LA-UR-98-4043

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Title: SEQUENTIAL READ-OUT ARCHITECTURE FOR MULTI-CHANNEL SQUID SYSTEMS

CONF-9809130--

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Submitted to: Conference Proceedings for the Applied Superconductivity Conference, Palm Desert, CA Sept. 13-18,1998

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Sequential Read-out Architecture for Multi-Channel SQUID Systems

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Abstract—We describe a novel multi-channel sequential SQUID read-out technique that requires fewer wires than conventional units and also simplifies the electronics significantly. We designed and experimentally tested the sequential read-out electronics with up to 8 channels using LTS 8×8 mm^2 magnetometers with about 3fT/√Hz field resolution. We have investigated noise performance, amplitude-frequency characteristics, and cross-talk of the sequential read-out electronics for 2, 4, and 8 channels. We observed field resolution better than 4fT/√Hz, 6fT/√Hz, and 9fT/√Hz for 2-, 4-, and 8-channel versions, respectively. We observed 10 kHz frequency bandwidth for the 8-channel version using 200kHz modulation frequency. Cross-talk better than –90dB was measured for this system. A single-channel simulation was used to estimate the field resolution for systems with up to 128 channels. We found that the expected field resolution can be better than 15fT/√Hz, 20fT/√Hz, and 30fT/√Hz for 32-, 64-, and 128-channel systems, respectively, with the sequential read-out technique.

I. Introduction

The conventional SQUID read-out technique requires a minimum of four wires for each SQUID, i.e. two wires for read-out voltage and bias supply, and two wires for modulation and feedback currents. Thus, an N-channel conventional SQUID system would require at least 4N wires (512 wires for a 128-channel system). Larger numbers of wires cause several problems including dewar heat load and general system complexity and reliability. In this paper, we present a new sequential read-out technique that, in principle, requires only 2N+1 wires for N-SQUIDs while also simplifying the electronics tremendously. The sequential read-out technique connects all of the SQUID voltage-bias leads in series. Only two wires (instead of 2N for conventional systems), a matching circuit, and a low-noise amplifier are needed to read out the voltages from all of the sensors. Modern fabrication techniques allow high-yield production of SQUID devices with similar operational characteristics (eg. I_{C1} and I_{C2}). This similarity between devices allows all of the SQUIDs to perform at approximately the same operating point with the common bias current that is slightly below I_{C1} for all devices. The modulation and feedback current is sequentially and uniquely activated for each SQUID while all other SQUIDs remain in the superconducting state and thus do not add any signal to the read-out voltage. The results presented here are based on specific SQUID magnetometers, however the technique can be applied to any SQUID device.

Manuscript received September 15, 1998
This work was supported by the U. S. Department of Energy Office of Defense Programs.

II. Principle

Fig. 1-3 illustrate the operating principle of the sequential read-out technique for a 4-channel system. All of the SQUID voltage-bias leads are connected in series, as shown in Fig. 1.

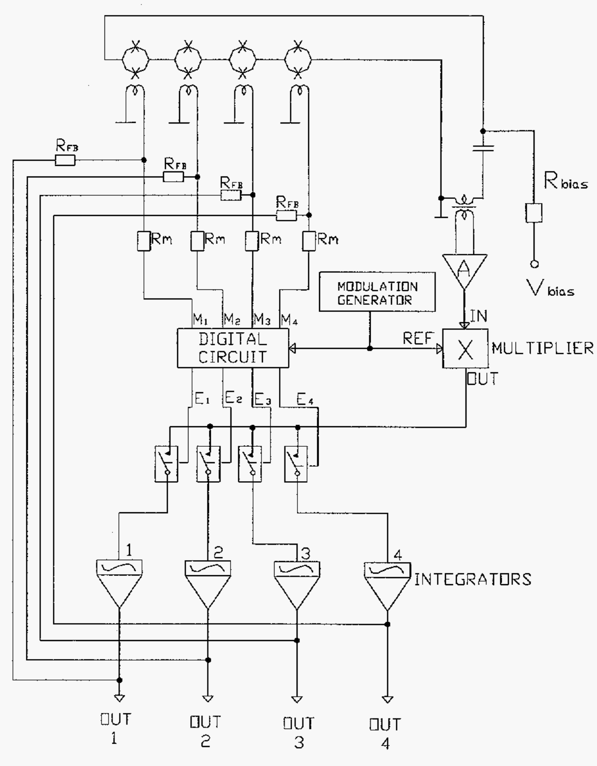

Fig. 1. 4-channel sequential read-out scheme. M_1, M_2, M_3 and M_4 are modulation signals; E_1, E_2, E_3 and E_4 are enable digital signals; 'A' is a low-noise amplifier; R_{FB} and R_m are feedback and modulation resistors respectively; V_{BIAS} and R_{BIAS} provide a bias current.

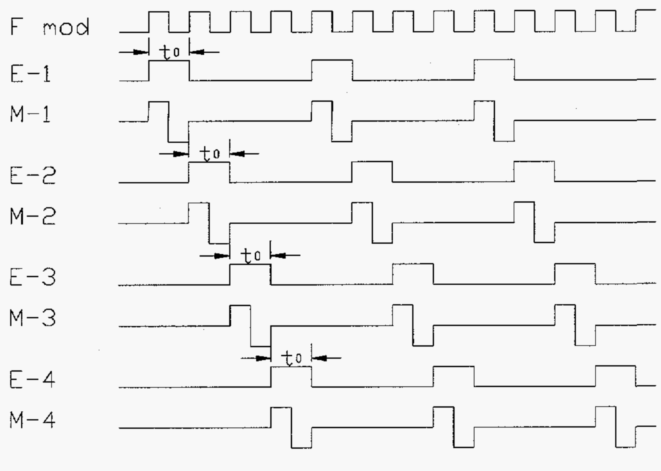

Fig. 2.The modulation signals M_1, M_2, M_3, M_4; the enable signals E_1, E_2, E_3, E_4 and the modulation generator output signal F_{mod} (F_{mod} is about 200 kHz).

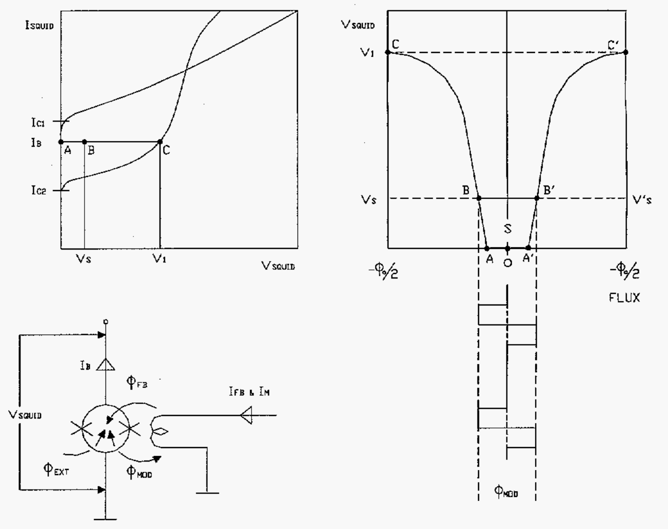

Fig.3. DC SQUID A-V (upper left) and V-Φ (upper right) curves. I_B is a working bias current; I_{C1} and I_{C2} are critical currents at $n\Phi_0$ and $(n+1/2)\Phi_0$ respectively; Φ_{MOD} is a flux modulation.

The common voltage and bias twisted pair is connected to a matching circuit in room temperature electronics prior to a low-noise amplifier. The amplified signal is then routed to an analog multiplier that operates as a synchronous detector using the modulation generator output as the reference. The synchronous detector output is connected to a 4-channel multiplexer that sequentially routes the signal to four integrators (an N-SQUID system requires a N-channel multiplexer and N integrators). A bias voltage, V_{BIAS}, is connected in parallel to the output twisted pair through a large resistor that supplies the same bias current to all SQUIDs. Each integrator generates an output voltage that is fed back to the corresponding SQUID through a resistor to compensate for input flux.

The modulation generator output signal is a continuous square-wave that is used to synchronize generation of a bipolar square wave using a digital circuit that is unique in time for each channel. The digital circuit also generates synchronized enable signals, E_i, to sequentially switch the multiplier output between the integrator for each channel. An example of the shape and time sequence of the modulation generator continuous output, M_i, and E_i signals are shown in Fig. 2. During the first time interval, t_0, the modulation generator output is switched to the first SQUID producing the modulation pulse, M_1, while the enable signal, E_1, activates the multiplier output for the first integrator. During t_0 all other M_i and E_i are at baseline and their associated SQUIDs remain in the superconducting state. The output signal from the first integrator then provides the feedback current to the first SQUID to compensate for the change in the flux, equivalent in principle to conventional DC SQUID electronics. During the second time interval, t_0, M_2 and E_2 are activated while all other M_i and E_i are at baseline. This in turn causes the second multiplier to activate and the second integrator to provide a feedback current for the second SQUID. Each successive SQUID is activated until all SQUIDs have been activated and the pattern repeats.

The modulation signal consists of one positive and one negative pulse, as shown in Fig. 2. The behavior of each SQUID when both DC bias current and bipolar modulation signals are applied is shown in Fig. 3, and the bias current, I_B, is less than the larger device critical current, I_{C1}, as shown in Fig. 3 (upper left). For an N-channel system, I_B must be less than the smallest I_{C1} and greater than the largest I_{C2}. The SQUID voltage-flux (V-Φ) curve and the modulation signal are shown in Fig. 3 (upper right). In the superconducting state, the SQUID operating point on the V-Φ curve is shown as point "A" in Fig. 3 (upper left), and segment A-A' in Fig. 3 (upper right). The applied modulation signal provokes the SQUID to jump from the superconducting to resistive state at working point B and B' for negative and positive modulation signals, respectively. At working points B and B', the SQUID will generate output voltages V_s and V'_s. If the starting point S is centered on the superconductive segment A-A', then output SQUID signals V_s and V'_s are equal and the average multiplier output signal is zero causing there to be no net integrator output and consequently no feedback current is generated. If, however, S is not exactly centered on the A-A' segment, then V_s and V'_s are not equal and the integrator will generate a feedback current that will compensate for the net signal and move the operating point S back to the exact center of A-A'. It is similar to conventional electronics operation. During subsequent time intervals when the modulation pulse is off, this SQUID will remain superconducting provided the change in flux linkage into the SQUID remains sufficiently small.

We have described how the modulation and feedback current to each SQUID is sequentially and uniquely activated for readout of that SQUID while all other SQUIDs remain superconducting and thus do not contribute to the output voltage. The measured field resolution for this sequential read-out technique should be $N^{1/2}$ times worse than for conventional techniques. We have experimentally verified the basic sequential read-out technique for up to 8 physical channels and up to 128 channels using a single-channel simulation. In all cases we used 8×8mm^2 LTS single-chip SQUID magnetometers that have 0.84nT/Φ_0 field sensitivity and better than 3fT/√Hz field resolution [1].

III. Single-Channel Simulation

The single-channel simulation configuration that was used to estimate noise for large numbers of channels is shown in Fig. 4. A single SQUID, S_1, was connected to the sequential read-out electronics that allowed one bipolar modulation signal, I_m, to be generated once every Nt_0 time periods where N could be varied from 1 to 128. The second SQUID sensor, S_2, was connected to S_1 through four 25Ω resistors and a 4μF capacitor to form a low-pass filter (Fig.4). This configuration was used to read out the averaged signal from the first SQUID voltage leads allowing us to observe the actual working point of the V-Φ curve for S_1 on a X-Y plot. Conventional read-out electronics were used for S_2 [2].

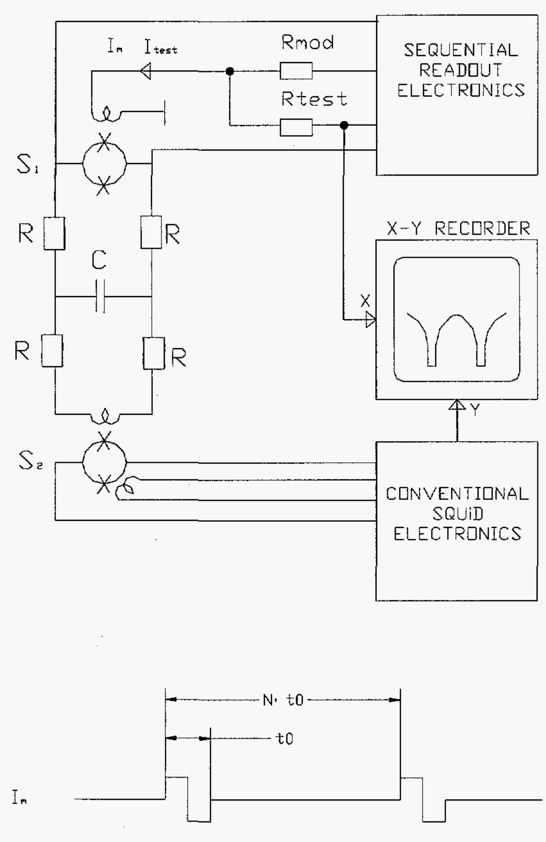

Fig. 4. One-channel simulation scheme. The sequential readout electronics provides the modulation signal I_m with different N from 1 to 128. The second SQUID sensor, with conventional electronics, is used to measure the average voltage on the first SQUID's voltage leads to plot its V-Φ curve.

TABLE I

White Noise vs. Number of Channels [fT/√Hz]

N	1	2	4	8	16	32	64	128
Noise	2.5	3.3	4.5	6.4	9.0	13	18	26

The white noise figures for N=1 to 128 using the single-channel simulation system are shown in Table I. N=1 corresponds to conventional read-out technique. The noise is observed to grow as $N^{1/2}$, as expected based on contributions of multiple white noise sources. SQUID S_2 allowed us to determine the polarities when the operating point, S, was placed on the superconducting segment A-A'. We observed that changing the reference signal polarity changed the operating point from S to C on the V-Φ curve (Fig. 3).

IV. Eight-Channel Sequential Read-out System

All aspects of the sequential readout technique were finally proven using a complete 8-channel system. SQUIDs with similar critical current were used for this system because the common bias current applied in the sequential read-out technique, as described above. We found, however, that our system does not require extremely closely matched SQUID critical currents. Individual modulation of the SQUIDs allows adjustment to attain the best noise performance for each channel, even for some devices that are biased rather far from the critical current. The only requirement is that all SQUIDs exhibit a reasonable superconducting A-A' segment at the applied bias current.

Table II lists the operational parameters of the eight SQUID magnetometers used in this system. The white noise figures at 2 kHz of four different configurations (with different numbers of channels, N) corresponding to the field resolution for the sequential read-out system as a function of N are also tabulated. The bias current used for these measurements was 27.3 μA. The measured noise did not change significantly for bias currents in the range from ~24μA to ~28μA. The modulation currents must be adjusted for each channel individually after the bias current change.

The measured field resolution for the sequential read-out technique degrades by $N^{1/2}$ as compared to the conventional technique, as expected. Nevertheless, the field resolution for our 8-channel sequential read-out system was measured to be better than 9 fT/√Hz in the 10kHz frequency bandwidth, sufficient for even most biomagnetic applications. The channel-one noise spectra for various N are plotted in Fig. 5.

TABLE II

White Noise of the 8-Channel Sequential Read-out System at 2 kHz [fT/√Hz], I_{C1}, I_{C2} [μA].

#	1	2	3	4	5	6	7	8
I_{C1}	20	19	20	18	19	20	21	18
I_{C2}	30	29	30	28	29	30	31	28
N=1	2.2							
N=2	3.3	4.1						
N=4	4.3	5.5	5.9	5.2				
N=8	7.8	8.9	8.8	8.4	8.3	7.5	8.3	8.9

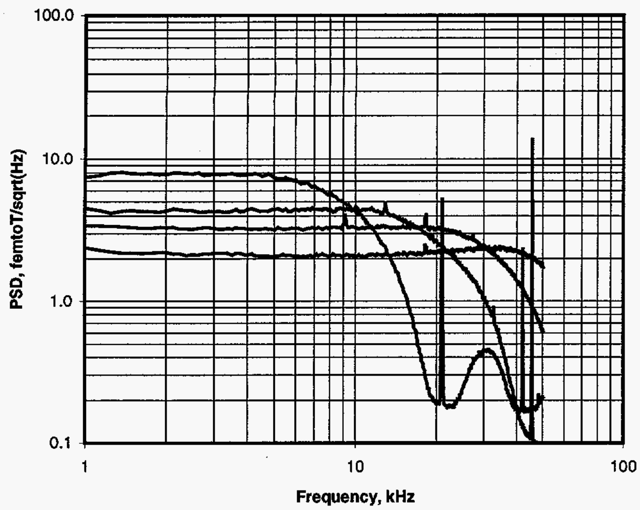

Fig. 5. Noise spectra of the channel number one of the eight-channel magnetometer with the sequential read-out electronics. Spectra from the bottom to the top correspond to N equal to 1, 2, 4 and 8 respectively.

The slew rate for the 8-channel system was measured to be approximately 5×10^3 Φ_0/sec for all channels. The cross-talk differed substantially between channels from –60dB to better than –90dB at 250Hz owing to differences in grounding, connections, and wiring of the bread-board system. The best experimentally measured cross-talk was about –94dB at 250Hz. Cross-talk was observed to be proportional to test signal frequency up to at least 1 kHz for all channels. We used copper twisted pairs without individual shields for all channels to connect the SQUID magnetometers to the sequential electronics, all twisted pairs were placed inside one 0.5" stainless-steel tube. We believe that using individual shields for each channel connections can decrease cross-talk. Phosphor bronze twisted pairs can be used for all feedback and modulation connections, and it can significantly decrease a cryogenic probe heat load.

V. Conclusion

We have developed a novel read-out technique for multi-channel SQUID systems, which is based on sequential readout of signals from several sensors connected in chain. The single-channel simulation was developed to prove our new approach and to estimate the field resolution for systems with up to 128 channels. The noise is observed to increase as $N^{1/2}$, as expected based on contributions of multiple white noise sources. We have shown that the expected field resolution can be lower than 30fT/√Hz for 128-channel system, which is based on $8\times8mm^2$ LTS single-chip SQUID magnetometers. We have designed and experimentally tested the eight-channel magnetometer based on sequential read-out technique, which showed us 10kHz frequency bandwidth and better than 9fT/√Hz magnetic field resolution.

Acknowedgment

The authors are grateful to Dr. R. Cantor and V. Vinetsky for useful discussions and valuable comments.

References

[1] R. Cantor, "DC SQUID: Design, Optimization and Practical Applications", In: *SQUID Sensors: Fundamentals, Fabrication and Applications*, ed. by H. Weinstock, NATO ASI Series, Kluwer Academic Publishers, Dordrecht/Boston/London, pp. 179 – 233.

[2] pcSQUID™, Conductus, Inc. , 969 W Maude, Sunnyvale.