Measurement of Magnetic Particles by Hexagonal Pseudo Seven-Channel HTS SQUID Array

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Abstract. We developed a high-Tc superconducting (HTS) three-channel Superconducting Quantum Interference Device (SQUID) array and applied it to the measurement of a flow of magnetic nano-particles (MNPs). Three magnetometers were positioned in-line with a separation of 2.3 mm. The pick-up loop consisted of a 1 mm × 1 mm square loop; the size of a SQUID washer slit was 5 µm × 60 µm. Using this array, we arranged a hexagonal pseudo seven-channel SQUID array. The signal from the water-diluted MNPs, Resovist, in motion was measured by the array in a DC bias magnetic field and an AC modulation magnetic field. The dependence of the SQUID signal on the angle of the MNP flow to the baseline of the array was measured and discussed. The results suggest that the signal peak values are highly dependent on the flow path angle and that most of the flow path can be identified by the shape of the waveforms. This method is a promising candidate for brain activity investigation of small animals.

1. Introduction

f-MRI, EEG, MEG, MPI [1] and other techniques are commonly used to investigate brain activity. However, each method has advantages and disadvantages, for example, space resolution, time resolution, device size or cost. We have developed a method to measure the brain activity of a small animal by measuring blood flow with magnetic nanoparticles (MNPs), using a multichannel high-Tc Superconducting Quantum Interference Device (SQUID) [2]. Using this SQUID array it was possible to estimate the flow path of MNPs from the signal waveform obtained in each channel. We employed a method of detecting a second harmonic response by applying an AC modulation magnetic field and a DC bias field [3]. The SQUID array was mounted on a sapphire thermal conduction rod in a cryostat and cooled to 77 K by liquid nitrogen. Resovist, a commercially available MNP in a water base, was flown in a fine tube above the SQUID. The SQUID array was rotated 60° and 120° with respect to the direction of the magnetic field and the flow path of the MNPs to realize a hexagonal pseudo seven-channel SQUID array. In this paper we will discuss the dependence of the signal waveform on the angle of the MNP flow to the pseudo seven-channel SQUID array.

2. Experimental setup and measurement method

2.1. Three-channel SQUID array

Three direct coupled SQUID magnetometers were designed and fabricated on one chip as a SQUID array. They were made from a sputtered YBa$_2$Cu$_3$O$_{7-y}$ (YBCO) thin film with a thickness of 200 nm on
a 10 mm × 10 mm SrTiO₃ bi-crystal substrate. Figure 1 shows the design of the SQUID array. Three direct coupled SQUID magnetometers are in-line with a separation of 2.3 mm. The pick-up loop consists of a 1 mm × 1 mm square loop; the size of a SQUID washer slit is 5 µm × 60 µm, which corresponds to an inductance of 35.5 pH. The SQUID array was mounted on a sapphire thermal conduction rod in a cryostat and cooled to 77 K by liquid nitrogen. Noise properties measured on the sapphire rod are shown in Figure 2. The white noise of each magnetometer varied from 20 to 30 µΦ₀/Hz¹/₂ at 1 kHz. The magnetometer with the lowest noise was observed at ch1.

Figure 1. Design of three-channel SQUID Array. Three direct coupled SQUID magnetometers are in-line with a separation of 2.3 mm. The pick-up loop consists of a 1 mm × 1 mm square loop; the size of a SQUID washer slit is 5 µm × 60 µm.

Figure 2. Flux Noise of the SQUID array mounted on the 77K sapphire rod. The white noise of each magnetometer was from 20 to 30 µΦ₀/Hz¹/₂ at 1 kHz. The magnetometer with the lowest noise was observed at ch1.
2.2. Method of the measurement

Figure 3 shows the method of the measurement. (a): The SQUID array was located in the centre of the Helmholtz-type coil. An AC with a DC offset magnetic field was applied to the MNPs, which were commercially available Resovist. It was composed of Fe$_3$O$_4$ particles coated with dextran. The particles were suspended in water. The average diameter of each particle was about 45 - 60 nm. The iron content of the original solution of Resovist was 27.8 µg/µl. An AC and DC magnetic field were 4.20 mT$_{\text{P-P}}$/µ$_0$ @79 Hz and 2.12 mT/µ$_0$ respectively. (b): When an AC field with a proper DC offset magnetic field was applied so that the working point met at the field knee point (FKP) in the $M$-$H$ curve of the MNPs, the response signal became a half-wave rectified waveform as shown in (c) due to nonlinearity of the $M$–$H$ characteristics [3]. (d): It contained a second harmonic $2f_0$ and was stronger than any other harmonic except for the fundamental component $f_0$.

![Figure 3. Method of the measurement](image)

2.3. Setup of the experimental system

The SQUID array was mounted on top of a sapphire rod with a diameter of 15 mm anchored to a copper liquid nitrogen reservoir in vacuum. Figures 4 (a) and (b) show pictures of the chip on the sapphire rod in a cryostat. The cryostat was designed to allow access to the pick-up loop of each magnetometer as close as 1 mm, which is separated by a thin sapphire vacuum window. It is so-called “SQUID Microscope” type cryostat [4].

Figure 4(c) shows a schematic drawing of the experimental system. DC and AC Helmholtz-type coils were located on the top of the cryostat, where a Teflon (fluorocarbon) thin tube with an inner diameter of 0.8 mm was threaded at the center of the coils. The lift-off distance between the center of the tube and the sensitive surface of the SQUID array was 1.5 mm. Each SQUID was driven by SQUID electronics (PC-1000: STAR Cryoelectronics), and the output signals were introduced into DAQ via a lock-in-amplifier. A high-pass filter and a 60 Hz band elimination filter were applied.

A sample of MNPs was injected into a Teflon thin tube for measurement. The length and the volume of
Each sample was 3 mm and 1.5 µl, respectively. The sample was moved above the SQUID at different angles, in the order ch3, ch2, and ch1. Figure 5 shows a schematic diagram of the flow path above the SQUID array. The MNPs sample was moved along different flow path angles to the baseline of the SQUID array and the magnetic field. The output signal from each SQUID was measured when the MNPs samples were passed above the SQUID array.

**Figure 4.** Experimental setup. (a) Close-up view of the SQUID array mounted on the sapphire rod. (b) Picture of the SQUID array through the vacuum window. (c) Schematic drawing of the experimental system. Output signals were introduced into DAQ via a lock-in-amplifier.

**Figure 5.** Schematic diagram showing the flow of the Resovist sample. The MNPs sample was moved along different flow path angles to the baseline of the SQUID array and the magnetic field.
3. Results and discussion

3.1. Waveform of one dimensional three-channel SQUID array

Figure 6 shows the waveform of the output signal of each SQUID ch1 to ch3 with different angles of flow path. In each case of (a), (b) and (c), the angle of the flow path can be characterized by the shape of the waveform. However, the waveforms of the flow path of 45° (d) and -45° (e) are identical and it is hard to distinguish each flow angle from the waveforms. Thus a new method to overcome this issue was needed. One solution might be to increase the number of SQUID channels to form a two-dimensional array. Therefore we created a hexagonal pseudo seven-channel SQUID array by rotating the three-channel SQUID array 60° and 120° with respect to the direction of the magnetic field.

3.2. Waveform of two dimensional pseudo seven-channel SQUID array

The method to create the pseudo seven-channel SQUID array is shown in Figure 7. (a) shows the waveforms of the one dimensional three-channel SQUID array when the flow path angle was 30°, which were the same as in Figure 6 (a). Figure 7 (b) shows the waveforms when the SQUID array was rotated 60° with respect to the direction of the magnetic field. Note that the angle between the direction of the magnetic field and the flow path of MNPs was kept fixed. In this case, each SQUID of ch1 and ch3 corresponded to pseudo ch6 and ch5, respectively. Then the waveforms were taken when the SQUID array was rotated 120° with respect to the direction of the magnetic field in the same manner. (c) shows all the waveforms of the two-dimensional pseudo seven-channel SQUID array with the exception of ch1 to ch3, when the flow path angle was 30°. Clear signals could be recorded and these time positions are reasonable.

Figure 6. Waveform of each SQUID ch1 to ch3 with different angles of flow path. (a) Flow path with angle of 30°. (b) Flow path with angle of 60°. (c) Flow path with angle of 90°. (d) Flow path with angle of 45°. (e) Flow path with angle of -45°. (f) Schematic diagram showing the configuration.
3.3. Measurement of flow path of 45° pseudo seven-channel SQUID array

The technique mentioned above was applied to the measurement of the flow path of 45° and -45°. Figure 8 shows the results of pseudo seven-channel SQUID array. The waveforms of ch5 and ch6 when the flow angle was 45° and -45° are shown in (b) and (c) respectively. In the case of the flow angle of 45° (b), both positive and negative peaks can be seen in the waveform, while in the case of the flow angle of -45° (c), only the positive or negative peak is indicated. As a result, we could distinguish the flow angles from the shape of the waveforms by using the hexagonal pseudo seven-channel SQUID array.

Figure 8. Results of hexagonal pseudo seven-channel SQUID array. (a) Configuration. (b) Waveforms when flow path angle was 45°. (c) Waveforms when flow path angle was -45°.
4. Conclusions
In this study, we developed a detection system for a flow of MNPs' using a three-channel HTS SQUID array. A method detecting a second harmonic response was employed by applying an AC modulation magnetic field with a DC bias field. However, in the case of the flow path of 45° and -45°, the waveforms were identical and it was hard to distinguish each flow angle from the shape of the waveforms. Therefore, a hexagonal pseudo seven-channel SQUID array was created by rotating a three channel SQUID array 60° and 120° with respect to the direction of the magnetic field in order to solve this issue. As a result, we could distinguish the flow path angles of 45° and -45° from the shape of the waveforms. We will extend this technology to real blood flow with magnetic nanoparticles in the near future.

References
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