Scalar Potassium Magnetometer Based On Amplitude Modulated Nonlinear Magneto-Optical Rotation

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***Abstract*—In this work, a scalar potassium magnetometer based on amplitude modulated nonlinear magneto-optical rotation (AM NMOR) is experimentally built and reaches noise level of 30 fT/$\sqrt{\text{Hz}}$ under a low-noise bias magnetic field. Our potassium magnetometer could be applied to a large earth's magnetic field, where the performance of cesium magnetometer is limited by nonlinear Zeeman effect (NLZ). A group of totally separated magnetic-resonance lines are got and each line has a FWHW (full width half maximum) of ~10 Hz , which is 10-times narrower than cesium's magnetic-resonance linewidth in the same case. The noise-level of 130 fT/$\sqrt{\text{Hz}}$ is achieved under bias magnetic field of 100000 nT, which is mainly due to ambient magnetic-field noise.**

Keywords—Potassium; AM-NMOR; nonlinear-Zeeman effect

I. INTRODUCTION

Optically-pumped magnetometers (OPMs) with alkali-metal atoms could measure magnetic field with ultra-high sensitivity and have found its applications in wide range of field. Such as fundamental-physics research [1], geophysical exploration, and detection of bio-magnetic field [2].

Alkali-metal OPMs based on nonlinear magneto-optical rotation (NMOR) with modulated laser light have advantages of both great sensitivity and large dynamic range [3]. However, the performance within the measuring range is affected by the nonlinear Zeeman effect (i.e., the broadening and splitting of the magnetic-resonance lines, as well as line-shape asymmetries, decreases the performance of alkali-metal OPMs). Among different alkali-metal species, potassium has the largest quadratic shift of the magnetic sublevels, for which the neighboring resonances do not overlap [4]. The potassium OPMs is suitable for working in a large earth's magnetic field using single magnetic-resonance line.

Here we experimentally build a potassium magnetometer based on AM-NMOR. The noise level of 30 fT/$\sqrt{\text{Hz}}$ is achieved under a low-noise bias magnetic field. we also demonstrated that potassium magnetometer based on single magnetic-resonance line could work normally under large earth's magnetic field.

II. METHODS/RESULTS

Fig. 1 shows the experimental scheme of our potassium magnetometer based on AM NMOR. Two-beam structure is employed in our system. The pump laser is generated with a potassium D1 (770 nm) laser and tuned to F = 1 → F' = 2 transition. The laser beam is circularly polarized and be modulated by adjusting the modulation level of the AOM (acousto-optic modulator). Probe light is linearly polarized and detuned from potassium D2 line (766 nm) We use a Dichroic Atomic Vapor Laser Lock (DAVLL) scheme to lock the frequency of the pump beam.

A cylindrical potassium paraffin-coated cell has a diameter of 25 mm and be kept warm up to 48°C. The linearly-polarized probe laser passes through the vapor cell and the polarization-rotate angle is measured with a balanced photo-detector. During the measurement, the pump power is chosen to be 35 μW, while the probe power is 80 μW. The direction of magnetic field is perpendicular to the directions of the pump and the probe laser beam.

To measure the intrinsic sensitivity of our potassium magnetometer, a low-noise magnetic-field generator is employed, through which the magnetic-field noise is measured and actively compensate. More details about the integrated cesium magnetometer and the method of magnetic-field stabilization could be found in [5-6].

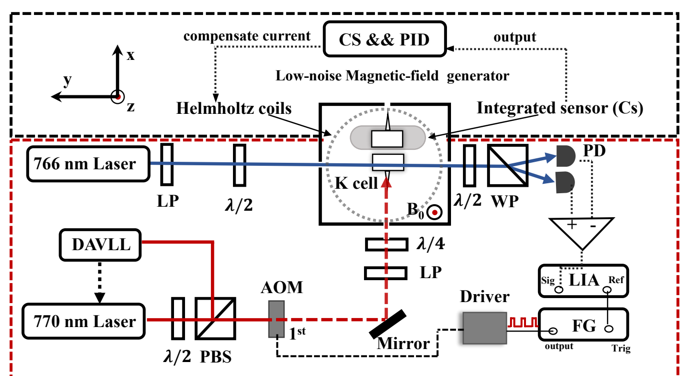

Fig. 1. Experimental scheme of K OPM based on AM-NMOR (bottom) and arrangement of low-noise magnetic-field generator (top). LP: linear polarizer; FG: function generator; LIA: Lock-in amplifier; PD: photo-detector; WP: Wollston prism; CS: voltage-controlled current source.

Fig. 2 shows the power spectral density (PSD) of magnetic-field noise measured with potassium magnetometer under 300 nT ambient magnetic field. There are two main sources of the residual noise. First, while cesium and potassium vapor cell are spatially separated at 3 cm distance, the magnetic-field noise could not be compeletly suppressed due to the magnetic-field

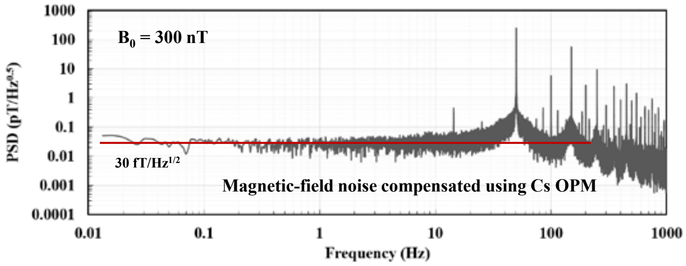

Fig. 2. Spectral density of magnetic-field noise under ambient field of 300 nT . the magnetic-field noise is compensated using Cs magnetometer based on AM-NMOR.

gradient. The second term is the systemic noise of the potassium magnetometer. Different types of noise sources are experimentally measured and calculated, as shown in Table 1.

TABLE I. NOISE SOURCE

Noise source		*Value*	*Method*
a	Light shift (pump, probe)	10 fT	Measure
b	Technical noise	10 fT	Measure
c	Date collection	7 fT	Measure
d	Photon shot noise	0.5 fT	Calculate
f	Spin-projection noise	15 fT	Calculate

The values in Table 1 represent the contribution to the power spectral density at 1 Hz point. (a). Light shift (includes laser power fluctuations and laser frequency fluctuations of both pump and probe light) is measure by actively adding modulation signal in light source and getting light-to-magnetic-field noise conversion factors, then multiply by the actual light-source noise under the normal working state; (b). Polarimetry technical noise is obeserved by switching off the modulated frequency usd for lock-in detection; (c). Data-collected noise is measured by switching off the output of magnetometer; (d) , (f). photon shot noise and spin-projection noise is calculated with actual measured parameters (e.g., atomic vapor density, laser power and transverse relaxation time).

Fig. 3 (c) shows the comparison of magnetic-resonance spectrum of potassium (red) and cesium (black) under ambient magnetic field of 100000 nT. Partially-separated line shape and broadening of the linewidth could be seen in the magnetic-resonance spectrum of cesium atoms. However the magnetic -resonance spectrum of potassium become well separated. A single line has a FWHM (full width half maximum) of about 10 Hz , which could be 10-times narrower than cesium's magnetic-resonance linewidth in the same case. The noise level of potassium magnetometer reaches noise floor of 130 $\mathrm{fT}/\sqrt{\mathrm{Hz}}$ under bias field of 100000 nT, which is larger than result shows in Fig. 2. The difference mainly comes from magnetic-field noise instead of systemic noise sources that listed in Table 1.

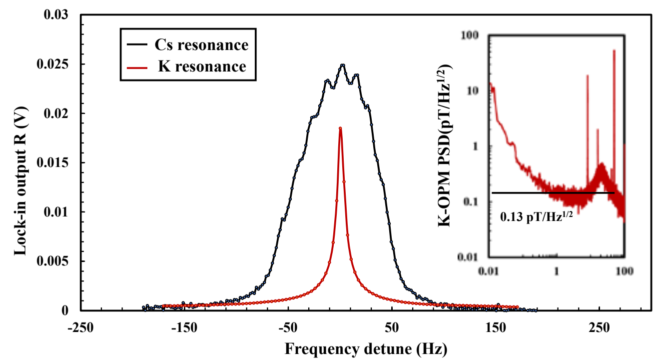

Fig. 3 Magnetic-resonance spectrum of Cs (black line) and K (red line) under ambient magnetic field of 100000 nT. The paraffin-coated Cs vapor cell and K vapor cell has same size and similar intrinsic spin-relaxation properties. The magnetic-resonance spectrum and power spectral density of magnetic-field noise is achieved in an unshielded environment..

III. CONCLUSIONS

In this work, a sensitive scalar potassium magnetometer based on nonlinear magneto-optical rotation with amplitude modulation light is demonstrated and reaches noise floor of 30 $\mathrm{fT}/\sqrt{\mathrm{Hz}}$ within a magnetic shield where a low-noise bias magnetic field is generated using active magnetic compensation. Different types of systemic noise sources are experimentally measured and calculated, which could guide for further improvement of the noise level. Potassium magnetometer based on single magnetic-resonance line could work normally under large earth's magnetic field where cesium magnetometers suffers from NLZ. An extension of this work would further study the overall performance of potassium magnetometer in large dynamic range of earth's magnetic field and realize gauss-range active magnetic-field stabilization.

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