A SERIES ARRAY OF DC SQUIDS*

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Abstract
We have fabricated a series array of 100 dc SQUIDs using trilayer Nb-AlOx-Nb junctions. The SQUIDs are modulated with a common flux bias line and produce an output voltage swing of several millivolts across the array. The large output voltage will allow direct connection to room temperature electronics without the transformer coupling and resulting frequency limitations commonly associated with dc SQUID amplifiers. We have measured a bandwidth of dc to at least 175 MHz for a 100-SQUID array. The series array will be used as the output stage for a multistage integrated SQUID amplifier.

Introduction
To take advantage of the extremely low inherent noise of a dc superconducting quantum interference device (SQUID) amplifier, it is necessary to achieve good impedance matching between the SQUID and the room temperature preamplifier to which it is connected. Amplifiers using dc SQUIDs have usually been operated in a flux-locked loop mode, with transformers or resonant circuits to provide impedance matching. These impose severe bandwidth limitations, and the systems are complex to use. The best frequency response achieved by these techniques has been around 70 kHz, using a tuned double transformer. Tuned and untuned radio frequency amplifiers have been made using single dc SQUIDs coupled directly to a room-temperature amplifier, and have operated at up to 100 MHz. However, this technique is not suitable for low frequency measurements. Digital readout techniques have also been used to eliminate the transformers, operating at digital sampling frequencies of around 20 MHz with much lower usable bandwidth.

The goal of the work described here is to develop a multistage integrated SQUID amplifier with sufficient gain and output voltage to allow direct connection to a room temperature preamplifier. In addition to simplifying the readout electronics, such an amplifier will greatly increase the available bandwidth. The series arrays described here will serve as the output stage of the amplifier. To preserve the full sensitivity of a single-SQUID input stage, intermediate stages of amplification will be necessary to insure that the noise of the input stage is amplified sufficiently to exceed the noise of the room temperature electronics. The magnitude of the voltage modulation of the output stage must be in the millivolt range to provide an adequate signal to noise ratio at the input of a low-noise room temperature preamplifier.

Figure 1 shows a schematic diagram of the output stage array. Individual dc SQUIDs are connected in series and modulated coherently by current in a common flux bias line. The array is biased at constant current. Coherence means here that the flux through each SQUID is approximately the same, and that the period of the voltage modulation with respect to applied flux is approximately the same for all SQUIDs in the array.

Design and Fabrication
The SQUID design parameters were chosen to maximize the output voltage, subject to the constraints that the SQUID parameter $\beta_0$ should equal approximately 1 for optimum performance, and that the hysteresis parameter $\beta = (2\pi/\Phi_0) L I_{c0}^2 C$ should be around 0.25 to insure that the junctions are well into their non-hysteretic regime and do not damp any SQUID resonances. Here $L_{q0}$ is the SQUID loop inductance, $I_{c0}$ is the sum of the critical currents $I_c$ of the two junctions, $\Phi_0$ is the flux quantum, $R_s$ is the junction shunt resistance, and $C$ is the junction capacitance. The junction areas were chosen to be about 3.5x3.5 $\mu$m$^2$, with critical current of about 110 $\mu$A. The SQUID inductance was chosen to be around 12 pH. The junction shunt resistors were approximately 1 $\Omega$.

The SQUID arrays were fabricated as thin-film integrated circuits based on Nb-AlOx-Nb trilayer junctions. The trilayer structure was first sputter-deposited over the entire wafer by a process described in detail elsewhere, followed by a 5 masking-level patterning and deposition process. The top and bottom Nb junction electrodes were etched by a reactive ion etching process, followed by evaporative liftoff deposition of In-Au resistors, an SiO insulating layer, and a Pb-In wiring layer.

Several different SQUID and array designs have been fabricated and tested. The arrays occupy areas comparable to or smaller than those of typical thin-film transformers used in SQUID circuits. The array for which experimental results are presented here is the most compact fabricated thus far, with dimensions of about 54x120 $\mu$m.

Figure 2 shows an 8-SQUID segment of the array. The array consists of back-to-back pairs of small washer-type SQUIDs, connected in series along a serpentine path. Individual SQUID loops are defined by the L-shaped slots in the Pb-In washer layer, and the Nb base electrodes. The bias current flows into the base electrode of SQUID1, up through the junctions into the washer, across and down through the junctions of SQUID2 and into the base electrode. It continues through the base electrode into SQUID3, and similarly through the other SQUIDs in order as numbered. Flux is coupled into all SQUID loops simultaneously by current in the modulation line, which consists of two parallel lines running through the center of the array, down its length. The modulation current enters and exits at one end of the array. The two lines are connected at the other end of the array to form a single folded line, which acts as a one-turn input coil around each SQUID loop. The modulation line

\[ I_{mod} \]

\[ V_{out} \]

\[ I_{bias} \]
is fabricated in the Nb base electrode layer, and is isolated from the SQUID electrodes by the SiO insulation layer. The modulation line was designed to have equal mutual inductance with each SQUID in the array.

Results and Discussion

Figure 3a shows the output voltage of the array at constant current bias as a function of the current $I_{mod}$ through the flux modulation line. The bias current was adjusted for maximum voltage modulation, which occurred slightly above $I_{c0}$. The corresponding curve for a single SQUID of the same design is shown in Figure 3b. The array voltage was about 100 times higher than the single SQUID voltage, as expected for coherent modulation of the SQUIDs in the array. The periodicity of the curve implies that the mutual inductance between the SQUIDs and the flux modulation line was about 3.7 pH. For different squids and arrays of the same design, the maximum voltage modulation varied by about ±10%.

The shape of the $V-I_{mod}$ curve for the array is somewhat different than for the single SQUID, with the array curve more sharply peaked at higher voltage. We attribute this to small variations in the actual amount of flux present in the individual SQUID loops due to variations in junction critical current, flux trapping, local external fields, or some combination of these. Larger amounts of trapped flux caused severe distortions of the $V-I_{mod}$ curve. The trapped flux could easily be expelled by warming the chip to slightly above its superconducting transition temperature using a resistance heater built into the chip holder. The voltage swing for both the single SQUID and the array are consistent with the actual $I_{c0}$ of about 0.125, which was lower than intended because the shunt resistors were inadvertently made with too little resistance.

The magnitude of the voltage swing for this array dropped monotonically by about 20% as the modulation current was increased to a value corresponding to 100\% of applied flux. We attribute this to small differences in the mutual inductance among the individual SQUIDs, causing each SQUID to operate with slightly different periodicity in flux. The small differences in period cause phase differences between the individual SQUIDs to accumulate for large values of applied flux. This problem tended to be worse for SQUIDs with small inductance, in which photolithographic and fabrication variations were a larger fraction of the area which defined the loop inductance.

The results from SQUID designs other than the one presented were generally similar. Test arrays of 100 single junctions in series were included on all wafers. The total variation in critical current among the 100 junctions was usually ±2-3% for 3.5 μm junctions.

For initial bandwidth measurements, we coupled a pulse generator to the flux modulation line through 50 Ω coaxial cable. To provide good impedance matching, an on-chip 50 Ω resistor was fabricated in series with the modulation line, and a 10 dB attenuator was inserted in the coaxial cable just off the chip. Current biasing of the array and output voltage measurement was done through a second 50 Ω coaxial cable connected to the output leads of the array. The voltage was amplified by an RF amplifier with a gain of 20, then displayed on a high-speed oscilloscope.
Figure 4 shows the output voltage across the series array in response to a square wave input to the flux modulation line. The square wave amplitude and dc offset were adjusted to give about 1/4 $\Phi_0$ of flux bias and 1/4 $\Phi_0$ of signal amplitude. The rise time of the input pulses was varied down to as little as 2 ns (the fastest available from the generator). One can see that the rise time of the voltage output (also 2 ns) was not limited by the array response, implying that the bandwidth of the array is at least 175 MHz. The magnitude of the output voltage did not change with variations in the pulse rise time or repetition rate.

Conclusions

It is possible to make series arrays of dc SQUIDs which modulate coherently with applied flux from a common modulation line. The output voltage of the 100-SQUID array scales as about 100 times the voltage of a single SQUID. The bandwidth of the array is at least 175 MHz for a signal input impedance of 50 $\Omega$.

This work indicates that the primary requirements for coherent voltage modulation in series dc SQUID arrays are that the SQUIDs should be sufficiently identical in critical current and loop inductance, that the mutual inductance $M$ should be approximately the same between all SQUIDs and the modulation line, and that there be little or no random flux offset between the individual SQUIDs. It is not necessary for the SQUID voltages to be phase-locked at the Josephson frequency, since we are amplifying signals at frequencies far below this range.

It appears that wide latitude is allowable in the SQUID geometry, and that one can optimize the design based on practical considerations such as overall size and minimization of modulation line inductance. The latter is desirable to maximize the $R/L$ cutoff frequency due to the resistance of the input signal source, and the inductance of the modulation line.

These arrays are being developed to provide a large output voltage swing for a multi-stage amplifier, with single SQUID preamplifier stage(s) and on-chip feedback. Our plans are to make a high-gain SQUID amplifier which can be connected directly to a room temperature amplifier, without complicated read-out electronics.

This work was supported in part by the Office of Naval Research under contract no. N00014-88-F-0077.

References

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