Superconducting Quantum Interference Device

Xiangyi Meng* and Donghyun Kim
Department of Physics, Boston University, Boston, Massachusetts 02215, USA
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The superconducting quantum interference device is useful for measuring weak magnetic field with a very high level of precision. In this experiment, we studied how a typical SQUID works, observed several characteristic phenomena of the superconductivity and Josephson effects, and built a precise magnetometer using a flux-locked circuit.

Introduction.–Superconductivity was first discovered in 1911. Scientists found that some metal lost its resistance in extremely low temperature. Twenty years later, the ability of superconductors to expel magnetic flux (i.e., the Meissner Effect) was first observed. As time went by, scientists discovered the phenomenon of magnetic flux quantization and the Josephson effects, accordingly. Finally, in the mid-1960's, Superconducting quantum interference devices (SQUIDs) were first theoretically studied and soon successfully made [1].

From quantum mechanics, it is known that closed loops can only contain discrete units of magnetic flux. The minimal possible flux in a superconducting system is $h/2e$, where $2e$ is the minimal electric charge of a Cooper pair. A (DC) SQUID is actually made of two Josephson junctions (see Fig. 1). If there are non-integer magnetic flux quanta existing inside the loop, some current must also appear in the loop so as to compensate for the total magnetic flux. The induced current therefore changes the critical current (the maximally allowed superconducting current) of the SQUID. This change of critical current which implies the existence of magnetic flux can be detected easily from electronic devices.

In this experiment, we studied a SQUID sample, Mr. SQUID, made by STAR Cryoelectronics, LLC. We successfully observed the V-I and V-Φ curves of SQUID, and also built a flux-locked loop circuit which can measure magnetic field with an error of only ± 0.08 mT. With the help of microwave signals, we also directly observed the AC Josephson effect, thereby measuring the e/h ratio precisely, with a statistical error of $\pm 0.42 \times 10^{14}$ Hz/V.

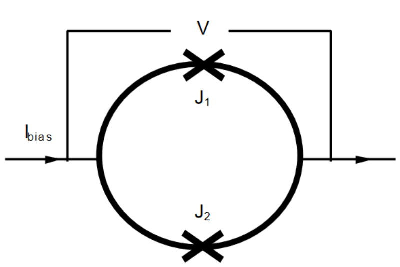

FIG. 1: Schematic representation of (DC) SQUID [1].

* xm@bu.edu

Method.–To allow our SQUID sample to function correctly, we put the sample into a container filled with liquid nitrogen which has a temperature of ~ 77 K. The whole setup of equipments are placed in a Faraday's cage in order to eliminate the influence of Earth's magnetic field. The circuits for measuring the V-I and V-Φ curves are already integrated in the auxiliary device box (Mr. SQUID box), and the signals can be read out all as voltages from the X and Y ports. All one has to do is to convert the signals into correct physical dimensions using the conversion factors given in the instruction booklet.

The following experiments require additional equipments. To construct a magnetometer for precise measurement of magnetic field, one has to construct a flux-locked loop circuit to lock the flux signal and convert it to a voltage signal. The schematic diagram of the feedback circuit is shown in Fig. 2. The input signal can be read at Test Point 1. The negative feedback output signal at Test Point 2 goes through a second coil which is already attached to outer layer of the sample.

Next, to observe the AC Josephson effect, a pair of microwave generator/receiver is required. The ~ 10 GHz microwave signal can induce an AC electric field across the Josephson junctions. The current response is a superposition of Bessel functions and should show discontinuity and look like a step function.

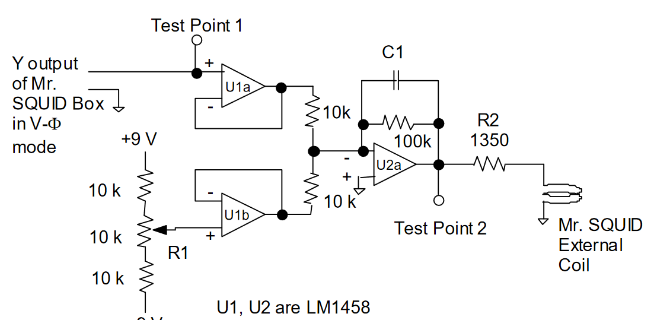

FIG. 2: Schematic diagram of the analog flux-locked loop circuit [1].

Data Analysis.–The V-I curve of SQUID is plotted in Fig. 3. The plateau at the center of Fig. 3 has a width of 380 mV, which corresponds to a width of $\Delta I \approx 38$ μA in the electric current dimension. Since the two Josephson junctions are connected in a parallel way in

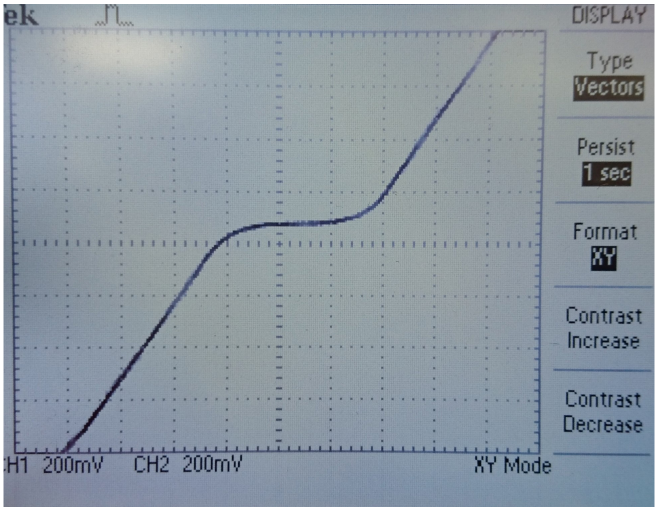

FIG. 3: (Color online) The V-I curve of SQUID. The conversion factors of the X and Y signals are 10^{-4} mA/mV and 10^{-4} mV/mV, respectively.

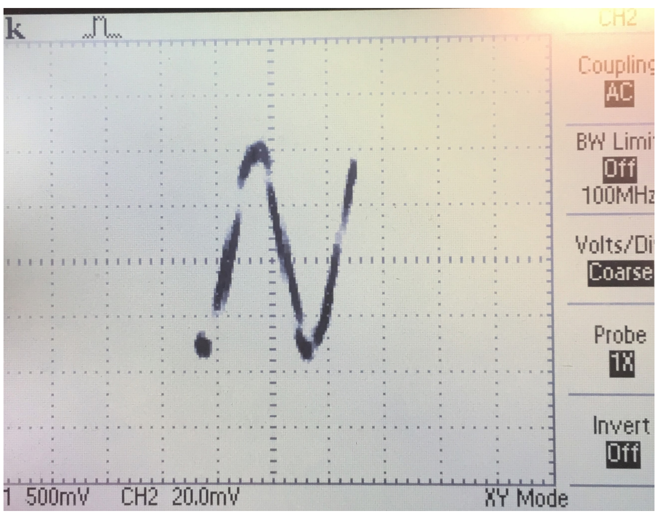

FIG. 4: (Color online) The V-Φ curve of SQUID. The conversion factors of the X and Y signals are 10^{-4} mA/mV and 10^{-4} mV/mV, respectively.

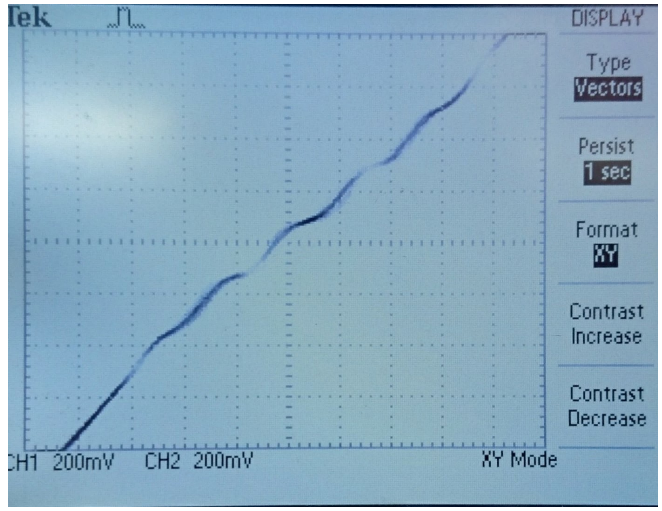

FIG. 5: (Color online) The V-I curve of SQUID, with a 10.5 GHz microwave signal turned on.

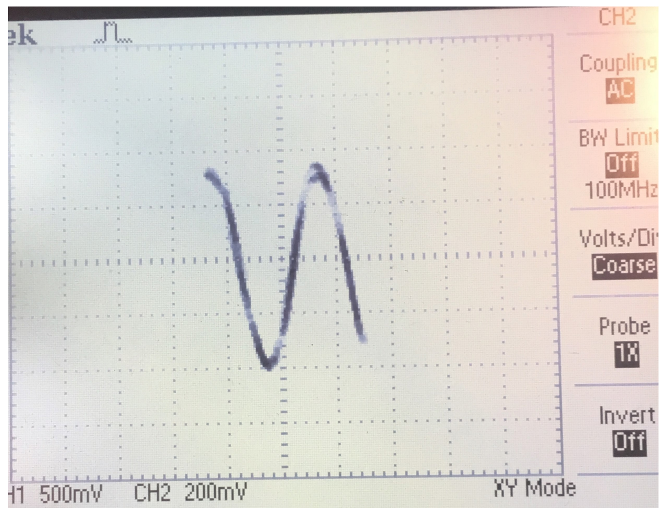

FIG. 6: (Color online) The negative feedback signal which is negative ten times the input (see Fig. 4).

a SQUID, the critical current for one junction is in fact $I_c = \Delta I/2/2 \approx 9.5$ μA. The resistance of the junctions can also be found by linearly approximating the V-I curve. The slope is approximately 7.37 Ω, which is the resistance of two parallel junctions. For one junction it is therefore $R_N \approx 14.75$ Ω. Finally, the characteristic quantity $I_c R_N$ is near 140.13 μV, close to the expected value given in the instruction booklet.

The V-Φ plot should obviously be periodic, as expected (see Fig. 4). The period of the signal in X-axis approximately corresponds to a current of 96 μA, yet we know that one period is also equal to a change of one magnetic flux quantum, $\Phi_0 \approx 2.07 \times 10^{-15}$ Wb. This allows us to quantify the mutual inductance of the sample, $\Phi_0/(96\ \mu\text{A}) \approx 21.6$ pH.

After turning on the microwave generator, a 10.5 GHz signal penetrates into the sample and change the shape of the V-I curve, as shown in Fig. 5. One can clearly see the plateaus. Those small plateaus, however, are not perfectly horizontal because of the instability of those field modes generated inside the sample. A little calculation shows that the height of one step is determined directly by the microwave frequency, along with two basic physical constants, e and h. From Fig. 5 the height can be measured immediately, and is $\Delta V \approx 0.02 \pm 0.0032$ mV. As a result, one can find that $e/h = f/2\Delta V \approx (2.63 \pm 0.42) \times 10^{14}$ Hz/V, which is close to the accepted value, 2.42×10^{14} Hz/V.

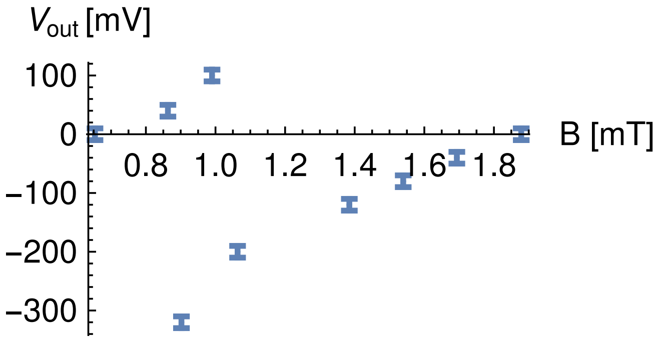

FIG. 7: (Color online) The change of output voltage of the flux-locked loop circuit with respect to the change of magnetic field. A jump occurs between 0.9 mT and 1.1 mT.

Last but not least, we successfully constructed the flux-locked loop circuit and observed the signal being locked by the negative feedback signal (the feedback signal is negative ten times the input and should itself look like Fig. 6). The output should be a perfect horizontal DC voltage offset, of which the amount is proportional to the magnetic flux inside the SQUID sample. However, due to imperfection of the operational amplifiers the feedback was not strong enough to fully compensate the noise, and what we observed was actually an inclined straight line. Furthermore, we placed the sample between Helmholtz coils and recorded the change of output signal with respect to the generated magnetic field (see Fig. 7). After the magnetic field increases larger than 1.1 mT, the output voltage becomes stable and proportional to the field, and so does the flux. The error is $\sim \pm 10$ mV, which corresponds to ± 0.08 mT for measurement of magnetic field.

Conclusions.—In this experiment, we successfully observed several phenomena related to the SQUID. These successful observations need somewhat tricky techniques. For example, after setting up the flux-locked loop circuit, one has to adjust the initial DC offset properly so as to keep the negative feedback in the right range. Sometimes the circuit cannot lock automatically and requires more subtle adjustments [2]. In conclusion, our results are reasonable and the experimental process has helped both of us to reach a deeper understanding of this novel quantum device, so-called SQUID.

We sincerely thank Yaokun Situ and Dan Arcaro for their valuable help.

[1] Mr. SQUID User's Guide, STAR Cryoelectronics, LLC, 1996.

[2] L. R. Sulak, Boston University, "Notes on Error Analysis".