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A simple three-channel dc SQUID system using time domain multiplexing

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Conventional multichannel superconducting quantum interference device (SQUID) systems require a SQUID read-out circuit for each channel, as well as many wires connecting each individual SQUID and feedback coil to the room temperature electronics. We present a simple time domain multiplexed read-out scheme which requires only a single SQUID read-out circuit that is successively switched between all the SQUIDs. By connecting all the SQUIDs and all the feedback coils in series, this time domain multiplexed system requires many fewer wires between the SQUIDs and the room temperature read-out circuit than other multichannel systems. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1777381]

I. INTRODUCTION

Superconducting quantum interference devices (SQUIDs) are very fast sensors for magnetic flux. SQUIDs can respond to flux changes much faster than nanoseconds.[1,2] Even when operated in a flux-locked loop,[3] which is usually used to linearize the periodic flux-to-voltage transfer function of the SQUID, a SQUID can follow flux changes in the megaHertz range. Some applications, such as SQUID microscopy[4,5] and nondestructive evaluation,[6] do not always require this MHz speed, as the object under test is moved mechanically and thus relatively slowly. In order to reduce the scanning time, many SQUIDs can be employed simultaneously, which then scan different parts of the sample. In a conventional multichannel SQUID system,[7] each individual SQUID requires its own read-out circuit and up to six wires connecting each SQUID to the room temperature read-out. If, however, the maximum frequency of interest is well below the upper frequency limit of the flux-locked loop, it is not necessary to operate all the SQUIDs all the time. In particular, each SQUID could be switched on and read out for only a short period of time during which all the other SQUIDs are switched off. In this case it should be possible to use only one read-out circuit which is successively switched between all the SQUIDs. All the SQUIDs can thus share the same readout, and possibly also the wires connecting the SQUIDs and feedback coils to the room temperature electronics. One only needs to add a circuit to control the switching on and off of the SQUIDs. In this article we describe two possible ways to realize such a system and show some results on their performance.

II. TIME DOMAIN MULTIPLEXING OF MANY SQUIDS WITH ONLY ONE READ-OUT CIRCUIT

Several interesting ideas have been published regarding the time domain multiplexing of SQUIDs.[8–10] Furukawa and Shirae[9] suggested a multichannel system in which the sum of the voltages produced by each channel modulates a further SQUID, which then requires only one transmission line between the SQUID and room temperature, as well as only one amplifier to be read out. The response of the individual channels is separated in the room temperature electronics by one phase detector or per channel. A disadvantage of this scheme would be nonlinearities in the SQUIDs[11] and read-out circuit which could produce spurious signals. Also, each SQUID still requires four wires to room temperature for its bias current and its feedback coil.

Some time ago, we proposed a three-channel rf SQUID system with time domain multiplexing, requiring only a single transmission line between all SQUIDs and the room temperature electronics.[12] Some parts of the read-out electronics were shared by all channels. In order to distinguish between the individual channels, the rf SQUIDs were operated at different rf bias frequencies. Hence, the tank circuit of each rf SQUID responded only to a rf bias at its resonant frequency. Switching the SQUIDs on and off was accomplished by switching the corresponding rf generator on and off. A simple logic circuit operated the switches for the three rf generators. In order to use only a single transmission line between the SQUID array and the room temperature electronics, the feedback coils of all three SQUIDs were connected in series. Since each SQUID was operated only a fraction of the time, the value of the flux measured by the SQUID was stored and again applied to its feedback coil prior to the next operation cycle by the integrator of the flux-locked loop. A short time before switching on a certain SQUID, its integrator was connected to the feedback coil and prior to switching off the SQUID, the integrator input was again disconnected from the phase detector.

As the use of dc SQUIDs is more common today, we have adapted the principle described above to conventional dc SQUIDs. It turns out that very little needs to be changed

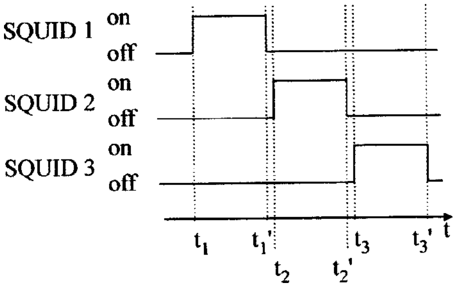
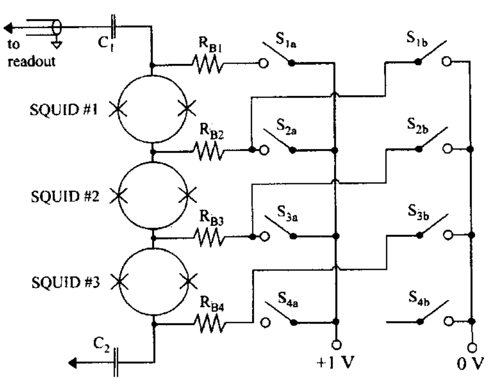


FIG. 1. Timing diagram of a time domain multiplexed SQUID system using only one SQUID read-out circuit. At t_1 SQUID #1 is switched on. The other two SQUIDs are off. At t_1' the output voltage of the SQUID electronics, which is now a measure for the flux threading SQUID #1, is measured by a 16-bit ADC. SQUID #1 is then switched off. The compensation flux of SQUID #2, measured at t_2' of the previous cycle, is reapplied to the feedback coils by a 16-bit DAC. Operations performed for SQUID #1 at t_1 and t_1' are repeated at t_2 and t_2' for SQUID #2 and at t_3 and t_3' for SQUID #3.



SQUID	# 1	# 2	# 3
$S_{1a,b}$	on	off	off
$S_{2a,b}$	off	on	off
$S_{3a,b}$	off	off	on
$S_{4a,b}$	off	off	off

FIG. 2. Schematic diagram of the bias current distribution circuit of a three-channel SQUID system using time domain multiplexing. The table shows the states of the switches required in order to operate only the SQUID identified by a given number.

in the room temperature electronics. However, some means has to be found for switching the dc SQUIDs on and off in order to be able to reduce the number of wires between all the SQUIDs and the room temperature electronics. As proposed by Likharev *et al.*, one way to do this is to use Josephson junctions as switches. The entire multiplexing circuitry can then be realized using single flux quantum logic.[13] However, fabricating such circuits is a fairly complicated process. In our approach, we have developed a system which uses conventional semiconductor components for the switches, as well as readily available SQUID sensors and readout electronics.

In Fig. 1, we briefly outline the timing diagram we used for our time domain multiplexed SQUID system using only one SQUID read-out circuit. Each SQUID is given a certain time interval during which it is switched on while all other SQUIDs are switched off. For example, at t_1, SQUID #1 is switched on and connected to the SQUID read-out, while the other two SQUIDs are off. The flux SQUID #1 measured during the previous cycle is reapplied to its feedback coil. At t_1', the output voltage of the SQUID electronics, which is now a measure of the flux threading SQUID #1, is determined and stored for further use. SQUID #1 is then switched off. Operations performed for SQUIID #1 at t_1 and t_1' are repeated at t_2 and t_2' for SQUID #2 and t_3 and at t_3' for SQUID #3. The entire multiplex cycle is continuously repeated.

If only one transmission line is to be used to read out all the SQUIDs, the SQUIDs should be connected in series. Switching a certain SQUID on and off can be accomplished by making its bias current zero (SQUID off) or the optimum value (SQUID on). If one SQUID is switched on in this way, the bias current for the other SQUIDs must be zero. These off SQUIDs then behave as a short piece of superconducting wire and thus do not interfere with the operation of the SQUID which is on.

The bias currents for the individual SQUIDs can be generated at room temperature. In this case, two wires to room temperature are required for biasing each SQUID. In the case of a multichannel system, this leads to a large number of wires between the cold SQUIDs and room temperature. We have therefore used a semiconductor switch to generate the bias currents at 4.2 K, and which for n SQUIDs requires only $\log_2 n$ wires to room temperature. Conventional CMOS analog switches perform well at 4.2 K,[14] and can be used to switch these bias currents at cryogenic temperatures. Unfortunately, their resistance when switched on is still a few hundred ohms and thus the switches cannot be used to switch a conventional SQUID readout directly to different SQUIDs. However, switching bias currents is possible as the bias resistors are much larger than the on-resistance of the switch. When in the off state, the resistance of the switches is sufficiently large ($>10\ \text{M}\Omega$) to prevent a bias current from flowing through the SQUIDs. We have tested three different versions of CMOS analog switches, a conventional 4052, and the HEF and 74 HCT counterparts. All switches worked properly at 4.2 K. The HEF and 74 HCT versions were able to work at supply voltages as low as 1.6 V. With a supply voltage of 2.5 V, the power dissipated in the switch was about 10 μW at a switching rate of 10 kHz. The heat produced by the device is thus negligible. The switching speed at 4.2 K was somewhat higher than at room temperature, being about 50 ns for the 74 HCT 4052 with a supply voltage of 3 V.

Figure 2 shows the circuit configuration we used in our three-channel system. Using the CMOS circuit 74 HCT 4052, which contains eight on-off switches, we apply the appropriate bias voltages across the bias resistors R_{Bn} ($n=1-4$) connected to the SQUIDs. The resistors are chosen such that the optimum bias current flows through the SQUID if the voltage across each resistor is 0.5 V. If, for example, SQUID #2 (the middle one) is to be switched on, a voltage of 1 V is applied to bias resistor R_{B2}, and zero volts are applied to bias resistor R_{B3}. This is accomplished by switching on S_{2a} and S_{2b}. The switches connected to bias resistors R_{B1} and R_{B4} (i.e., S_{1a} and S_{3b}) are off, so that no

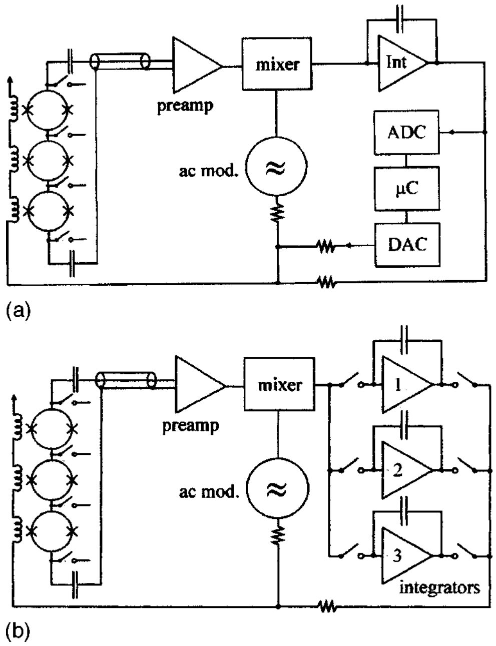


FIG. 3. Configuration of the two different three-channel SQUID systems using time domain multiplexing investigated in this article. Each SQUID is operated for only a fraction of the time. For clarity, the bias current distribution network has been omitted. (a) A single conventional ac-flux modulated SQUID read-out circuit is used for preamplifier, phase detector and ac-flux generator. A separate integrator is used for each channel and is switched on and off synchronously with its SQUID. (b) A single conventional ac-flux modulated SQUID circuit is used. Before a SQUID is switched off, its momentary flux is measured by a 16-bit ADC. This flux is reapplied to the SQUID by a 16-bit DAC just before it is switched on again at the next multiplex cycle.

current can flow through SQUIDs #1 and #3. We note that the 74 HCT 4052 is configured such that switches S_{na} and S_{nb} $(n=1-4)$ are switched on and off simultaneously. Also, if one pair of switches, say S_{1a} and S_b, is on, all other pairs are off. The switches $S_{4a,b}$ are not used in our case.

The SQUIDs are ac-flux modulated and the information about the flux threading a SQUID is contained in the amplitude and phase of the ac voltage which develops across the SQUID which is in the on state. This voltage is processed by a room temperature preamplifier which is connected to the SQUIDs via a transmission line. Two capacitors C_1 and C_2 prevent the dc bias current from flowing to ground.

Finally, for flux-locked loop operation, the individual compensation flux for each SQUID must be measured and stored during the time that the SQUID is switched off. We have studied two possibilities, either using the integrator capacitor as an analog memory—which requires the use of an individual integrator for each channel—or by measuring the momentary voltage across the feedback resistor with an analog-to-digital converter (ADC) and reapplying this voltage with a digital-to-analog converter (DAC) at the beginning of the next multiplex cycle.

III. EXPERIMENTAL SYSTEM CONFIGURATION

The configuration of two time domain multiplexed three-channel systems requiring only one SQUID read-out are shown in Figs. 3(a) and 3(b). In both systems, the three SQUIDs are connected in series and ac-coupled to the preamplifier of the room temperature readout by two 1 μF capacitors. The feedback coils of the SQUID are also connected in series. The bias currents are applied to the SQUIDs via a cold (4.2 K) 74 HCT 4052 analog switch as described above. In the system shown in Fig. 3(a), all channels share the preamplifier as well as the phase detector in the readout. In order to store the information about the magnetic field each SQUID experiences, each channel uses a separate integrator. The integrators are switched to the phase detector and the feedback resistor by analog switches. When the integrator is disconnected from the phase detector, the charge on the integrator capacitor is a measure for the magnetic field at the SQUIDs. The switching on and off of the SQUIDs and integrators is controlled by a microcontroller [μC in Fig. 3(a) and not shown in Fig. 3(b)], a modulation frequency of 4 MHz was chosen for the SQUIDs in order to allow for fast switching between the channels.

In a second system, shown in Fig. 3(b), we relinquished the use of a separate integrator for each channel, but instead measured the charge on the integrator capacitor—which is a measure for the magnetic field the SQUID experiences—with an analog-to-digital converter and restored this charge on the capacitor at the next multiplex cycle. In this case, we could use a commercially available SQUID readout.[15] The only additional part was the cold switch. Compared to a conventional three-channel system, this multiplexed system requires only one readout electronics instead of three, as well as fewer wires connecting the SQUIDs to room temperature.

IV. MEASUREMENTS

All measurements were done in a helium storage dewar. The dc SQUIDs used had a hole size of 200×15 μm^2 and a washer size of 0.5×0.5 mm^2. The SQUID inductance was about 75 pH. Standard Nb/Al/Al$_2$O$_3$/Nb tunnel junctions served as the Josephson junctions. We found that all the SQUIDs were working independently, and no crosstalk or interference between channels was noted. The noise of the system was similar to that measured without multiplexing. As long as the frequency of interest is below half of the multiplex frequency, there should be no difference in the sensitivity of a conventional or a multiplexed system.[6]

Since in our time domain multiplexed systems, the SQUIDs are not operated continuously, but only for a fraction of a multiplex cycle, the input flux applied to the SQUIDs must not change by more than $\Phi_0/2$ during the time a SQUID is switched off. Due to the periodic transfer function of the SQUID, greater flux changes will cause an offset in the output signal by $n\Phi_0$, or cause the loop to unlock. Because of this, the slew rate which can be expected of such a system is smaller than for a conventional system using the same ac-flux modulation frequency.

Figure 4 shows the measured peak-to-peak amplitude variation in the input signal at which the system shown in Fig. 3(a) unlocked. The two curves in Fig. 4 were measured for two different multiplex cycle times. For a cycle time of 100 μs (each SQUID is operated for 33 μs and then switched off for 66 μs during which the other two SQUIDs are read out), a maximum slew rate of $2\pi\times4000\ \Phi_0/s$

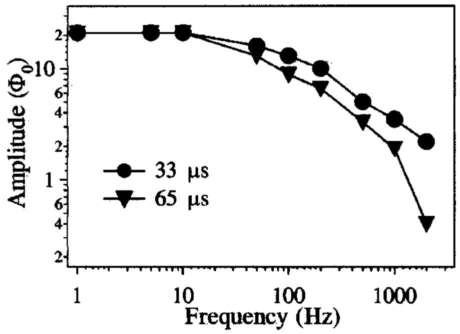


FIG. 4. Maximum permissible peak-to-peak input flux as a function of frequency for two different multiplex cycle times, measured for the system shown in Fig. 3(a).

$\approx 2.5 \times 10^4 \Phi_0/s$ was measured at an input frequency of 2 kHz. A cycle time of 155 μs reduced the slew rate to about $1.5 \times 10^4\ \Phi_0/s$.

Figure 5 shows the maximum permissible peak-to-peak input flux variation for the system shown in Fig. 3(b). As we used a relatively slow analog-to-digital converter, the cycle time was much larger than that of Fig. 3(a), which had separate integrators for each channel. Hence, the maximum slew rate achieved was only about $3 \times 10^3\ \Phi_0/s$. For the data taken in both Figs. 4 and 5, the feedback resistor used allowed for a dynamic range of 25 Φ_0 and the integrator time constant was 2 μs.

We note that in the system shown in Fig. 3(a), drift in the integrator, e.g., by a leaky capacitor, can further reduce the slew rate, so that the compensation flux applied to the SQUID at the beginning of a new multiplex cycle will be different from its original value. In our system an integrator drift (measured with open input) of 2 mV/s was measured, corresponding to about 2 $m\Phi_0/s$ or 0.2 $\mu\Phi_0$/cycle. This amount of drift is negligible.

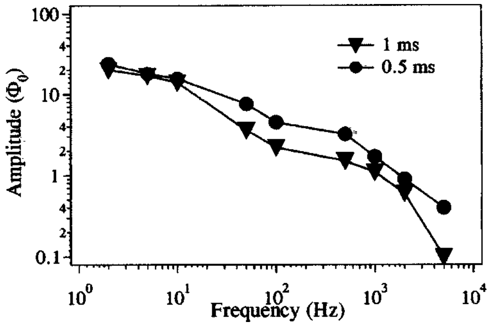


FIG. 5. Maximum permissible peak-to-peak-peak input flux as a function of frequency for two different multiplex cycle times measured for the system shown in Fig. 3(b).

V. FUTURE DEVELOPMENTS

We have designed and produced two implementations of a three-channel dc SQUID system with time domain multiplexing. Such a system uses only commercially available components and much reduces the wiring necessary between room temperature and 4.2 K. It also requires only a single electronics box to control all three SQUIDs.

Using the principle described above, we can speculate on the maximum number of channels that could be read out by a single SQUID electronics. The maximum number of channels is limited by the upper frequency one wants to measure, and the minimum possible cycle time. A rough estimate for the minimum cycle time is $(0.1 \times f_{\mathrm{mod}})^{-1}$, where f_{mod} is the ac-flux modulation frequency. As modulation frequencies above 10 MHz have been demonstrated, multiplex cycle times of 1 μs appear to be possible. If a maximum input signal frequency of 200 Hz is assumed (a typical upper frequency in biomagnetic measurements), the multiplex frequency can be 400 Hz, i.e., each channel is read out once every 2.5 ms. In this case, the theoretical maximum number of channels would be about 250, and the obtainable slew rate about 3000 Φ_0/s. This is sufficient for a moderately shielded system. A single SQUID read-out circuit could be sufficient to read out all the SQUIDs.

ACKNOWLEDGMENTS

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