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Development of an optically pumped atomic magnetometer using a K-Rb hybrid cell and its application to magnetocardiography

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We have developed an optically pumped atomic magnetometer using a hybrid cell of K and Rb. The hybrid optical pumping technique can apply dense alkali-metal vapor to the sensor head and leads to high signal intensity. We use dense Rb vapor as probed atoms, and achieve a sensitivity of approximately 100 $fT_{rms}/Hz^{1/2}$ around 10 Hz. In this case, the sensitivity is limited by the system noise, and the magnetic linewidth is narrower than that for direct Rb optical pumping. We demonstrated magnetocardiography using the magnetometer and obtained clear human magnetocardiograms.
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Recently, optically pumped atomic magnetometers have become attractive as highly sensitive magnetometers for biomagnetic measurements such as magnetocardiography (MCG),[1–4] magnetoencephalography (MEG),[5,6] and magnetic resonance imaging (MRI).[7,8] Superconducting quantum interference devices (SQUIDs) have been used to measure biomagnetic fields so far. However, they cost a great deal to maintain the systems because cryogenic cooling such as liquid helium is required. In contrast, the atomic magnetometers work without any cooling systems, so that it is easy to be downsized and low-cost. Furthermore, the atomic magnetometers are theoretically expected to achieve sensitivities of up to approximately 0.01 $fT/Hz^{1/2}$ under spin exchange relaxation free (SERF) conditions.[9–11] The magnetometers use spin-polarized alkali-metal atoms as a sensor. Although dense alkali-metal vapor causes high signal intensity, which leads to high sensitivity, it is difficult to achieve homogeneous spin polarization throughout the whole sensor cell with dense alkali-metal atoms.

To address this issue, hybrid optical pumping, which has been used for hyperpolarized noble gases,[12,13] has been applied in recent years to dense alkali-metal vapors. We have demonstrated an optically pumped atomic magnetometer using a hybrid cell of K and Rb in 100-Hz resonant operation and obtained a sensitivity of 30 $fT_{rms}/Hz^{1/2}$ around 100 Hz.[14] Romalis has also demonstrated 4.5 times higher spin polarization of K than by direct optical pumping of K.[15] However, for biomagnetic measurements, a magnetometer must achieve high sensitivity in the frequency range below several tens of Hz.

In this study, our developed optically pumped atomic magnetometer using a K-Rb hybrid cell is operated under SERF conditions for biomagnetic measurements. Consequently, we applied the magnetometer to an MCG as an example of a biomagnetic measurement.

Figure 1 shows the schematic of our experimental setup. The glass cell, which contains K and Rb with He and N_2 as buffer gases, works as a sensor cell. The volume in the cell is $30 \times 30 \times 30$ mm^3;

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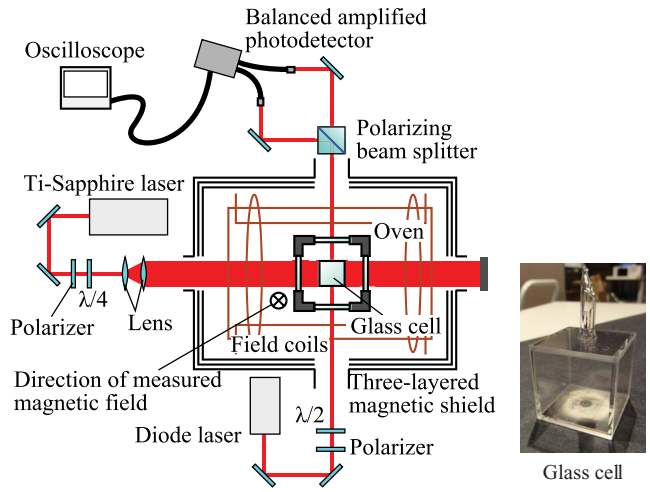

FIG. 1. Schematic of the experimental setup (left) and a photograph of the glass cell with droplet of K and Rb in the branch (right). The pump beam is expanded to the cross-sectional area of the glass cell.

the total inner pressure is 150 kPa at room temperature, and the ratio of He to N_2 is 10 to 1. The glass cell is set in an oven and heated by hot air up to 453 K. To cancel environmental magnetic noise, the oven is surrounded by a three-axis field coil system. A pair of coils in the system is also used to apply a test signal to estimate the noise level of the sensor. The coil system is placed in a three-layered magnetic shield, whose inner size is $173 \times 92 \times 92$ cm^3, with a shielding factor of 10^6 at 10 Hz. One kind of atoms in the cell are spin-polarized by circularly polarized light from a Ti-sapphire laser with a linewidth less than 75 kHz. A diode laser with a linewidth less than 300 kHz is used as a linearly polarized probe beam perpendicular to the pump beam.

The spin polarization of the atoms resulting from the pump beam is transferred to the other kind of atoms by spin exchange collisions, following which that of these atoms is rotated around the measured magnetic field orthogonal to both the pump and probe beams, in accordance with the Bloch equation. We can measure the magnetic field by detecting the Faraday rotation angle θ of the polarization plane of the probe beam. In this situation, θ is given by the following equation:[16]

$$\theta = n r_e c f \frac{\nu_{\text{probe}} - \nu_0}{(\nu_{\text{probe}} - \nu_0)^2 + (\Gamma/2)^2} l S_{\parallel}, \tag{1}$$

where n is the density of alkali-metal atoms, r_e is the classical electron radius, c is the speed of light, f is the oscillator strength, l is the dimension of the cell, ν_{probe} is the frequency of the probe beam, ν_0 is the resonant frequency of the alkali-metal atoms, Γ is the spectral broadening, and $S_{\parallel}$ is the spin-polarization component parallel to the probe beam. We measure θ with a polarimeter consisting of a polarizing beam splitter and a balanced amplified photodetector.

To begin with, we investigated the densities of K and Rb atoms by laser absorption spectroscopy.[17] Because the pressure in our glass cell is higher than atmospheric pressure, the pressure broadening is of several tens of GHz; hence, the Doppler effect of several tens of MHz contributes little to the spectral broadening compared with the pressure broadening. Therefore, we consider only the pressure broadening.

Figure 2 shows the densities of K and Rb measured by laser absorption spectroscopy as a function of temperature. We measured the densities around the D1 transition wavelength of K (770.11 nm) and the D2 transition wavelength of Rb (780.24 nm), because of the limitation of the laser. For comparison, we also display the saturated vapor pressure curves of pure K and pure Rb. As for Rb, the experimental values agree well with the saturated vapor pressure curve below 400 K. Above 400 K, the density of Rb exhibits slightly negative deviations from the saturated vapor

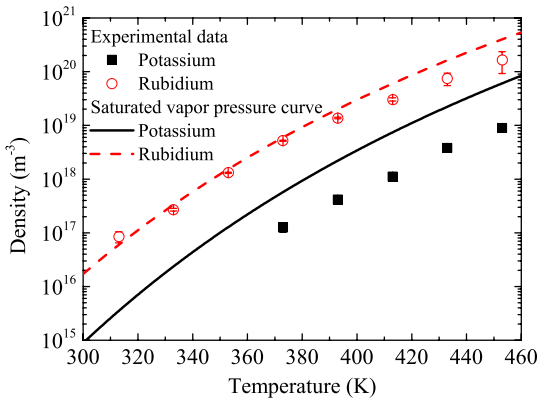

FIG. 2. Densities of K and Rb as a function of vapor temperature. Dots show the densitiy measured by laser absorption spectroscopy whereas lines show densities evaluated by the saturated vapor pressure curve.

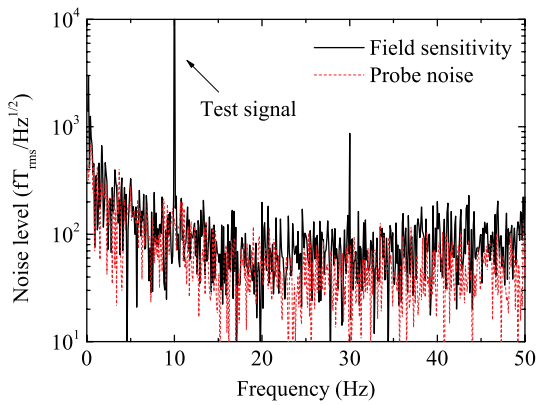

FIG. 3. Noise level as a function of frequency of the measured magnetic field at a pump-beam power density of 21.5 mW/cm^2. A 10 Hz sinusoidal magnetic field was applied as a test signal.

pressure curve. On the other hand, the density of K is below the saturated vapor pressure curve at all temperatures.

At 453 K, which is nearly the limit of our system, the densities of K and Rb were approximately 1×10^{19} m^{-3} and $(1.6 \pm 0.7) \times 10^{20}$ m^{-3}, respectively. These values are approximately 10 times less than those obtained from the saturated vapor pressure curves. Therefore, in our cell, the density of Rb was 10 to 20 times higher than that of K. In general, K exhibits a lower spin-destruction cross section than that of Rb; that is, probing K to measure magnetic fields is expected to be more sensitive than probing Rb. However, in this study, we use Rb as probed atoms because the signal response depends on the Faraday rotation angle of the probe beam, which is proportional to the probed-atom density, as shown in Eq. (1).

Secondly, we measured the noise level of the magnetometer using the hybrid cell of optically pumped K and probed Rb atoms. The wavelength and power density of the pump beam were 770.11 nm and 21.5 mW/cm^2, respectively. The wavelength of the probe beam was 794.38 nm, which was slightly detuned from the D1 resonant frequency of Rb, and the power of the probe beam was 2.5 mW with a diameter of 2 mm. We applied a 10 Hz sinusoidal magnetic field of 96 pT$_{pp}$ as the test signal.

The noise level corrected by the frequency characteristics is shown in Fig. 3. In general, optically pumped atomic magnetometers have frequency characteristics versus magnetic fields.[18] Even in this case, we should consider the frequency characteristics, and the magnetic linewidth was approximately 10 Hz. This value is about 80 times smaller than the calculated linewidth[10, 18] when

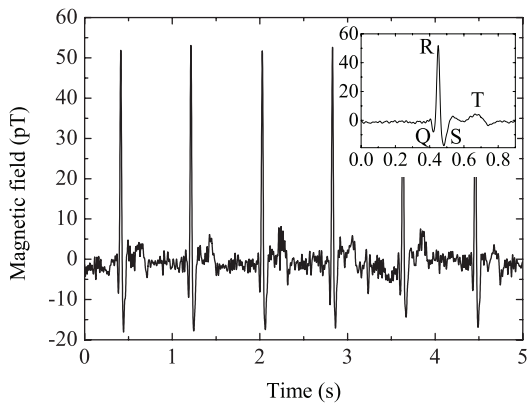

FIG. 4. Magnetocardiogram measured with our system. The subject was a 23-year-old healthy male and the sampling frequency was 1 kHz. The inset shows the 13-time averaged waveform of the magnetocardiogram.

Rb atoms are directly pumped. This fact indicates that the K-Rb hybrid cell suppresses the spin relaxation by the pump beam because of the different resonant frequencies of K and Rb.

The optically pumped atomic magnetometer has noise level around 100 $fT_{rms}/Hz^{1/2}$ between several Hz and several tens of Hz. The noise level is similar to the probe noise, which was measured when the pump beam was off. That is, in our system, the sensitivity of the magnetometer is limited not by magnetic noise but by the system noise. Dang *et al.* achieved magnetic field sensitivity 0.16 $fT/Hz^{1/2}$ at 40 Hz using a pure K cell at 473 K.[19] Their magnetometer was much more sensitive than ours. This is thought to be due to probing dense K atoms. Furthermore, in their case, gradiometric measurements could improve the sensitivity because it was limited by magnetic noise. Therefore, if we can reduce the system noise, the sensitivity may be much more improved.

Consequently, we performed MCG measurements with the magnetometer. The subject was a 23-year-old healthy male. We installed a wooden bed whose height was the same as the oven in the magnetic shield. The subject lay facedown on the bed and the distance between the sensing volume and the subject was about 4.5 cm. We measured the MCG over a 10 s period with a sampling frequency of 1 kHz.

Figure 4 shows a part of the MCG measured with our system. The inset illustrates its 13-time averaged waveform. The experimental data were corrected by the frequency characteristics of the magnetometer and then filtered by a 0.5 to 50 Hz bandpass filter to remove the 60 Hz noise from the utility power. The experimental data show typical features of a magnetocardiogram, such as regular heart beats and the QRS complex as well as the T wave. These features are similar to the magnetocardiogram obtained with an optically pumped Cs atomic magnetometer,[1–3] a chip-scale atomic magnetometer[4] and a SQUID.[4,20] Therefore, we demonstrated human cardiomagnetic fields with a magnetometer that uses a hybrid cell of K and Rb.

In conclusion, we developed an optically pumped atomic magnetometer that uses a hybrid cell of K and Rb and achieved a sensitivity of 100 $fT_{rms}/Hz^{1/2}$. Thus, the sensitivity is now limited by the system noise. We then used the magnetometer to acquire MCG, although the sensitivity is not sufficient to perform MEG.

We plan to demonstrate MEG with the magnetometer in the near future. This will be possible if the sensitivity can be improved by suppressing the system noise. To suppress the system noise, vacuum cells could be used as light paths to suppress air noise, and lock-in detection may further reduce the noise. The use of these techniques should enable MEG measurements with the magnetometer.

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