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SUMMARY

Many of the activities of the human body manifest themselves by the presence of a very weak magnetic field outside the body, a field that is so weak that an ultra-sensitive magnetic sensor is needed for specific biomagnetic measurements. Superconducting QUantum Interference Devices (SQUIDs) are extremely sensitive detectors of magnetic flux and have been used extensively to detect the human magnetocardiogram and magnetoencephalogram and other biomagnetic signals. In order to utilize a SQUID as a magnetometer, its transfer characteristics should be linearized. This linearization requires extensive peripheral electronics, thus limiting the number of SQUID magnetometer channels in a practical system. The proposed digital SQUID integrates the processing circuitry on the same cryogenic chip as the SQUID magnetometer and eliminates the sophisticated peripheral electronics. Such a system is compact and cost effective, and requires minimal support electronics. Each chip, in addition to having on-chip processing circuitry coupled to a SQUID, also has an integrated superconducting transformer to facilitate its interface to an external pick-up coil. As a result of this effort, it will be possible to design and fabricate single chips that will contain arrays of digital SQUIDs for integration in a multi-channel SQUID system, thereby reducing the cost and complexity of such systems. The major cost associated with the present SQUID-based biomagnetometer systems is the shielded room environment which can be on the order of \$0.5M to \$1M. The proposed digital SQUID significantly relaxes the requirements on the low frequency magnetic field shielding and reduces the shielding cost considerably. Significant cost savings are also realized by eliminating much of the peripheral electronics, thus allowing multi-channel systems to be built very cost effectively. Under a DOE-sponsored SBIR program, we designed, simulated, laid out, fabricated, evaluated, and demonstrated a digital SQUID magnetometer. The design involved a SQUID magnetometer that integrates a SQUID-based pre-amplifier with a high sensitivity comparator gate and feedback circuitries on the same chip. The comparator gate is an asymmetric SQUID gate driving two SQUID quantizers in series with the feedback coil. The chip's sensitivity and noise level are primarily determined by the pre-amplifier SQUID. The pick up coil is in series with the feedback transformer. Since the current in the feedback coil is maintained close to zero, the dynamic range of the chip can be extremely wide and is independent of the SQUID pre-amplifier or comparator architectures. As a matter of fact, experimental results demonstrated wide dynamic range in digital SQUID chips. The chip's slew rate is determined by the bipolar clock biasing the comparator gate. Clocks running in the tens of MHz result in a magnetometer system with slew rate exceeding $10^5 \Phi_0/s$ ($\Phi_0 = 2.07 \times 10^{-7}$ Gauss-cm²). This report summarizes the accomplishments under this program and clearly demonstrates that all of the tasks proposed in the phase II application were successfully completed with confirmed experimental results.

TABLE OF CONTENTS

INTRODUCTION	4
CIRCUIT DESIGN	10
CIRCUIT SIMULATION	14
FABRICATION AND EXPERIMENTAL RESULTS	17
PERIPHERAL ELECTRONICS	22
CONCLUSION	22
REFERENCES	31

INTRODUCTION

This project leads to the development of an all thin film digital magnetometer/gradiometer chip. This chip utilizes a Superconducting QUantum Interference Device (SQUID) as an ultra-sensitive magnetometer and integrates superconducting processing circuits and transformers with these magnetometers. The processing circuitry utilizes a novel superconducting circuit architecture that when employed with analog SQUIDS, results in a digital SQUID with extremely wide dynamic range. Such a chip is a self-contained magnetometer with on-chip peripheral processing circuits that requires minimal support electronics. Consequently, arrays of such chips can be realized very cost effectively for integration in multi-channel SQUID magnetometer systems. These systems have applications in non-invasive biomedical instruments such as multi-channel magnetocardiograms and magnetoencephalograms, as well as in high resolution SQUID arrays being developed for in vitro studies for physical and biological sciences. One of the potential uses of a SQUID magnetometer is in multi-channel imaging systems. Such systems use a significant number of sensors, each backed by a high resolution analog to digital converter (ADC). For example, a typical ADC array utilized in a biomedical imaging system requires at least an effective 16 bits of resolution and 100 MS/s (million samples per second) rate in a multiplexed system. Each sensor and ADC can be replaced by a digital SQUID magnetometer. The processing performance of such systems improves significantly by such a replacement. The superconducting circuit is simple and dense, so a relatively high packing density can be achieved in an imaging system. In addition, the major cost associated with the present SQUID-based biomagnetometer systems is the shielded room environment which can be on the order of \$0.5M to \$1M. The proposed digital SQUID significantly relaxes the requirements on the low frequency magnetic field shielding and reduces the shielding cost considerably. Significant cost saving is also realized by eliminating much of the peripheral electronics, thus allowing multi-channel systems to be built very cost effectively.

Many of the physiological processes of the human body manifest themselves by the presence of a magnetic field outside the body. For example, electrical currents are associated with electrical activity in heart muscle (magnetocardiogram), in the brain (magnetoencephalogram), and in skeletal muscle (magnetomyogram) and give rise to weak magnetic fields as determined by the law of Biot and Savart.¹ While biomagnetic fields have been measured with induction-coils^{2,3} and fluxgate magnetometers⁴, virtually all recent measurements of the magnetocardiogram (MCG) and magnetoencephalogram (MEG) utilize SQUID magnetometers.

SQUIDS are extremely sensitive detectors of magnetic flux and are superior in performance to other types of magnetometers (Fig. 1). Such devices are routinely used as high resolution magnetometers, susceptometers, neuromagnetometers, motion detectors and ultra-sensitive voltmeters. A SQUID is a superconducting ring interrupted by one or two Josephson tunnel junctions made of a superconductor such as niobium (Nb) films. Nb is the material of choice for superconducting circuits, because it has the highest critical temperature among the elemental superconductors (9.3 K). This alleviates certain uniformity and repeatability concern that must be taken into account when using compound superconductors. Josephson tunnel junctions using niobium as electrodes and thermally oxidized aluminum as tunnel barriers have been investigated

rather extensively, and has been brought to a state of maturity suitable for medium scale integrated circuits by several laboratories including HYPRES.⁶⁻¹³ One of the unique features of Josephson junction is the presence of a tunnel current through the device at zero bias voltage. The magnitude of this current which is normally referred to as the Josephson current is magnetic field dependent. When two Josephson junctions are paralleled their combined Josephson currents exhibit an interference pattern. The periodicity of this pattern is in multiples of the flux quantum $\phi_0 = h/2e = 2.07 \times 10^{-7}$ Gauss-cm² (h = Planck's constant, e = electron charge). The same periodicity also translates to the volt-ampere characteristic of a properly shunted junction. This sensitivity of the Josephson current to an external magnetic field is exploited in building ultra-sensitive SQUID-based magnetometers.

Fig. 1 Comparison of magnetic field resolution of different types of magnetometer systems as a function of frequency. The superiority of DC SQUIDS over other types of magnetometers is evident in this exhibit. All of the data shown in this figure are for laboratory devices. For example, the DC SQUID was fabricated at IBM research laboratory for a practical SQUID having a noise figure approaching its quantum limit ($h=10^{-34}$ J/Hz). Reprinted from Ref. 5.

The SQUID magnetometer was first used in 1970 by Cohen, et. al.¹⁴ to detect the human magnetocardiogram. Since then, this type of magnetic flux detector has been used as the main tool for biomagnetism. The SQUID is inherently very sensitive. Indeed, the principal technical challenge by researchers has mainly been discrimination against the high level of ambient noise.

A SQUID magnetometer system has a SQUID gate coupled to a transformer. The transformer is, in turn coupled to a matched pick-up loop. The SQUID and its associated superconducting components are maintained at 4.2 K by immersion in a bath of liquid helium in a cryogenic dewar. Superconducting coils and transformers are essential elements of all superconducting magnetometer systems. The SQUID and its transformer are surrounded by a superconducting shield to isolate them from the biomagnetic and ambient fields. The transformer acts as a focusing device. In such a loop, the flux trapped in the circuit is fixed and subsequent changes in the applied field are exactly canceled by changes in the screening current around the ring. Since there is no energy dissipation, the superconducting ring is a noiseless flux to current transducer. The loop operates at arbitrarily low frequencies, thus making it extremely useful for very low frequency applications.

The field imposed on the SQUID is transformed to a voltage by the SQUID and is sensed by an electronic circuit outside the dewar. Complete SQUID systems are currently commercially available for biomedical and other applications. Until recently, most of these systems used an RF SQUID because of their ease of fabrication. The prefix RF refers to the type of bias current applied to the SQUID. An RF SQUID is a single junction in a superconducting loop. Magnetic flux is normally inductively coupled into the SQUID via an input coil. The SQUID is then coupled to a high Q-resonant circuit to readout the current changes in the SQUID loop. This tuned circuitry is driven by a constant current RF oscillator. RF SQUIDS are slowly being phased out because of their lower energy sensitivity (5×10^{-29} J/Hz at a pump frequency of 20 MHz), as compared with DC SQUIDS.

The DC SQUID differs from the RF SQUID in its number of junctions and bias condition. The DC SQUID, which was first developed by Clark¹⁵, consists of a superconducting ring of inductance interrupted by two Josephson junctions. The Josephson junctions are resistively shunted to remove hysteresis in the current-voltage characteristics. When the DC SQUID is biased at a constant current, the expected behavior to an external magnetic field is through a periodic dependence of output voltage on input magnetic flux. The SQUID's sensitivity to an external field can be improved by coupling the device to a multi-turn superconducting transformer.

The minimum energy sensitivity for DC SQUIDS is estimated to be on the order of h (Planck's constant, 6.6×10^{-34} J/Hz; this is the quantum white noise floor for SQUIDS). DC SQUIDS, without on-chip transformer, operating at $5h$ have been fabricated and evaluated in the laboratory.¹⁶ The performance of these Josephson tunnel junction SQUIDS is actually limited by the Johnson noise generated in the resistive shunts used to eliminate hysteresis in the current-voltage characteristics. Early systems used a single SQUID in a small dewar.¹⁴ Subsequently, 7-channel and then 37-channel SQUIDS were introduced to allow localization of non-repetitive

events, such as those associated with interictal epileptic spikes. Recently, systems with approximately one hundred channels have been announced.^{6,7} More recent developments in SQUID magnetometry are described in the numerous papers published in the last few years in the International Conferences on Biomagnetism.¹⁸⁻²⁰ All of these SQUID systems have used conventional RF and DC SQUIDs with room-temperature electronics. Wikswo, et. al^{22,23} are using a 4-channel, high resolution SQUID to image currents in skeletal, cardiac and smooth muscle. As the number of channels increases, the wiring requirements (four wires per SQUID), the physical size of available DC SQUIDs and SQUID electronics, and the cost (\$5,000 to \$10,000 per channel) becomes prohibitive. Consequently, one eventually must turn to multiplexed digital SQUIDs.

In order to utilize a SQUID as a magnetometer, its periodic transfer characteristic should be linearized. This linearization also substantially increases the dynamic range of the SQUID magnetometer. Figure 3 exhibits a DC SQUID system with peripheral electronics. The function of the feedback coil is to produce a field which is equal to but opposite to the applied field. The circuit uses a lock-in amplifier and a reference signal to facilitate a narrowband, lock-in type of measurement. The output is proportional to the feedback current, and hence, to the amount of flux required to cancel the measured field, and is independent of the SQUID transfer characteristic. Thus, the SQUID magnetometer circuit with the feedback coil, lock-in amplifier, oscillator, DC amplifier and the on-chip signal coil, serves as a null detector. More detailed explanations of the operating principles can be found in the review articles by Gifford,²⁵ Clark,¹⁵ Lounasma,²⁶ and other researchers.^{27,28}

Figure 2 shows the evolution in the number of SQUID channels and demonstrates exponential growth over the last few years.²⁴ It is estimated that a useful SQUID system for biomagnetism should have substantially more than 100 channels and possibly close to 1000 channels. A 128-channel system requires at least 512 wires attached to the superconducting chip and needs a set of 128 channels of sophisticated electronics. Because of lack margins in analog SQUID chips, individual bias lines for each SQUID gate are a necessity. On the other hand, a similar digital SQUID requires less than 30 connections to the chip with minimal support electronics at the expense of a more sophisticated superconducting chip. It should be also pointed out that the reduction in heat leak to the chip due to the reduction in the number of connections is also substantial. A bundle of wires containing 200 connections to a superconducting chip and held between 4.2 K and 300 K leaks 1 W of heat, or consumes about 1.5 liters of liquid helium per hour. Consequently, a 128 channel analog SQUID system requires at least a 2.5 W system, while a similar digital system requires less than ¼ W system. The next table makes a comparison between two 128 channel analog and digital SQUID systems. While the number of wires, heat load, and cost of peripheral electronics increase linearly with the number of channels in an analog system, the digital system characteristics are independent of these elements. Noise and sensitivity are comparable for both systems.

Comparison Between Two 128 Channel Analog and Digital SQUID Systems

	Analog	Digital
Number of wires to superconducting chip	512	~30
Heat load	2.5 W	¼ W
Cost of room temperature electronics	>\$5,000 per channel	~ \$1,000 per system
Number of room temperature electronic channels	128	1

Fig. 2 Evolution in the number of demonstrated multi-channel SQUID-based magnetometers for biomedical applications. (Reprinted from reference 24).

Over the past couple of years there has been considerable interest in the dynamics of digital SQUIDs.²⁹⁻⁴¹ Two basic types of designs have emerged for such SQUIDs. They either interface the analog SQUID with a counter, or integrate the feedback circuitry with the SQUID device. In both cases, the digital output of the chip represents the input magnetic flux and can be processed by a standard digital processor. Researchers have shown, in principle, that the concept of digital SQUID is viable, and indeed this concept essentially eliminates the need for sophisticated peripheral electronics.

Fig. 3 A DC SQUID with peripheral electronics. A feedback circuitry is needed to linearize SQUID characteristics. The dotted line shows the components normally at room temperature. The output resistor can be on- or off-chip.

A counter-type digital SQUID integrates an analog SQUID (a quantizer) with a counter.³¹⁻⁴¹ HYPRES has already demonstrated such a counting type digital SQUID.^{31,44} A major disadvantage of this type of SQUID is its rather low sensitivity of ϕ_0 ($=2.07 \times 10^{-7}$ Gauss-cm²).

An alternative to a counter-type digital SQUID is an analog SQUID with on-chip feedback circuitry. This sensitivity for such SQUIDs can be as good as $10^{-6} \phi_0$. This single chip SQUID magnetometer integrates the feedback electronics with the SQUID magnetometer, and eliminates the need for the lock-in amplifier, DC amplifier and the oscillator. Fig. 4 shows the block diagram for the proposed system, which is far less elaborate than the conventional system exhibited in Fig. 3. Several versions of this type of SQUID circuits have been proposed by

researchers.^{29,30,32,33} A major disadvantage with majority of these circuits is a small dynamic range which is limited by the size of the feedback coil. (The exception is the circuit proposed by Rylov³² that possesses very wide dynamic range.) Increasing the size of this coil improves the dynamic range but also compromises the circuit density. As explained in the next section, we have realized a new circuit architecture that completely eliminates this problem and when combined with a multi-bit superconducting counter results in a digital SQUID chip with wide dynamic range and high sensitivity.

Fig. 4 Block diagram of a digital SQUID magnetometer chip with the peripheral counter. Front end is a one-bit comparator that is coupled to a multi-bit counter.

CIRCUIT DESIGN

The digital SQUID circuit developed under this program combines the Rapid Single Flux Quantum (RSFQ) logic family with the conventional latching logic. RSFQ logic uses an entirely new approach to Josephson junction-based logic circuitry. In this approach, the information is presented by very short (picosecond) voltage pulses rather than by the DC voltage (as in all semiconductor transistor logics, as well as superconducting logics). The RSFQ pulses can be generated, reproduced, amplified, stored and processed by Josephson junctions.

Our demonstrated digital SQUID essentially uses a well proven analog SQUID as a simple comparator to create a new class of digital SQUIDs. Its block diagram is shown in Fig. 4. It contains a comparator SQUID with feedback coupled to a counter. As far as the counter is concerned, HYPRES, under support from several Federal agencies, has already shown the viability of the concept using its niobium technology by demonstrating a 12-bit ADC which consists of a sensitive quantizer and one counter chain connected to the positive output of the quantizer.⁴⁴ Under the present DOE-supported program, we designed, fabricated and evaluated the front end of this module. Fig.5 shows the circuit diagram for the comparator SQUID which also acts as a one bit digital SQUID.

A typical analog SQUID possesses a flux sensitivity better than $6 \times 10^{-7} \Phi_0/\text{Hz}^{1/2}$ which is more than adequate for many practical applications. The circuit diagram for a single-chip magnetometer without its pre-amplifier is shown in Fig. 5. It consists of a comparator SQUID

with single bit digital output when biased by a bipolar clock. The comparator SQUID is coupled to an input coil through the feedback loop. The loop is terminated at both ends by two separate SQUID-based *write gates* that are controlled by the comparator SQUID. In this circuit, a single loop is used to couple both the input and the feedback flux to the input comparator SQUID. The dynamic range of the SQUID chip is improved considerably by the addition of the double *write gates* into the feedback loop. To improve the sensitivity of this single chip magnetometer, a sensitive analog SQUID can be coupled to the input coil of the feedback loop as suggested by Rylov (Fig. 6).³² Due to the complexity of single-chip magnetometers and the ease of multiplexing digital circuits, these chips are best suited for multi-channel biomedical systems, such as encephalogram. Such systems require a field sensitivity of $10 \text{ fT/Hz}^{1/2}$ for an input coil of around $1 \text{ } \mu\text{H}$ and pick up coil area of $A=1 \text{ cm}^2$. This gives rise to a needed current sensitivity of $1 \text{ pA/Hz}^{1/2}$. Required dynamic range is determined by interference which has a slew rate of approximately $3 \text{ } \mu\text{T/s}$ at 60 Hz for a gradiometer system in a typical environment. The field sensitivity of the input pre-amplifier SQUID (B_m) should be better than $10 \text{ fT/Hz}^{1/2}$, or $B_m = \Phi_m n / A < 10 \text{ fT/Hz}^{1/2}$, where Φ_m is the flux noise of the SQUID and n is the current transfer ratio between the transformer and the SQUID loop inductance (L_s). Assuming $\Phi_m = 6 \times 10^{-7} \text{ } \Phi_0 / \text{Hz}^{1/2}$, then an upper bound for the turn ratio is about 830 turns for a pick up coil area of 1 cm^2 . Since $L_p \sim L_i \sim 1 \text{ } \mu\text{H} = n^2 L_s$, then $L_s = 10^6 / n^2$ in pH. Typical values for n and L_s are 150 turns and 45 pH , respectively.

Fig. 5 Circuit diagram for a single-chip SQUID magnetometer with coupling loop and double write gates. There is no intrinsic limit to the dynamic range for this type of SQUID magnetometer since the input flux is cancelled by the feedback current. Dynamic range is only limited by the current-carrying capacity of the input coil. The SQUID inductance is $12/8=1.5 \text{ pH}$ and the coupling transformer inductance is nominally $48 \times 8 \sim 380 \text{ pH}$. For simulation purposes, the coupling coefficient between inductors is assumed to be 0.7.

A typical value for the current gain of an analog SQUID pre-amplifier with its transformer is assumed to be about 100. Thus, a $1 \text{ pA/Hz}^{1/2}$ at the input translates to $100 \text{ pA/Hz}^{1/2}$ at the output. For a system with 7.5 MHz bandwidth (15 MS/s sampling frequency), this current is about $0.27 \text{ } \mu\text{A}$ which is the sensitivity needed from the comparator. This current sensitivity is, obviously, considerably higher than the intrinsic noise level of the comparator gate. However, it should also

be larger than the comparator's hysteretic current. To ensure the latter, the comparator's loop inductance is made of 8 parallel washers, each coupled to a 10-turn transformer (Fig. 7). All of these transformers are then put in series with the output resistor of the DC SQUID array amplifier. The current transfer ratio of the transformer between the pre-amplifier and the comparator with this arrangement is approximately 80, giving rise to a minimum current requirement of about 22 μA for the comparator.

Fig. 6 Circuit diagram for a very sensitive single-chip SQUID magnetometer with DC SQUID array pre-amplifier and feedback circuitry. The comparator consists of 8 washers to improve its sensitivity by accommodating the coupling of large inductance to its loop inductance. There is no intrinsic limit to the dynamic range for this type of SQUID magnetometer since the input flux is cancelled by the feedback current. Dynamic range is only limited by the current-carrying capacity of the input coil and the sensitivity of the input analog SQUID. The pick up coil is integrated with the feedback loop to improve the sensitivity of the over-all chip. For simulation purposes, the coupling coefficient between inductors is assumed to be 0.7.

Fig. 7 Layout schematic of the comparator circuit. It consists of 8 parallel washers to accommodate coupling of the 10 nH inductor into the SQUID loop. This substantially increases the sensitivity of the comparator gate.

In order to be able to fully reconstruct the signal from the output of the single-chip magnetometer, the sampling frequency should be at least twice the signal bandwidth or about 1 kHz. On the other hand, a signal slew rate of $3 \mu\text{T/s}$ or $1.5 \times 10^5 \Phi_0/\text{s}$ requires a clock frequency of at least 15 MHz to discriminate against spurious 60 Hz signals. At this clock frequency, the noise floor is about $10 \text{ fT/Hz}^{1/2} \times (15 \text{ MHz}/2)^{1/2} = 27 \text{ pT}$, which is the noise floor of the digital chip. Consequently, the hardware least significant bit (LSB) is 27 pT. Since this scheme uses digital filtering by over-sampling at a rate of $15 \text{ MHz}/1 \text{ kHz} = 15,000$, the minimum detectable magnetic field (software LSB) is $27 \text{ pT}/15,000^{1/2} = 220 \text{ fT}$. The hardware LSB also determines the minimum value for the feedback loop inductance. Given the minimum magnetic field of 27 pT and pick up coil of $1 \mu\text{H}$, the maximum current per fluxon in the feedback coil for proper operation should be $I_m = 2.7 \text{ nA}$. On the other hand, each Φ_0 in the feedback loop corresponds to $\Phi_0/(L_i + L_p) \sim 1 \text{ nA}$ which is less than I_m , as required. Decreasing the size of the pick up coil to a smaller area and lower inductance value, will not affect the overall system sensitivity as long as Φ_0/bit in the feedback coil is less than the 2.7 nA. In this design, the pick up coil is directly integrated in the feedback loop to obtain the desired minimum current in the feedback loop for each emitted fluxon and/or antifluxon. In addition, 1 nA/bit of feedback current corresponds to about 100 nA at the input of the comparator, which is less than the hysteretic current of the comparator gate, as required.

CIRCUIT SIMULATION

The simulation effort involved extensive computer analysis of the digital SQUID circuit to obtain optimum values for Josephson junctions, inductors and other circuit parameters. The SPICE computer program, enhanced considerably at HYPRES, was used in the design of circuits. This program can incorporate digital SQUID circuit elements as well as parasitics associated with its layout into a lumped circuit and analyze the performance of the digital SQUID chip. Optimization of the circuit was achieved by iterating the analysis for various values of the circuit elements and selecting the circuit parameters for the best performance. A digital SQUID chip with a wide dynamic range, and high signal-to-noise ratio, and wide operating margins was the objective of this program.

The detailed operation of the single-chip SQUID magnetometer circuit is as follows. The comparator SQUID has an asymmetric threshold characteristic as shown in Fig. 8. This SQUID gate is biased slightly over its critical current using a bipolar current source. In the absence of any external field, the output voltage at the clock bias point resembles the bipolar voltage shown in Fig. 9a. For a sufficiently large positive applied magnetic field, the junction settles to points (b1, b2) (Fig. 8) and only generates pulses in response to the negative portion of the applied gate current (Fig. 9b). The *write gates* are designed to have asymmetric threshold characteristics as shown in Fig. 10 and are biased below their thresholds. The bipolar current induced in the control lines of the *write gates* will cause the right and the left *write gates* to cross their lobes only in the positive and negative directions, respectively (Fig. 10) and produce SFQ pulses upon lobe crossing. The Josephson junctions are heavily shunted in order to emit only one SFQ pulse during each lobe crossing. When the feedback loop is closed and the comparator SQUID pulses

negatively, the left *write gates* launches fluxons into the storage loop. (Alternatively, when the comparator pulses positively, the other *write gate* launches antifluxons into the storage loop.) The injection of only fluxons or only antifluxons would continue in each clock period as long as the gate current of the comparator is below comparator's threshold current for positive or negative currents. With proper polarity, the SFQ-induced current in the superconducting feedback loop can eventually cancel the applied current and restore the comparator SQUID close to its original state (a1, a2) (Fig. 8). When the current in the feedback loop is close to zero, both *write gates*, alternatively, emit fluxons and antifluxons into the loop in each clock period, keeping the feedback current close to zero. One advantage of this scheme is that the size of the feedback loop can be very small and is actually determined by the desired signal slew rate. The polarity of the missing pulses determines the direction of the applied field, and the switching probability leads to a voltage across the comparator SQUID which is a measure of the strength of the input signal. The digital output is the difference between the number of negative and positive pulses across the comparator. A multi-bit up/down counter coupled to the output of the one-bit comparator can count the down pulses and subtract it from the up pulses to exhibit the output in digital form.

Fig. 8 Threshold characteristics of a comparator SQUID. Points a1 and a2 are the operating points when the total applied field to the comparator SQUID gate is zero. Points b1 and b2 are the SQUID's operating points under an applied field. The SQUID in steady state will always settle to points a1 and a2.

Since the current in the loop is always kept close to zero (regardless of the input magnetic flux), the dynamic range of this magnetometer chip is only limited by the current in the input coil and not the feedback loop or the pick up loop. Consequently, a system based on this chip running with a high speed clock has a virtually unlimited dynamic range and may be operated without elaborate magnetic shielding. This on-chip feedback circuitry is similar to the one described elsewhere²⁹⁻³⁰ with the added advantage of unlimited dynamic range.^{42,43} The novel architecture of combining two *write gates* to induce fluxons and antifluxons into the feedback loop gives this

digital magnetometer circuit its extremely wide dynamic range. This SQUID chip can be easily integrated with superconducting multiplexers to facilitate readout of multi-channel digital magnetometers. In addition, the pick up coil can be directly integrated with the feedback loop by putting it in series with the *write gates* and the control line of the comparator SQUID.

a

b

Fig. 9 Voltage across the comparator SQUID (C) in response to a bipolar source. a- In the absence of an external field, the junction voltage contains both positive and negative polarities. b- In the presence of an external negative magnetic field, comparator SQUID only generates negative pulses.

Fig.10 Threshold characteristic of the *write gates*. The *write gate* is biased below its minimum threshold current. This characteristic is designed to be asymmetric so that control current causes lobe crossing for positive (shown in this figure) or negative currents only.

Fig.11 shows the simulation results for a one-bit single chip digital SQUID. In the presence of a magnetic field, the comparator SQUID has missing pulses in one direction until the feedback current, induced by the clock, restores this SQUID to its original state. The first trace is the bipolar gate current to the comparator. The second trace is the output voltage of the comparator at its bias point. It is evident that the comparator misses several positive or negative pulses due to an external field until the comparator is restored to its original state by the feedback loop. The number of missing pulses is a measure of the applied field. A counter attached to the output of this chip can measure the applied signal by counting the positive pulses and subtracting the negative pulses from it. The last trace in this figure is the feedback current that approaches zero as the comparator is restored to its original state.

FABRICATION AND EXPERIMENTAL RESULTS

Figure 12 shows a photograph of a fabricated comparator SQUID chip together with the input coil and the *write gates* without the high sensitivity pre-amplifier. In this case, the feedback coil is directly integrated with the comparator SQUID. The comparator also functions as an analog SQUID as well as a one-bit comparator. This chip was fabricated using HYPRES' standard niobium process technology using 1 kA/cm^2 Josephson tunnel junctions and junction capacitance of $40 \text{ fF}/\mu\text{m}^2$. This circuit process utilizes 10-layers with all niobium electrodes and wiring, aluminum oxide tunnel barrier, Molybdenum (Mo) resistors, Au metallization and SiO_2 insulating

layers.¹⁰ Fig. 13 displays the threshold characteristics for the comparator SQUID. This characteristic is asymmetric as required for the proper operation of the comparator.

Fig.11 SPICE simulation results for a digital SQUID with feedback transformer. Traces from the top to bottom are: applied bipolar current source to the comparator SQUID, output voltage across the comparator SQUID, and the feedback loop current approaching zero causing the comparator to pulse in both direction.

The digital SQUID, without the pre-amplifier, operated properly as shown in Fig.14. In this figure, the top trace is the input signal. The middle signal is the voltage across the comparator with the number of missing negative pulses being the measure of the strength of the input signal. The comparator's sensitivity is approximately $0.1 \mu\text{A/bit}$ and can be improved further by increasing the size of the inductors in the feedback coil. The bottom waveform is the integrated output voltage and can be used to determine the slew rate of the circuit.

Fig.12 Photographs of fabricated digital SQUID chips using niobium technology.

Fig.13 Measured threshold characteristics of the comparator SQUID.

Experimental measurements indicate that the dynamic range of the digital SQUID amplifier is indeed large and is limited by the current-carrying capacity of the superconducting niobium lines. Figure 15 shows the experimental results for a double step input current. The height of each input step current is limited by the critical current of the Josephson junctions of the *write gates*. Any further increase in input current exceeds the critical current of these Josephson junctions and results in instability in the feedback coil. However, if the input current is kept below its threshold, the current in the feedback coil reaches its steady state value (which is close to zero) after several clock cycles, and one can increase the input current further, as evident by the second input step current, without causing any instability in the line. This increase in the input current can again be repeated until the DC level of the input current exceeds the current-carrying capacity of the input pick up coil. In practice, we have achieved approximately 20 mA for a 4 μm linewidth input line. The experimental results of Fig. 15 is significant because it overcomes one of the major problems associated with other types of digital SQUIDs using latching logic. Figure 16 shows a triangular input signal together with its integrated output. The clipping at the top of the output is due to the hysteresis in the comparator's characteristics which can be eliminated by the integration of a suitable analog SQUID pre-amplifier.

Fig.14 Experimental results for a one-bit digital SQUID chip without the high sensitivity SQUID pre-amplifier. Top trace is the applied signal of 2 μA . Middle trace is the bipolar signal from the comparator SQUID with frequency of 4 kHz (2 mV/div.). The number of negative pulses that are missing exhibits the strength of the input signal and can be counted by a multi-bit counter attached to the output of the SQUID. The comparator SQUID is eventually restored to its original state by the feedback inductor and pulses negatively and positively when the net current in the loop approaches zero. Bottom trace is the reconstructed output and can be used to determine the slew rate of the single-chip magnetometer at clock frequency of 4 kHz. The comparator SQUID is eventually restored to its original state by the feedback inductor and pulses negatively and positively when the net current in the loop approaches zero. Horizontal scale is 0.5 mSec.

Fig.15 Experimental results for a single-chip magnetometer exhibiting wide dynamic range. For each current step of the double step input current (0.15 mA), the feedback current (which is originally at its limit (just below the threshold current of the *write gates*), approaches zero, evident by the output voltage across the comparator. Upon feedback current approaching zero, the input current is further increased and is compensated by the clock through generation of fluxons or antfluxons into the feedback loop. This process can be continued until the current capacity of the input coil is exceeded by the input current, determining the upper bound for the dynamic range.

Fig.16 Top trace is the input signal to the single-chip magnetometer without the pre-amplifier. Bottom trace is the integrated output for clock frequency of 20 kHz. The horizontal scale is 1ms/div. The integrated output is not low-pass filtered and, consequently, shows significance out-of-band and quantization noise.

PERIPHERAL ELECTRONICS

We also designed and built the peripheral electronics for the digital SQUID magnetometer. A simple amplifier/integrator was designed and built to perform signal reconstruction. Figure 17 shows the circuit diagram for the amplifier/integrator. In addition, we assembled a 12-bit counter for interfacing with single-bit digital SQUIDs. This room temperature electronic module was tested and functions quite satisfactory. The complete peripheral electronics for the counter is shown in Figs. 18 through 24.

Fig.17 A simple amplifier/integrator circuit designed for signal integration.

We also procured a low noise probe and packaging for the digital SQUID. The SQUID package was built very similar to a cryogenic package that is commercially available for analog SQUIDs, and is believed to have quite satisfactory noise characteristics for magnetometer applications. The design is modular in a sense that packaged digital or analog SQUID magnetometers can be easily interchanged using this probe for evaluation or even field use.

CONCLUSION

We have demonstrated a single-chip magnetometer that has a very wide dynamic range limited by the current-carrying capacity of superconducting lines. This chip is similar to the single-chip magnetometer developed at Fujitsu laboratories but with the added advantage of accomplishing the desired dynamic range with considerably smaller feedback coil. In addition, due to its high dynamic range, it can be also operated in unshielded environments. It is believed that further optimization of this chip and the addition of a sensitive front-end analog SQUID coupled to a similar comparator gate, as well as better matching of inductors in the feedback loop, will result in a digital SQUID amplifier with read out capability down to sub-nano-amperes. In addition, the slew rate of the system can be improved considerably by operating the comparator with a relatively fast clock. The slew rate is given by $\phi_0/N \times F_c$, where N is the current transfer ratio

of the input transformer and F_c is the clock frequency. Consequently, with ordinary electronics and $N = 100$, slew rates in excess of $10^5 \Phi_0/S$ is easily possible. On-chip Josephson junction-based counters can easily improve the slew rate by an order of magnitude.

In summary, we have fulfilled all of the requirements of the phase II SBIR project. However, we intend to continue to the project to demonstrate a complete digital magnetometer system suitable for field application.

PERFORMANCE SUMMARY

	Demonstrated (Comparator alone)	Expected (with Pre-amplifier)
Dynamic Range	80 dB	>160 dB
Sensitivity	$0.1 \mu A (\sim 10^{-4} \Phi_0/Hz^{1/2})$	$10 pA (< 10^{-6} \Phi_0/Hz^{1/2})$
Slew Rate @ Clock Freq.	$1 k\Phi_0/s @ 100 kHz$	$100 k\Phi_0/s @ 100 MHz$

Fig.19 Pre-amplifier and comparator.

Fig.20 ECL to TTL converter and LED drivers.

Fig.21 Pulse shaper.

Fig.22 Accumulator.

Fig.23 Seven segment decoder and drivers.

REGULATORS

Fig.24 Regulators.

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