Low-noise magnetometer based on inductance modulation in high-critical-temperature superconductor coil

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We developed a magnetometer based on inductance modulation of a coil made from a high-critical-temperature superconducting material. The coil inductance was modulated over time via a modulation current applied to a magnetic wire that was inserted into the coil. The magnetic field was then converted into a signal voltage using this time-dependent inductance. The relationship between magnetometer performance and the modulation current conditions was studied. Under appropriate conditions, the magnetometer had responsivity of 885 V/T. The magnetic field noise was 1.3 pT/Hz$^{1/2}$ in the white noise region and 5.6 pT/Hz$^{1/2}$ at $f = 1$ Hz. © 2018 The Japan Society of Applied Physics

The induction-type magnetometer (or pickup coil) is widely used to measure signal fields in the presence of an excitation field because other high-sensitivity sensors, such as fluxgate and magnetoresistive sensors, are difficult to operate correctly during exposure to high excitation fields. However, the induction-type magnetometer cannot measure low-frequency signals with high sensitivity because its responsivity degrades with decreasing frequency. As a result, very few magnetometers can perform sensitive measurements of low-frequency signal fields in the presence of the excitation field, with the exception of Nb-based superconducting quantum interference device (SQUID) magnetometers.

To develop a suitable magnetometer for this purpose, we previously proposed a new type of magnetometer based on magnetic flux transfer and modulation using coils that were made from high-critical-temperature superconductor (HTS) materials. Two schemes were used in the development of this magnetometer. The first scheme involved the use of a flux-transfer scheme based on a closed loop that was formed by connecting two HTS coils with very low resistance properties. The closed loop could then transfer the magnetic flux, even at low frequencies of less than 1 Hz. The second scheme involved the development of a readout scheme based on coil inductance modulation over time. Using this time-dependent inductance, the magnetic field can be converted into a signal voltage. Using a prototype of this magnetometer, we successfully confirmed the validity of the proposed operating principle. However, improvement of the performance of this magnetometer was regarded as part of our future work.

In the proposed magnetometer, a magnetic wire is inserted into the coil and allows the coil inductance to be modulated over time by application of a modulation current to the wire. Therefore, the magnetometer performance will be strongly dependent on the modulation current conditions. In this study, therefore, we consider the relationship between the performance of the magnetometer and the modulation current conditions. When appropriate modulation conditions were determined, magnetometer performance showed significant improvement when compared with previous results. The noise level was 1.3 pT/Hz$^{1/2}$ at frequencies above 20 Hz and reached 5.6 pT/Hz$^{1/2}$ at 1 Hz.

Figures 1(a) and 1(b) show a circuit diagram and a photograph of the actual magnetometer, respectively. The magnetometer is composed of two coils: the pickup coil with inductance $L_p$ and the modulation coil with inductance $L_2$. These coils were made from a rare-earth barium copper oxide [(RE)BCO] HTS tape with a width of 2 mm (SuperPower SF2050). The inner and outer diameters of the pickup coil were 15 and 35 mm, respectively. The number of turns and the inductance of the coil were $N_p = 50$ and $L_p = 65$ µH, respectively. The modulation coil was formed using three stacked coils. The inner and outer diameters of each of these coils were 15 and 20 mm, respectively. The total number of turns and the inductance were $N_2 = 60$ and $L_2 = 50$ µH.
respectively. The pickup and modulation coils were soldered together\(^3\) with a connection resistance \(R_c = 27 \mu\Omega\). Note that the value of \(R_c\) is determined by the size of the joint area between the HTS tapes.\(^4\)

When a magnetic flux \(\Phi_s(t)\) is interlinked with the pickup coil, the magnetic flux \(\Phi_2\) that is transferred to coil \(L_2\) is given by\(^2\)

\[
\Phi_2(t) = \frac{L_2}{L_p + L_2} \Phi_s(t),
\]

where we assume that the signal flux frequency \(f_s\) satisfies the condition that \(2\pi f_s \gg \frac{1}{L_p} + \frac{1}{L_2}\). For the values of \(L_p\), \(L_2\), and \(R_c\) presented here, this condition is given by \(f_s \gg 0.04\) Hz.

To modulate \(L_2\), a magnetic wire with thickness of 35 µm and width of 500 µm (Aichi Steel SENCY 120FC20) was inserted into the modulation coil, and a modulation current \(I_B\) was supplied to the wire, as illustrated in Fig. 1(b). In this case, the wire was placed inside a miniature glass Dewar to prevent the wire being cooled by the liquid nitrogen. Note that the two HTS coils were cooled to \(T = 77\) K using liquid nitrogen.

First, we measured the change in \(L_2\) when the DC current \(I_B\) was applied to the magnetic wire; this experiment was performed while the two coils were disconnected. As Fig. 2 shows, \(L_2\) had a slightly complex dependence on \(I_B\) in that it initially increased and subsequently decreased monotonically with increasingly positive \(I_B\).

To cause vary \(L_2\) with time, we applied the modulated current \(I_B(t)\) given by

\[
I_B(t) = I_{DC} + I_{AC} \sin(2\pi f_{m}t),
\]

where \(f_{m}\) is the modulation frequency.

As may be expected from the characteristics shown in Fig. 2, the inductance \(L_2\) then varies with time in the following manner:

\[
L_2(t) = L_0 + \Delta L(t) = L_0(1 + K \sin(2\pi f_{m}t)),
\]

where \(K\) is a parameter that represents the degree of modulation. For example, we obtain \(L_0 = 50\) µH and \(K = 0.04\) from the characteristics in Fig. 2 when \(I_B\) with components of \(I_{DC} = 70\) mA and \(I_{AC} = 35\) mA is applied. Note here that the current \(I_{AC}\) allows the magnetization in the magnetic wire to vibrate around its equilibrium position. This vibration of the magnetization causes modulation of \(L_2\) over time, as in the case of the orthogonal fluxgate sensor.\(^{5-8}\)

The voltage across the terminals P and Q (Fig. 1) is then given by

\[
V_{PQ} = \frac{d\Phi_2}{dt} = \frac{L_2}{L_p + L_2} \frac{d\Phi_s}{dt} + \Phi_s \frac{d}{dt} \left( \frac{L_2}{L_p + L_2} \right).
\]

Note here that the second term yields a voltage when \(L_2\) varies with time. We use this voltage via the time-dependent inductance in the proposed magnetometer.

We previously showed\(^9\) that the second term of Eq. (4) becomes an amplitude-modulated voltage with carrier frequency \(f_{m}\) and has an amplitude that is proportional to \(\Phi_s\). When the voltage \(V_{PQ}\) is detected using a lock-in amplifier with reference frequency \(f_{m}\), the amplifier output, \(V(t)\), is given by

\[
V(t) = \frac{2\pi L_p L_0}{(L_p + L_0)^2} K f_m \Phi_s(t).
\]

We studied the magnetometer’s response when the conditions for modulation current \(I_B\) were changed. In the experiment, a signal flux \(\Phi_s = 110\) pWb at \(f_s = 3\) Hz was applied to the pickup coil using a small signal coil (Fig. 1), where the mutual inductance between the pickup and signal coils was 1.1 µH. Figure 3(a) shows the measured magnetometer response when the modulation frequency \(f_{m}\) given in Eq. (2) was varied; the other values were fixed at \(I_{DC} = 70\) mA, \(I_{AC} = 35\) mA, and \(f_{s} = 3\) Hz.
mA and $I_{AC} = 35$ mA. The vertical axis of Fig. 3(a) represents the field-to-voltage transfer coefficient of the magnetometer, i.e., the responsivity $K_{VB} = V_{f}/B_{f}$. Here, the signal field $B_{f}$ was calculated based on the relation $\Phi_{f} = B_{f}(\pi/4)D_{av}^{2}N_{p}$, where the average diameter $D_{av} = (15 + 35)/2 = 25$ mm and $N_{p} = 50$; as a result, $B_{f} = 4.5$ nT for $\Phi_{f} = 110$ pWb. As the results show, the value of $K_{VB}$ increased almost linearly with increasing $f_{m}$, as would be expected from Eq. (5).

Figure 3(b) shows the dependence of $K_{VB}$ on the amplitude of $I_{AC}$ for fixed values of $I_{DC} = 70$ mA and $f_{m} = 400$ kHz. As the figure shows, the value of $K_{VB}$ increased almost linearly with increasing $I_{AC}$. Therefore, we can obtain a high $K_{VB}$ value by increasing $I_{AC}$ and/or $f_{m}$ of the modulation current $I_{B}$. Specifically, we obtained a value of $K_{VB} = 885$ V/T when $I_{B}$ with values of $I_{DC} = 70$ mA, $I_{AC} = 35$ mA, and $f_{m} = 400$ kHz was applied to the magnetic wire.

Next, we measured the noise properties of the magnetometer. In the experiment, the current $I_{B}$ with $I_{DC} = 70$ mA, $I_{AC} = 35$ mA, and $f_{m} = 400$ kHz was applied to the magnetic wire, and the voltage noise of the magnetometer, denoted by $S_{V}^{1/2}$, was measured. The noise of the preamplifier (NF SA-421F5) was 0.5 nV/Hz$^{1/2}$. The measurements were performed inside a magnetic-shielding box composed of two permalloy layers. Using the value of $K_{VB} = 885$ V/T obtained earlier, the voltage noise $S_{V}^{1/2}$ was then converted into the magnetic field noise given by $S_{B}^{1/2} = S_{V}^{1/2}/K_{VB}$. Figure 4 shows the measured spectrum of $S_{B}^{1/2}$. As shown, $S_{B}^{1/2}$ became almost independent of frequency when $f > 20$ Hz, and we obtained $S_{B}^{1/2} = 1.3$ pT/Hz$^{1/2}$. The value of $S_{B}^{1/2}$ increased with decreasing frequency for values of $f < 20$ Hz, and became $S_{B}^{1/2} = 5.6$ pT/Hz$^{1/2}$ at $f = 1$ Hz. The $S_{B}^{1/2}$ peaks at around 10, 20, and 30 Hz were attributed to environmental noise.

The broken line shown in Fig. 4 represents the noise spectrum that was calculated using

$$S_{B}^{1/2} = \sqrt{S_{BW} + A/f^{2}},$$

where values of $S_{BW}^{1/2} = 1.1$ pT/Hz$^{1/2}$, $A^{1/2} = 5.5$ pT/Hz$^{1/2}$, and $\alpha = 1.2$ were chosen to obtain the best fit between the experimental results and Eq. (6). As indicated in Fig. 4, Eq. (6) explains the experimental results quantitatively, which indicates that the low-frequency noise of the magnetometer was expressed approximately as the $1/f$ noise.

We now discuss the noise when $f > 20$ Hz. Figure 5 shows the noise properties when the value of $I_{AC}$ of the modulation current $I_{B}$ was varied; the other values were fixed at $I_{DC} = 70$ mA and $f_{m} = 400$ kHz. The left vertical axis represents the voltage noise $S_{V}^{1/2}$, while the right vertical axis represents the field noise $S_{B}^{1/2} = S_{V}^{1/2}/K_{VB}$. As shown in the figure, $S_{B}^{1/2}$ decreased with increasing $I_{AC}$ while $S_{V}^{1/2}$ increased with increasing $I_{AC}$. This occurred because $K_{VB}$ increased with increasing $I_{AC}$, as shown in Fig. 3(b). This means that the increase in $S_{B}^{1/2}$ due to the increase in $I_{AC}$ was compensated by the increase in $K_{VB}$, and as a result, $S_{B}^{1/2}$ decreased with increasing $I_{AC}$.

Finally, we note that both the white noise and the low-frequency noise of the magnetometer are related to the dynamic behavior of the magnetization within the magnetic wire. The vibration of the magnetization around its equilibrium position, which is caused by $I_{AC}$, causes not only modulation of the coil inductance $L_{2}$ but also an increase in the noise, in a similar manner to the fluxgate sensor. Therefore, to enable further magnetometer performance improvements, it will be necessary to clarify the dynamic magnetization behavior. For this purpose, we must study the relationship between the modulation conditions and magnetometer performance over much wider modulation parameter ranges; this relationship was only investigated over a limited range of these parameters in this study.

Further performance improvements will also be possible by increasing the responsivity $K_{VB}$. For this purpose, it will be necessary to increase the degree of inductance modulation [i.e., the $K$ value in Eq. (3)] by increasing the magnetic coupling between the modulation coil and the magnetic wire. One possible method would be to use a modulation coil with a smaller diameter.

In summary, we have developed a low-noise magnetometer using HTS coils in combination with an inductance modulation scheme. The magnetic field noise was shown to be 1.3 pT/Hz$^{1/2}$ in the white noise region. The noise became roughly equivalent to $1/f$ noise at lower frequencies below 20 Hz, and reached 5.6 pT/Hz$^{1/2}$ at $f = 1$ Hz. It will be possible to produce further improvements in the performance of this magnetometer by increasing the magnetic coupling between the modulation coil and the magnetic wire. It
will also be necessary to clarify the dynamic magnetization behavior within the wire that is caused by the modulation current.

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