linewidth of the magnetic resonance [11], simply the slope of the optical rotation signal.

To optimize the magnetometer we observed peak-to-peak amplitude and width of the optical rotation signal in the near zero field resonance for pump power from 15 mW to 90 mW shown in Fig. 2. The width is linearly increased, while the amplitude of the signal appears saturated roughly. In this case the slope $(\partial\varphi/\partial B)$ is maximum at 55 mW. Mentioned above the slopes near the resonance provide the relative intrinsic sensitivity of magnetometer, the system is most sensitive when pump power is 55 mW. The dispersive curve shown in Fig. 3 is a typical optical rotation signal as a function of magnetic field obtained in the atomic system. The spectral width is about 0.2 mG when the pump beam power is 55 mW.

To investigate the effects of residual fields in *y*-direction in mu-metal chamber we applied a bias magnetic field in the *y*-direction. Fig. 4 shows the optical rotation signals for several different values of the bias magnetic field. The signal response related to change of magnetic field in y direction is influenced by the magnetic field in *z*-direction. In Fig. 4, the signal was asymmetrically varying according to the magnetic field strength. As magnetic field continues to increase, the peak-to-peak amplitude of signal decreased. At the negative magnetic field region change of signal is remarkable. This result means that there is negative detuned magnetic field in the *z*-direction. The other word, spin precession transients cannot decay completely before a measurement of signal is made.

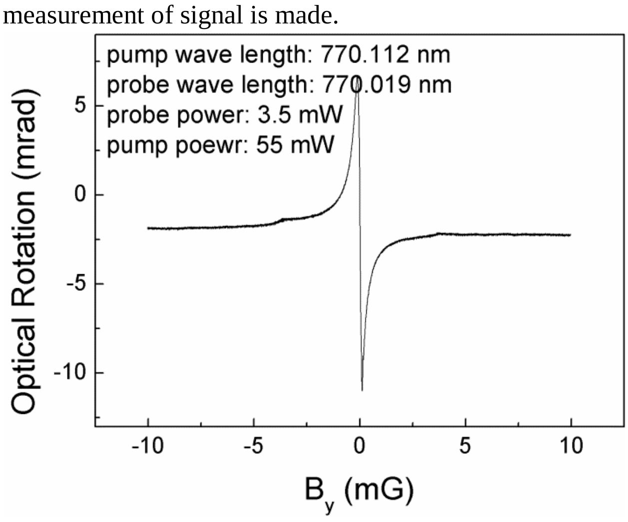

Fig. 3. The dispersion curve obtained from atomic magnetometer in a magnetically shielded environment with a linewidth of 0.15 mG.

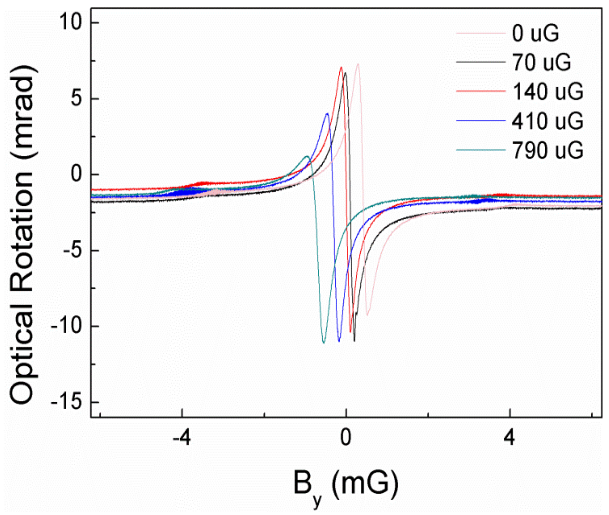

Fig. 4. Magneto-optical rotation signals for the magnetic fields in y direction.

We evaluate the performance of the magnetometer by monitoring the noise level at the output of the balanced polarimeter using a spectrum analyzer. To calibrate the magnetometer, we apply a small oscillating field of 7.7 Hz. The resulting spectrum is shown in Fig. 5. For the data, the powers of the pump and the probe lights were 55 mW and 3 mW, repectively, and the y-component ofthe magnetic field have been zeroed. The sensitivity was about 120 fT/Hz$^{1/2}$ at 10 Hz.

4. CONCLUSION

In conclusion, we demonstrated a K atomic magnetometer approaching to the spin exchange relaxation free regime. At 200 ^{o}C, we obtained magneto-optical rotation features with a linewidth of 0.15 mG. We achieved a sensitivity of 120 fT/Hz$^{1/2}$ at 10 Hz. We suppose that the demonstrated sensitivity was limited by a residual field in the magnetic shield mainly and the pump laser noise. It is expected that the atomic magnetometer can be applied to the MCG and MEG detector.

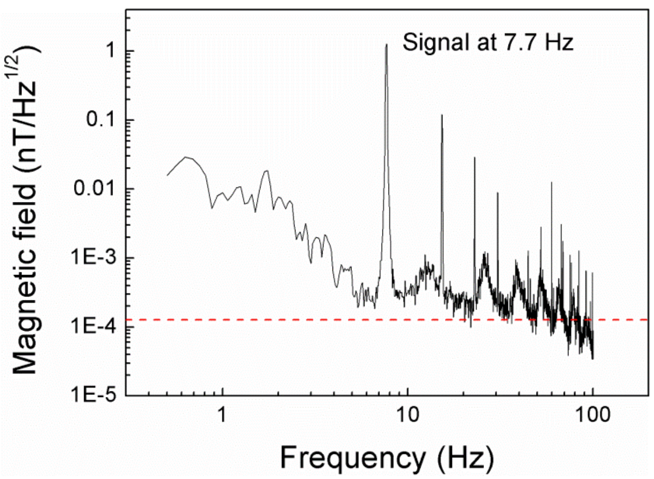

Fig. 5. The spectrum of the magnetic noise in the atomic magnetometer system approaching to the SERF regime. The driven modulation of the magnetic field to the *y*-direction at 7.7 Hz.

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