Magnetometer based on transfer and modulation of magnetic flux using high-critical-temperature superconductor coils

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Abstract. We developed a new type of magnetometer to measure low-frequency magnetic fields with an operational principle based on magnetic flux transfer and modulation. This magnetometer consists of three coils: pickup, input and readout coils. The pickup and input coils were made from high-critical-temperature superconductor (HTS) tape and were connected with very low connection resistance to form a closed loop. The magnetic flux that is collected by the pickup coil can be transferred to the input coil even at low frequencies below 1 Hz. The magnetic flux at the input coil is then detected by the readout coil using a readout scheme based on modulation of the mutual inductance $M$ between the input and readout coils. To modulate $M$ over time, a magnetic wire was inserted into the readout coil and a time-varying current was supplied to the wire. Using this time-varying $M$, the magnetic flux is converted into an amplitude-modulated voltage across the readout coil for measurements. A prototype magnetometer was fabricated for demonstration. This magnetometer can operate at low frequencies down to $f = 0.5$ Hz without responsivity degradation. The magnetic field noise levels were 8 and 60 pT/Hz$^{1/2}$ at 50 and 1 Hz, respectively.

1. Introduction
The induction-type magnetometer (or pickup coil) has been widely used to measure signal fields in the presence of an excitation field. This is because other sensitive sensors, such as the flux gate and giant magnetoresistive sensors, are difficult to operate correctly when they are exposed to large excitation fields. However, the main drawback of the induction-type magnetometer is that the device responsivity diminishes considerably at low frequencies because its responsivity is proportional to the frequency of the magnetic field. It is therefore important to develop a magnetometer that can measure signal fields at low frequencies with high sensitivity in the presence of the excitation field.

For this purpose, we proposed a new type of magnetometer [1]. The operation of the proposed magnetometer is based on transfer and modulation of the magnetic flux using coils made from high-critical-temperature superconductor (HTS) materials. Two schemes were used in development of this magnetometer. The first involved use of a flux-transfer scheme that is similar to the scheme used in Nb-based superconducting quantum interference device (SQUID) magnetometers [2]. A closed loop was formed using an HTS tape with very low connection resistance. This closed loop could then transfer the magnetic flux, even at low frequencies below 1 Hz. The second scheme involved development of a new readout scheme based on modulation of the coil inductance. In this case, the magnetic flux collected by the pickup coil is converted into an amplitude-modulated voltage for the readout; this scheme is similar to that of a fluxgate sensor [3], [4]. Using a prototype of this magnetometer, we experimentally confirmed the validity of its operating principle.
There are two possible ways to realize the proposed magnetometer based on transfer and modulation of magnetic flux. In our previous paper, we demonstrated one type of magnetometer, which was based on modulation of the coil’s self-inductance [1]. In this study, we have developed the second type of magnetometer. This magnetometer configuration is composed of three coils: the pickup, input and readout coils. The mutual inductance between the input and readout coils is modulated over time to obtain the readout voltage. First, we describe the operating principle of this magnetometer. Then, we present experimental results from a prototype of the magnetometer. The magnetometer demonstrated operation at low frequencies ranging down to $f = 0.5$ Hz without responsivity degradation. The noise levels of the magnetometer were 8 and 60 pT/Hz$^{1/2}$ at 50 and 1 Hz, respectively.

2. Operating principle of the magnetometer

Figure 1 shows an equivalent circuit for the proposed magnetometer. This magnetometer consists of pickup, input and readout coils. The pickup and input coils are formed from HTS tape and their inductances are denoted by $L_p$ and $L_i$, respectively. The two coils are connected with very low connection resistance $R_c$ to form a closed loop. Using this closed loop, we can transfer the magnetic flux $\Phi_s$ that is collected by the pickup coil to the input coil, even at low frequencies [1]. The magnetic flux that is transferred to the input coil is then detected using the readout coil; the mutual inductance between the input and readout coils is denoted by $M$. A magnetic wire is inserted into the readout coil and a current $I_B$ is supplied to the wire to modulate the value of $M$.

![Figure 1. Equivalent circuit for the proposed magnetometer.](image)

The operating principle of the magnetometer is described as follows. When the magnetic flux $\Phi_s(t)$ interlinks the pickup coil, a current $i(t)$ flows within the closed loop. Here, we consider the case in which the angular frequency $\omega_s$ of the signal flux satisfies the following condition [1].

$$\omega_s(L_p + L_i) >> R_c \cdot (1)$$

In this case, the current $i$ is given by

$$i(t) = \frac{1}{L_p + L_i} \Phi_s(t) \cdot (2)$$
The voltage across the readout coil, $v_s$, is then given by

$$ v_s(t) = \frac{d}{dt} \left( \frac{M}{L_p + L_i} \right) = \frac{M}{L_p + L_i} \frac{d \Phi_s}{dt} + \Phi_s \frac{d}{dt} \left( \frac{M}{L_p + L_i} \right). \quad (3) $$

Note that the first term on the right side of the equation is given by the time-derivative of the signal flux $\Phi_s$, and this term becomes very small at low frequencies. In contrast, the second term yields the voltage $v_s$ if $M$ varies with time. We use the second term in the proposed magnetometer.

The value of $M$ can be varied over time by applying current $I_B$ to the magnetic wire because the effective permeability of the wire is changed by $I_B$ [3], [4]. Here, we consider the case where $I_B$ is given by

$$ I_B(t) = I_{DC} + I_{AC} \sin(\omega_m t) \quad (4) $$

where $\omega_m$ is the modulation frequency.

Under application of $I_B$, the mutual inductance $M$ can be modulated over time as follows.

$$ M(t) = M_0 + \Delta M(t) = M_0 \left[ 1 + K \sin(\omega_m t) \right] \quad (5) $$

where $K$ is a parameter that represents the degree of inductance modulation.

The second term on the right of equation (3) then gives the voltage $v_s$ across the readout coil as

$$ v_s(t) = \frac{M_0}{L_p + L_i} K \omega_m \cos(\omega_m t) \Phi_s(t) \quad (6) $$

where, for simplicity, we tentatively neglect the change in $L_i$ due to $I_B$.

Equation (6) indicates that $v_s$ becomes an amplitude-modulated signal with carrier frequency $\omega_m$ and an amplitude that is proportional to $\Phi_s$. If $v_s$ is detected using a lock-in amplifier with reference frequency $\omega_m$, the amplifier’s output, $v_o(t)$, is given by

$$ v_o(t) = \frac{M_0}{L_p + L_i} K \omega_m \Phi_s(t) \quad (7) $$

Equation (7) shows that the voltage $v_o$ is proportional to $\Phi_s$ but is independent of the frequency of $\Phi_s$. Consequently, we can use the proposed magnetometer to measure magnetic fields at low frequencies without any response degradation. Based on the readout scheme used, we call the proposed magnetometer an inductance modulation scheme (IMS) magnetometer.

3. Experimental

We fabricated a prototype of the IMS magnetometer (figure 2). The pickup coil with inductance $L_p$ and the input coil with inductance $L_i$ were made from a (RE)BCO (rare-earth barium copper oxide) HTS tape (SF2050, SuperPower). The tape is 2 mm wide and the tape was coated with a 2-μm-thick layer of silver. The inner and outer diameters of the pickup coil were 15 mm and 35 mm, respectively. The number of turns and the inductance of this coil were $N_p = 50$ and $L_p = 65 \, \mu$H, respectively. The input coil was made from three stacked coils. The inner and outer diameters of each coil were 15 mm and 20 mm, respectively, and the number of turns in each coil was 15. The total number of turns and the inductance of the input coil were $N_i = 45$ and $L_i = 18 \, \mu$H, respectively. The pickup and input coils were soldered together. The connection resistance was estimated to be $R_c = 27 \, \mu\Omega$, as will be shown later in the paper.

The readout coil was made from Cu wire. The diameter and the length of the coil were 5 mm and 22 mm, respectively. The number of turns and the inductance of the readout coil were $N_d = 400$ and $L_d = 1.17 \, \text{mH}$, respectively. A commercial amorphous magnetic wire with thickness of 35 μm and width
of 500 µm (SENCY 120FC20, Aichi Steel) was inserted into the readout coil. The readout coil and the magnetic wire were placed concentrically inside the input coil, as shown in figure 2.

To modulate the mutual inductance $M$ between the input and readout coils, a current $I_B$ was applied to the magnetic wire. Figure 3 shows the experimentally measured change in $M$ when DC current $I_B$ was applied to the magnetic wire. The vertical axis represents the fractional change $\Delta M/M_0$ [see equation (5)], where $M_0 = 75$ µH. As shown, $\Delta M/M_0$ had a slightly complex dependence on $I_B$, where it increased and then decreased monotonically with increasingly positive $I_B$. The relative reduction was 27% at $I_B = 118$ mA.

![Figure 2. Photograph of the prototype magnetometer.](image)

![Figure 3. Relative change in inductance ($\Delta M/M_0$) when the DC current $I_B$ is applied to the magnetic wire.](image)

![Figure 4. Frequency response of the magnetometer. The vertical axis represents the output voltage ($V_{out}$) of the lock-in amplifier when normalized with respect to the value at $f_s = 10$ Hz.](image)
To vary $M$ over time in the experiments, we applied the modulated current $I_0(t)$ that was given in equation (4). The experimental values in this case were $I_{DC} = 55$ mA, $I_{AC} = 20$ mA, and $f_m = \omega_m/2\pi = 80$ kHz. In this case, the inductance $M(t)$ varies with time as shown in equation (5); an approximate value of $K = 0.06$ was estimated based on figure 3. Therefore, we obtain the time-varying voltage $v$, that was given in equation (6).

Figure 4 shows the magnetometer’s frequency response when the frequency of the signal flux $\Phi_s$ was varied from $f_s = 0.05$ to 10 Hz while maintaining a fixed amplitude. During the experiment, the magnetometer was cooled to $T = 77$ K using liquid nitrogen. The signal flux $\Phi_s$ was applied to the pickup coil with inductance $L_p$ using a small signal coil: the mutual inductance between the pickup and signal coils was 0.7 $\mu$H. The vertical axis represents the amplitude of the output voltage ($V_{out}$) of the lock-in amplifier when normalized with respect to the value at $f_s = 10$ Hz. Note here that $V_{out}$ was independent of $f_s$ when $f_s > 0.5$ Hz. At frequencies lower than 0.5 Hz, $V_{out}$ decreased with decreasing $f_s$.

Based on the equivalent circuit shown in figure 1, the frequency dependence can be determined as follows.

$$\frac{V_{out}(f)}{V_{out}(10\text{Hz})} = \frac{2\pi \tau}{\sqrt{1+(2\pi \tau)^2}} \quad \text{with} \quad \tau = \frac{L_p + L_i}{R_c} \quad (8)$$

The solid line in figure 4 was calculated using equation (8) with $\tau = 3$ s. By substituting the values $L_p + L_i = 83$ $\mu$H and $\tau = 3$ s into the equation, we find that $R_c = 27$ $\mu$Ω. The $R_c$ value obtained was larger than the previously reported value ($R_c < 6$ $\mu$Ω) [1]. Note that the value of $R_c$ can be reduced by increasing the size of the joint area between the HTS tapes [5].

We measured the noise spectrum of the magnetometer. During the experiments, we first measured the magnetometer’s responsivity using the following method. The output voltage ($V_{out}$) of the lock-in amplifier was measured when the amplitude of signal flux $\Phi_s$ was varied; the signal frequency was set at $f_s = 3$ Hz. The magnetometer output voltage, $V_s$, was then obtained using $V_s = V_{out}/G$, where $G$ is the amplifier gain. The signal field $B_s$ was calculated using the relationship $\Phi_s = B_s(\pi/4)D_{av}^2N_p$, with average diameter $D_{av} = (15+35)/2 = 25$ mm and $N_p = 50$. The $B_s$ vs. $V_s$ curve was obtained when $B_s$ ranging from nT to $\mu$T was applied. In this field range, the magnetometer showed linear response, and the field-to-voltage transfer coefficient of the magnetometer was obtained from the slope of the $B_s$ vs. $V_s$ curve as $V_s/B_s = 990$ V/T. Note that the measured value showed reasonable agreement with the transfer coefficient that was calculated using equation (7); the calculated value was 924 V/T.

The noise in the magnetometer voltage signal, which is denoted by $S_n^{1/2}$, was measured inside a magnetic shielding box composed of two layers of permalloy. A signal field with frequency $f_s = 3$ Hz was also applied as a reference. Using the field-to-voltage transfer coefficient of $V_s/B_s = 990$ V/T, the voltage noise $S_n^{1/2}$ was converted into the magnetic field noise $S_B^{1/2}$. Figure 5 shows the measured spectrum of the field noise $S_B^{1/2}$; the peak shown at $f = 3$ Hz corresponds to the signal field. As the spectrum shows, $S_B^{1/2}$ decreased with increasing frequency $f$. We obtained values of $S_B^{1/2} = 8$, 18 and 60 pT/Hz$^{1/2}$ at $f = 50$, 10 and 1 Hz, respectively.

The broken line in figure 5 is used to indicate the frequency dependence of the 1/f noise. As the spectrum shows, the measured noise displayed clear 1/f noise, although the origin remains unclear at present. It is therefore necessary to reduce this 1/f noise to greatly enhance the magnetometer’s performance. For this purpose, it would be useful to develop a gradiometer because the existing magnetometer is affected quite considerably by environmental noise. While we did use the magnetic shielding box that consisted of two layers of permalloy, the environmental noise was not suppressed to a sufficient degree. It will also be necessary to determine the optimum conditions for the modulation current $I_B$ that is supplied to the magnetic wire. This is essential because the noise generated by the magnetic wire is affected significantly by the bias condition of $I_B$, as previously demonstrated in the fluxgate sensor case [4], [6]-[8].
Figure 5. Magnetic field noise spectrum of the magnetometer, where the peak at $f = 3$ Hz represents the signal field. We obtained values of $S_B^{1/2} = 8, 18$ and $60$ pT/Hz$^{1/2}$ at $f = 50, 10$ and $1$ Hz, respectively. The broken line indicates the frequency dependence of the $1/f$ noise.

4. Conclusion
We have developed a new type of magnetometer based on transfer and modulation of magnetic flux using HTS coils. The magnetometer is expected to be able to measure signal fields at low frequencies with high sensitivity in the presence of large excitation fields. The prototype magnetometer operated at frequencies as low as $f = 0.5$ Hz without degradation of its responsivity. The magnetic field noise of the magnetometer was measured to be $8$ and $60$ pT/Hz$^{1/2}$ at $50$ and $1$ Hz, respectively. Because this noise was dominated by the $1/f$ noise, further work will be required to reduce the $1/f$ noise. It is also necessary to show operation of the magnetometer in the presence of large excitation fields.

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