PAPER

HTS-SQUID vector magnetometer with low crosstalk configuration

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Abstract
We propose an HTS-SQUID vector magnetometer with a new configuration reducing the crosstalk between a pickup coil of one SQUID and feedback coils of other SQUIDs. The new configuration is designed to mount three SQUIDs at symmetric positions where the crosstalk should be ideally zero while keeping minimal height of a probe head. In an actual HTS-SQUID magnetometer, however, either pickup coil or feedback coil is inevitably dislocated from the ideal symmetric positions. Numerical simulation of crosstalk revealed that the new configuration has smaller crosstalk than that of a conventional cubic configuration even if the positioning error from the ideal symmetric positions is as small as 1 mm. Three types of SQUID vector magnetometer were fabricated and their crosstalk was measured. The averaged crosstalk of an SQUID vector magnetometer using the new configuration was actually improved by about one order of magnitude as compared with the conventional cubic configuration.

1. Introduction

Superconducting quantum interference device (SQUID) is utilized as a magnetic sensor with the highest sensitivity. Since the SQUID loop or SQUID inductor has a dimension of several tenth micrometers, a pickup coil with dimensions from several millimeters to several tenth millimeters is usually magnetically coupled with the SQUID inductor to increase field sensitivity. A weak magnetic field normal to the pickup coil plane can be detected and a vector magnetometer is constructed using three orthogonally arranged magnetometers. SQUID vector magnetometers are used in various application such as geomagnetic survey [1-3].

SQUID exhibits nonlinear periodic V-Φ characteristics where V is the voltage across the SQUID and Φ is the applied flux. The period of V-Φ characteristics is equal to one flux quantum Φ0 (2.07 × 10−15 Wb). Usually, a SQUID magnetic sensor has to be operated in a flux-locked feedback loop to linearize the response of the SQUID to applied flux. Therefore, each SQUID sensor has a feedback coil which generates a cancelling field to keep the flux in the SQUID loop constant by a negative feedback.

In the case of low-temperature superconductor SQUID (LTS-SQUID), since, a relatively small feedback coil is effectively coupled with a SQUID inductor by using a multilayer technology, there is no significant crosstalk between the feedback coil and the pickup coils of adjacent SQUIDs. On the other hand, in the case of high-temperature superconductor SQUID (HTS-SQUID), usually the feedback coil is coupled with the SQUID inductor through a thin film pickup coil fabricated on the same substrate with the SQUID inductor as shown in figure 1. Since the feedback coil has a dimension as large as the pickup coil and is located near the pickup coil, the crosstalk between the adjacent SQUID sensors is rather large.

We have been developing an HTS-SQUID system based on a transient electro-magnetic method (TEM) for geophysical survey for metal resources [1]. In the TEM measurement, a large pulse magnetic field is applied on the ground surface to induce a current under the ground, then the secondary magnetic field from the induced current diffusing into deep ground is measured. The secondary field at the ground surface consists of vertical and rather weak
horizontal components. Therefore, a crosstalk of vertical field to the horizontal field reduces an accuracy of the measurement. In this paper, we propose a vector magnetometer with a new configuration to reduce the crosstalk between SQUIDs. The vector magnetometers with the new configuration are fabricated and characterized.

2. Basic structure and operation of SQUID magnetometer

An equivalent circuit of a directory-coupled SQUID magnetometer with a flux-locked feedback loop circuit (FLL) is shown in figure 1(a) [4]. Thick lines represent a superconducting part. The SQUID body consists of a superconducting loop with inductance of $L_{SQ}$ (SQUID inductor) and two Josephson junctions (JJs). Since the loop area of the SQUID body is too small (several hundred square micrometers), a much larger pickup coil is usually connected to the SQUID body to increase the field sensitivity. When an external magnetic flux $\Phi_{ex}$ is applied to the external pickup coil, a signal current $I_p$ flows in the pickup coil as well as the SQUID inductor and a signal flux $\Phi_s = I_p L_{SQ}$ is detected by the SQUID body. If one biases the SQUID with a constant current $I_b$, the voltage across the SQUID ($V_{SQUID}$) oscillates with a period of one flux quantum $\Phi_0$ as shown in figure 1(b).

Usually, a SQUID magnetic sensor has to be operated in a flux-locked loop (FLL) circuit to linearize the non-linear periodic response of the SQUID to applied flux [5]. The voltage change across the SQUID induced by an applied flux is amplified, integrated and fed back as an opposing flux using a feedback coil by a feedback current $I_f$ through a feedback resistance $R_f$. The feedback coil generates a cancelling field to keep the flux in the SQUID body at the nearest working point $W$ by a negative feedback. The working point is adjusted to steepest part by applying an offset voltage $V_{offset}$. Finally, a change of the readout voltage $V_{out}$ is proportional to the change of the external magnetic field. Note that the SQUID cannot measure an absolute magnetic field but a variation of the magnetic field.

3. Configuration of SQUIDs in vector magnetometer

There are several configurations of three SQUIDs in a vector magnetometer. Figure 2 shows three types of configurations. The circles in figures show three SQUIDs having a pickup coil and a feedback coil with similar size. The dotted arrows in figures represent a flux line generated from one of the feedback coils. In figure 2(a), the SQUIDs are located at three orthogonal surfaces of a cube [6]. We call this configuration ‘cubic configuration’. The flux line generated from the feedback coil apparently crosses the adjacent SQUIDs, resulting in crosstalk.
between the SQUIDs. Figure 2(b) shows another type of SQUID configuration, called ‘linear configuration’, in which orthogonally directed three SQUIDs are aligned on a line [7]. The flux line generated from the central SQUID apparently crosses the bottom SQUID. However, since the central SQUID is located on the vertical axis of the bottom SQUID, the amount of flux lines which enter or leave the bottom SQUID is equivalent. Therefore, the net flux which crosses the bottom SQUID is kept substantially zero. We call this relationship between the SQUID and the pickup coil of adjacent SQUID ‘symmetric relation’. On the other hand, since the flux line generated from the central SQUID passes the top SQUID in parallel to its surface, the flux line does not cross the top SQUID. We call this relationship between the SQUID and the pickup coil ‘parallel relation’. Since any pairs of three SQUIDs in the linear configuration should be in ‘symmetric relation’ or ‘parallel relation’, the crosstalk between the SQUIDs does not occur ideally. However, the linear configuration which needs a long vertical length leads to larger cryostat vertical length, larger filling amount of liquid nitrogen and less portability.

Figure 2(c) shows a new configuration proposed in this paper. In this configuration, the top SQUID (SQ_y) in the ‘linear configuration’ moves to the front of the central SQUID while keeping the location on the same x-z plane. The crosstalk between the SQUIDs does not occur ideally in this new configuration similarly to the case with the ‘linear configuration’. Therefore, the vertical length of the probe is kept comparable with the cubic configuration.

An actual HTS-SQUID sensor usually consists of a SQUID with pickup coil formed on one substrate and a feedback coil made of normal conducting metal like Cu formed on another substrate, meaning that the pickup coil and the feedback coil exist on different planes. Therefore, at least one of them must be slightly dislocated from the ideal symmetric position. Figure 3 shows the structure of our HTS-SQUID magnetometer module [8]. The SQUID body and the superconducting pickup coil which is directly connected to the SQUID body as shown in figure 1 are formed on a 0.5-mm-thick MgO substrate (SQUID chip). A resistive heater formed on a 0.5-mm-thick alumina substrate (heater chip) is inserted between the SQUID chip and a printed circuit board (PCB) which includes a feedback coil and an electric connector located at the backside. When a strong magnetic field is applied to the SQUID body, magnetic flux is trapped in the superconductor and generates an extra flux noise. A resistive heater is used to release a trapped flux by heating the SQUID chip above a superconducting transition temperature (T_c). Bonding pads are connected by Al wire bonding. The SQUID chip is hermetically sealed by a cap made of a fiber reinforced plastic (FRP) to protect it from environmental damages and keep thermal insulation during detrapping procedure using the resistive heater. The gap between the pickup coil and the feedback coil is about 1 mm. Therefore, it is impossible to realize the ideal configuration in which both the pickup coil and the feedback coil are set on the central axis of other SQUIDs.

In order to estimate the influence of dislocation from the ideal position on the crosstalk between adjacent SQUIDs, a numerical simulation using a finite element method is performed.
4. Numerical simulation of crosstalk

Numerical simulations are performed for two model cases shown in figure 4. Figure 4(a) shows a ‘parallel relation’ model. A feedback coil(z) generates a magnetic field as a feedback field. The vertical dotted line is a central line of the feedback coil(z). A pickup coil(x) located 1 mm below the feedback coil detects a reference magnetic field. A pickup coil(x) which detects a x-component of magnetic field drawn by a solid square is placed at an ideal symmetric position in which a magnetic flux generated by the feedback coil(z) does not cross the pickup coil(x). The distance between the feedback coil and the central line of the pickup coil(x) is denoted by $D_x$. When the pickup coil(x) position shifts from the ideal position to $x$ direction by a distance of $D_z$, as shown by a dotted square, a certain amount of flux crosses the pickup coil. The flux detected by the pickup coil(x) and the pickup coil(z) are calculated as a function of $D_z$. The crosstalk is defined as $\Phi_x/\Phi_z$ where $\Phi_x$ and $\Phi_z$ are flux detected by the pickup coil(x) and the pickup coil(z), respectively.

Figure 4(b) shows a ‘symmetric relation’ model. The pickup coil(x) detects a flux generated from the feedback coil(x) as a reference. The pickup coil(z) just below the feedback coil is shown by a solid square. Here, the net flux crossing the pickup coil(z) is zero. When the position of the pickup coil(z) shifts from the ideal position to $x$ direction by a distance of $D_z$, as shown by a dotted square, a certain amount of flux crosses the pickup coil(z) due to imbalance of in and out flux. The crosstalk is defined as $\Phi_x/\Phi_z$.

The feedback coil is designed as a square single loop with the inner and outer dimensions of 13 mm and 14 mm, respectively and the thickness of 0.1 mm. The pickup coil has a shape of 14 mm × 14 mm square plate. The numerical simulation is performed for three cases of distance $D_z$ (9, 22 and 35 mm) by a finite element method using a commercially available electromagnetic simulation software (JMAG (JSOL Corp.)).

Figure 5 shows the numerical simulation results of ‘parallel relation’ model and ‘symmetric relation’ model shown by dotted lines and solid lines, respectively. The crosstalk values are plotted as a function of $D_z$. Figures (a), (b) and (c) are corresponding to $D_z = 9$, 22 and 35 mm, respectively. Two curves for ‘parallel relation’ model and ‘symmetric relation’ model are almost the same. The crosstalk value increases with increasing $D_z$ from zero at $D_z = 0$, exhibits a maximum, and then gradually decreases. The maximum crosstalk value decreases with increasing $D_z$ because the absolute magnetic field is weakened. The vertical dashed lines show $D_y = D_z$ configuration which corresponds to the ‘cubic configuration’ where the two models become exactly the same configuration. Although our actual SQUID sensor has a 1 mm space between the SQUID and feedback coil, leading to deviation from the ideal position ($D_z = 0$), the crosstalk value even at $D_z = 1$ mm is apparently
smaller than that at $D_x = D_y$ (cubic configuration). The crosstalk value at $D_x = 1\,\text{mm}$ decreases with increasing $D_z$. It is easy to reduce the crosstalk value to less than 0.001 ($1/1000$) at $D_z = 35\,\text{mm}$. Therefore, increasing the distance between the SQUIDs is effective to reduce the crosstalk.

5. Experiments of crosstalk measurement

We have fabricated three SQUID probes to evaluate the new configuration. Figure 6 shows photographs of three probes. Three SQUID modules are attached to measure magnetic field of three orthogonal directions. The SQUID modules labeled by SQx, SQy, and SQz measure x, y and z axis components of the magnetic field. Probe A has a cubic configuration where each SQUID is located at 35 mm far from the center of the cube, corresponding to $D_x = 35\,\text{mm}$ in the numerical simulation model. Probe B has a new configuration where the distance between SQx and SQy is 22 mm and the distance between SQx and SQz is 35 mm. Since SQx and SQy are attached to connectors mounted at the inner side of a box frame, they approach each other. Probe C has also a new configuration with an enlarged frame where the distance between SQx and SQy is 37 mm and the distance between SQx and SQz is 45 mm.

Experimental procedure is as follows. The SQUID probe is cooled with liquid nitrogen in a three-layered permalloy magnetically shielding cylinder inside a magnetically shielded room. A sinusoidal current at a frequency of about 800 Hz is added to the feedback coil of SQx to generate a test signal. The magnetic field at SQx ($B_{SQx}$) is detected by that SQUID module which is operated by a negative feedback control using a flux locked loop circuit (FLL). The output voltage signal from FLL is characterized by a spectrum analyzer (HP 35670A, FFT Dynamic signal analyzer). The peak intensity at the test signal frequency in the spectrum is defined as a detected signal. The magnetic fields at SQy ($B_{SQy}$) and SQz ($B_{SQz}$) are also measured in order. During the measurement of the magnetic field, the feedback control of SQUID modules except for the sensing SQUID module is suspended to avoid an influence of a feedback control. Signal ratios of $B_{SQy}/B_{SQx}$ and $B_{SQz}/B_{SQx}$ are calculated as values of crosstalk from SQy to SQx and SQz. The crosstalk from the feedback coils of SQy and SQz are measured in a similar way.

Figure 7 shows the measured spectra of detected magnetic signals using Probe A. Results obtained by applying the test signal to the feedback coil of SQy, SQx, and SQz are shown in (a), (b) and (c). The peak at 805 Hz is corresponding to the test signal and other peaks are probably due to noises from a current source. The noise level of the spectrum of $B_{SQx}$ shown in (a) is rather high because the large full scale setting of spectrum analyzer is used. A strong peak appears in the SQUID corresponding the feedback coil used for applying the test signal and smaller peaks appear in other SQUIDs. Crosstalk values are calculated from the peak intensities and summarized in table 1(a).
Figure 5. Results of numerical simulation of crosstalk. (a) $D_z = 9$ mm, (b) $D_z = 22$ mm, and (c) $D_z = 35$ mm.

Table 1. Results of crosstalk measurement.

(a) Probe A (cubic configuration)

|          | $F_{Bx}$ | $F_{By}$ | $F_{Bz}$ |
|----------|----------|----------|----------|
| $S_{Qx}$ | 0.0657   | 0.0879   |
|          | (1/1521) | (1/1138) |
| $S_{Qy}$ | 0.128    | 0.169    |
|          | (1/780)  | (1/591)  |
| $S_{Qz}$ | 0.159    | 0.159    |
|          | (1/629)  | (1/629)  |

Averaged crosstalk value is 0.128%.

(b) Probe B (new configuration)

|          | $F_{Bx}$ | $F_{By}$ | $F_{Bz}$ |
|----------|----------|----------|----------|
| $S_{Qx}$ | 0.0802   | 0.0062   |
|          | (1/1247) | (1/14656)|
| $S_{Qy}$ | 0.201    | 0.0181   |
|          | (1/496)  | (1/5517) |
| $S_{Qz}$ | 0.0289   | 0.0353   |
|          | (1/3440) | (1/2829) |

Averaged crosstalk value is 0.062%.

(c) Probe C (revised new configuration)

|          | $F_{Bx}$ | $F_{By}$ | $F_{Bz}$ |
|----------|----------|----------|----------|
| $S_{Qx}$ | 0.0101   | 0.0222   |
|          | (1/9936) | (1/4497) |
| $S_{Qy}$ | 0.0483   | 0.0127   |
|          | (1/2070) | (1/7900) |
| $S_{Qz}$ | 0.000701 | 0.000683 |
|          | (1/14267)| (1/14625)|

Averaged crosstalk value is 0.017%.
Figure 6. Photographs of three types of HTS-SQUID vector magnetometer probes. (a) Probe A (cubic configuration), (b) Probe B (new configuration), and (c) Probe C (refined new configuration).

Figure 7. Magnetic signal spectra measured using Probe A. A test signal at 805 Hz is generated by using (a) the feedback coil of SQx, (b) the feedback coil of SQy, and (c) the feedback coil of SQz.
Figure 8 shows the measured spectra of detected magnetic signals using Probe B. Results obtained by applying the test signal to the feedback coil of SQx, SQy and SQz are shown in (a), (b) and (c). Only a peak value is plotted as BSQy in (b) due to a failure of saving data. A strong peak appears in the SQUID corresponding the feedback coil used for applying the test signal and much smaller peaks than those in figure 7 appear in other SQUIDs, indicating a reduction of crosstalk. Crosstalk values are calculated from the peak intensities and summarized in table 1(b).

Figure 8. Magnetic signal spectra measured using Probe B. A test signal at 805 Hz is generated by using (a) the feedback coil of SQx, (b) the feedback coil of SQy and (c) the feedback coil of SQz.

Figure 9 shows the measured spectra of detected magnetic signal using Probe C. Results obtained by applying the test signal to the feedback coil of SQx, SQy and SQz are shown in (a), (b) and (c). The peak at 828 Hz is corresponding to the test signal. Crosstalk values are also calculated from the peak intensities and summarized in table 1(c).

Table 1 shows the result of crosstalk measurement for Probes A, B and C. Crosstalk values are listed using percentage and fraction. The columns named ‘FBx’, ‘FBy’, and ‘FBz’ represent the feedback coil where the sinusoidal current flows and the rows named ‘SQx’, ‘SQy’ and ‘SQz’ represent the sensing SQUID module. The average of six crosstalk values is shown below the table.
The crosstalk values for Probe A (cubic configuration) are around 0.1% (1/1000). The averaged crosstalk becomes 0.128% which is consistent with the calculated crosstalk value of 0.15% shown in figure 4(c). The averaged crosstalk for Probe B (new configuration) is 0.062% which is better than that of Probe A. However, the crosstalk between SQx and SQy becomes worse probably due to their short distance. Therefore, Probe C was designed to increase the distance between SQx and SQy. In a TEM measurement using in-loop configuration in which a magnetometer is located at the center of a large loop coil, the z-axis component of both the applied primary field and the induced secondary field is usually several orders of magnitude larger than those of x-axis and y-axis components, resulting in a large influence of the crosstalk from SQz. Therefore, Probe C was also designed to further separate SQz from SQx and SQy.

As shown in table 1(c), the crosstalk between SQx and SQy is reduced as expected. The crosstalk from SQz is also improved. The averaged crosstalk is as low as 0.017%, which is approximately one order of magnitude smaller than that for Probe A with the cubic configuration. We have recently developed a new TEM system using a SQUID vector magnetometer with the new configuration.
6. Conclusion

A SQUID vector magnetometer with a new configuration enabling small crosstalk and small height was designed and fabricated. Numerical simulation of crosstalk revealed that the new configuration should have smaller crosstalk than that for cubic configuration even if there is a positioning error of 1 mm from an ideal symmetric position where the crosstalk is zero. Three types of SQUID vector magnetometers were fabricated and their crosstalk was measured. It was confirmed that the averaged crosstalk of SQUID vector magnetometer using the new configuration is reduced by about one order of magnitude as compared with the cubic configuration.

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