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51. Internationales Wissenschaftliches Kolloquium
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September 11 - 15, 2006

T. Reich, Th. Ortlepp, F. H. Uhlmann

Development of a digital SQUID device for high sensitive measurement of widely varying magnetic fields

INTRODUCTION

Analog superconductive quantum interference devices (SQUIDs) are favorite devices to detect very weak magnetic fields, far below the strength of the earth field. For example it is possible to measure the field due to fetal heart beat signals and human brain activities. All other systems for magnetic field measurement cannot compete with the analog SQUIDs in terms of resolution far below the single magnetic flux quantum Φ_0=h/2e with h is Planck's constant and e is the elementary charge. But the application of the superconducting rapid single flux quantum (RSFQ, [1]) digital electronics for high sensitive measurement of magnetic fields can bring significant advantages to conventional analog SQUID applications, especially in terms of slew rate and dynamic range. This makes superconducting digital devices interesting for applications in unshielded environment exposed to high magnetic fields. Furthermore utilizing an unconventional generalized single flux quantum (SFQ) logic with bidirectional operation principle comes up with an additional decreased effort in superconducting electronics, which is especially required for high temperature superconductor (HTS) realizations. We developed a low complexity single-stage digital SQUID device utilizing bidirectional SFQ technique [2]. This novel device can be assumed to be operated at frequencies in gigahertz range corresponding to slew rates of several 10^9 Φ_0/sec. We present first experimental results for the proper digital function as pre-stage for a digital SQUID magnetometer device. The presented measurements are performed for a reliable low temperature superconductor (LTS) technology at liquid helium temperature (4.2K), nevertheless the very low complexity of superconducting digital circuitry gives a promising prospect for a working digital SQUID based on HTS technology.

THE SINGLE-STAGE DIGITAL SQUID

The block diagram in Fig.1 shows the overall function of our digital SQUID concept as a counter for single magnetic flux quanta. The notation 'single-stage' stands for the simplest configuration of the digital SQUID with an intrinsic flux feedback and respectively a resolution capability of one Φ_0 as the smallest quantization unit. A change of the analogue input signal, for example a magnetic field in a magnetometer or gradiometer configuration or direct currents, will be detected and processed by the superconducting digital electronics due to short SFQ pulses.

Illustrations in Fig.2 gives more details about the function principle of the single-stage digital SQUID, described in [2]. A special kind of superconducting output converter (SFQ/dc converter) was developed. It is featured by the capability of converting very short (≈5ps) and weak SFQ pulses (with $\int V_{pulse} dt = \Phi_0$) into voltage level signals, detectable for semiconductor readout electronics. This special SFQ/dc converter distinguishes from conventional converters applying a Toggle-Flip-Flop architecture (e.g. [1]). The rising edge of the alternating bias signal (signal (2) in Fig.2) is used to produce one SFQ pulse, generated by the dc/SFQ converter and used to ensure the decision of the comparator stage. Corresponding to the analog

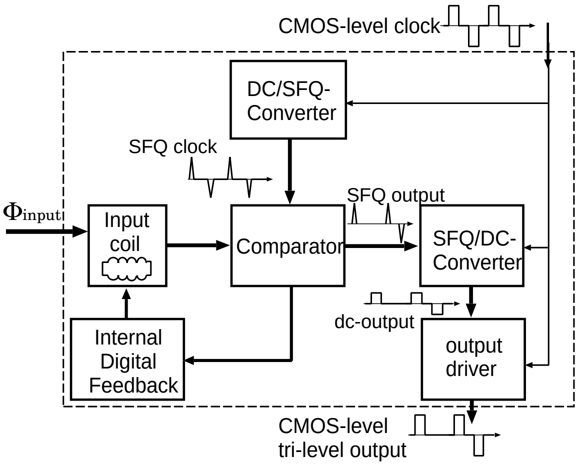
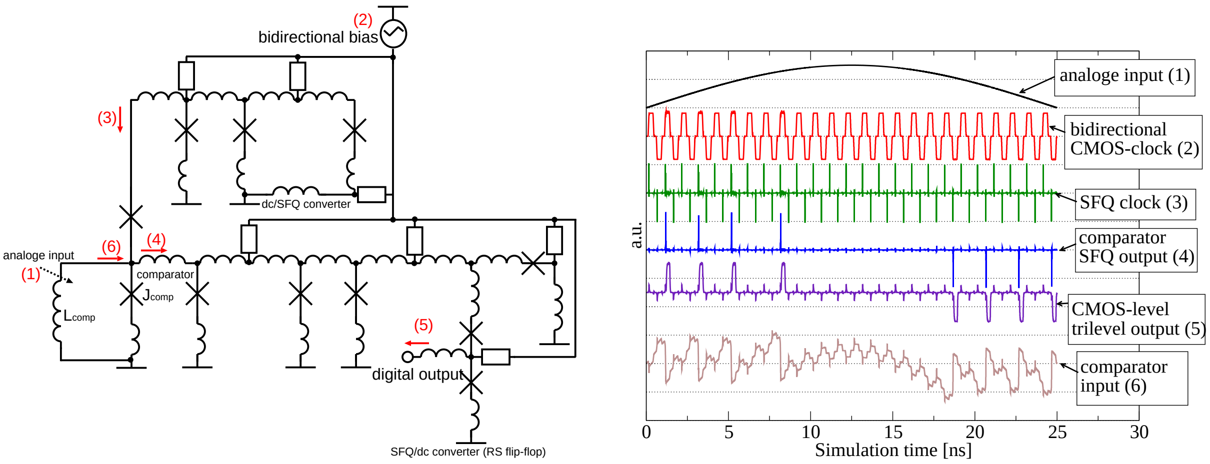


Fig. 1. The whole digital SQUID sensor concept in overview: The analogue input field is detected and converted to digital tri-level signal (-1,0,+1) with the frequency of CMOS-level clock signal.

input signal (signal (1) in Fig.2) the comparator may send one SFQ pulse to the output stage, which causes a voltage swing on the output (signal (5) in Fig.2). In our case the falling edge of the alternating bias signal is used to reset the output converter. So the following clock cycle can be used to proceed the next SFQ pulse. Hence the clock frequency is equal to the slew rate of the system.



(a)

(b)

Fig. 2. Single-stage digital SQUID: (a) circuit diagram of the simplest configuration, (b) Transient simulation for illustration of the function principle.

Using an alternating bias comes up with a tri-level output, which is able to represent positive, negative or no changes in the analoge input signal. Focusing this approach of ac bias supply, which gives additional challenges corresponding to high frequency signal propagation, is justified in the demand for a very low complexity in superconducting circuitry, especially in HTS technology. Concerning a reasonable output voltage of around 150μV at frequencies in the GHz range, an amplification of the output signal before post processing is indispensable. This can be realized on chip by special superconducting circuitry (e.g. [3]) or by semiconducting rf-amplifiers. The switching probability distribution of the comparator in Fig.3 gives information about the sensitivity of the comparator stage. For the low performance digital SQUID for first experimental analysis the inductance L_{comp} was set to a small value, which corresponds to a current quantization $\Delta I \approx \Phi_0/L_{comp}$ of some tens of μA. In this case ΔI is far above the grey zone of the comparator. But for digital SQUID devices with higher current resolution (e.g. for digital SQUID magnetometers for high sensitive magnetic field measurement) ΔI will drop far below 1μA. Now the comparator performance becomes more important: adjusting the operation point to a high slope in the probability distribution effects the oversampling effort for a desired sensitivity of the system.

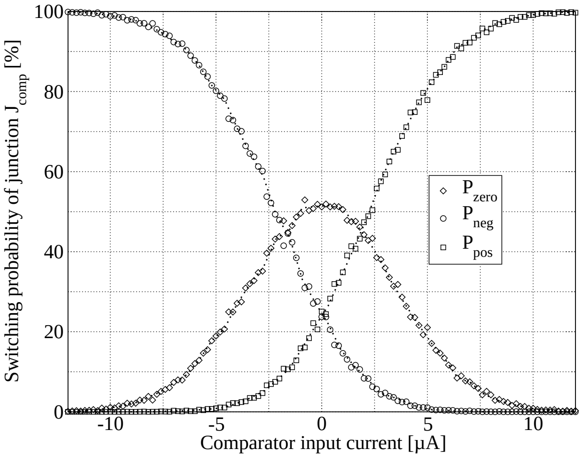


Fig. 3. Simulation of the switching probability of the comparator with tri-level operation at 4.2K (liquid helium temperature). 10GHz alternating bias signal was applied. P_{pos} denotes the probability for one positive switching event per clock cycle, P_{neg} for one negative switching event and P_{zero} for no switching, which also includes positive and negative switching per clock cycle.

EXPERIMENTAL ANALYSIS

For the first experimental validation, following an extended optimization process [4], chips have been fabricated in low temperature superconductor (LTS) niobium technology at JeSEF [5] (Fig.4).

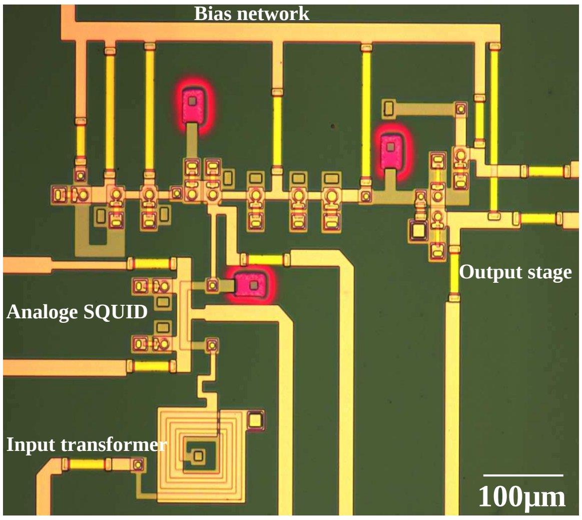


Fig. 4. Chip photograph of the single-stage digital SQUID in a low performance configuration, fabricated in LTS niobium technology at JeSEF [5]: an input current is inductively coupled to the inductance of the comparator stage L_{comp}. The overall ac biasing is realized by a bias resistor network. Nevertheless single bias lines are included for adjusting the operation point. The analoge SQUID, included for investigating sub-Φ_0-resolution, was ignored for experiments.

In a first phase, the experimental analysis of digital test circuits has been investigated with standard SFQ cells, as well as with novel SFQ/dc converters. Indeed, this was necessary to insure the proper digital processing, of the magnetic flux to detect, by the superconducting circuitry. The characterization of the digital parts has been performed by a dc/SFQ/dc converter, which contains all major parts of the digital SQUID, except the comparator stage. This testing circuit is essential to validate the proper SFQ pulse propagation applying the unconventional alternating bias current. A special focus was set to the SFQ/dc converter with an RS

Flip-Flop like topology for tri-level operation, described above. This SFQ/dc converter, used for the digital SQUID device, produces maximum output voltages V$_{out}$>200μV due to adaption of McCumber parameter β_c to values greater than unity. In Fig.5 an output voltage of 175μV was measured, which is still too weak for high frequency operation. According to this problem experiments with the additional voltage multiplier ([3], [2]) show a voltage amplification, standing unfortunately below the expected factor 2. Measurements of the digital test circuit have also been performed successfully with sinusoidal bias current. They brought very good expectations for operation frequencies in the Gigahertz range. Nevertheless, in this case, it was not possible to achieve output pulse lengths of the order of a quarter clock cycle. Althogether this experimental results for proper function of the SFQ basic cells are essential for the validation of the digital SQUID.

Following we investigated the feasibility of our digital SQUID in a low performance configuration. In operation without oversampling a small change in the input signal is represented by each single output pulse. In fact this mode is not suitable to achieve a high current sensitivity, but it allowed us to prove experimentally the proper behavior of the SFQ circuit without external data preprocessing outside the superconducting environment. Figure 5 shows the reconstruction of a 5Hz sinusoidal input current with low frequency sampling of 1kHz. The experimental dynamic range was far below the predictions by simulation results. This restricted performance is caused by the chosen current sensitivity of the comparator and the current transformer ratio for the 'proof of principle' device setup. For operation up to 10kHz bias margins of ±12.3% have been achieved, which are close to the expectations from simulation studies. More detailed experimental results can be found in [6].

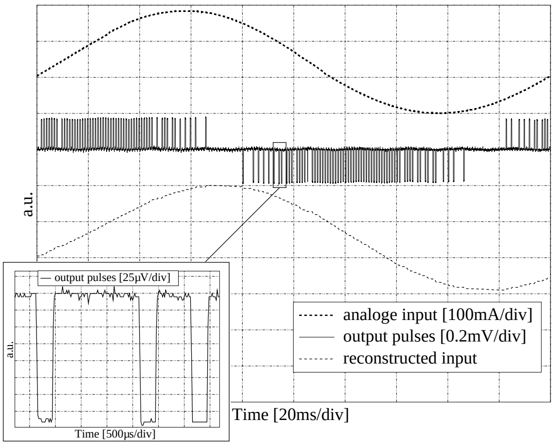


Fig. 5. Experimental analysis of the digital SQUID device: low frequency sampling of sinusoidal input current, inductively coupled to the comparator loop L$_{comp}$. Inlay: shape of the CMOS-compatible voltage level output pulses.

REALIZATION IN HTS TECHNOLOGY

Digital circuits based on RSFQ technique are esthablished in LTS technologies, which are characterized by well controlled technology with acceptable spread in relevant technological parameters. They were multiple realized, even with high complexitiy ([7], [8]). In the middle of the eighties new material combinations were found with higher critical temperatures, which was very interesting, especially in terms of cooling effort. Further higher characteristic voltages come up with higher operation speeds as one of the most important issue nowadays. This is well promising for more efficient application of superconducting digital electronics. Unfortunally HTS technologies (e.g. HTS technologies in $YBa_2Cu_3O_7$ (YBCO) with critical temperature T$_c$=92K) in its current state suffers from technological difficulties and realizing complex digital circuits is difficult and not presented yet. In addition hysteretic Josephson junctions are not available due to intrinsic shunting. But in principle one can say, HTS technologies are applicable for digital circuits [9] and this was proven by experiments [10], [11]. Taking into account the technological restrictions we started to develop the digital SQUID concept, described above. In the simplest configuration the whole circuitry requires 11 non hysteretic junctions, which is sufficient for the applied HTS ramp-type technology, composed by 3 superconducting layers [12] (Fig.6).

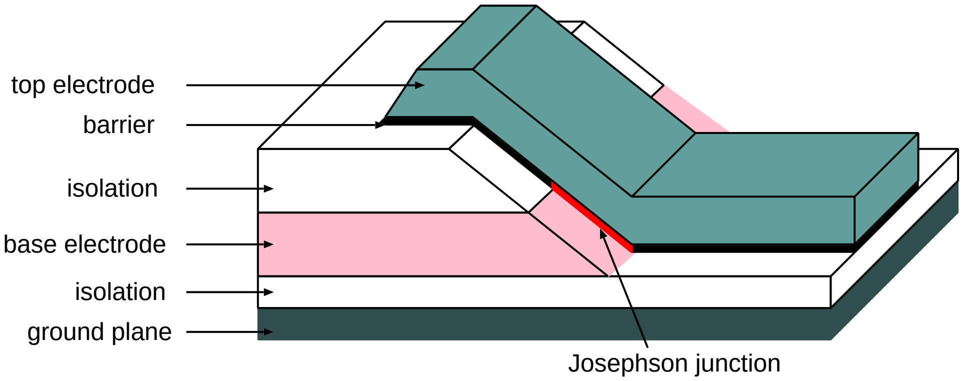
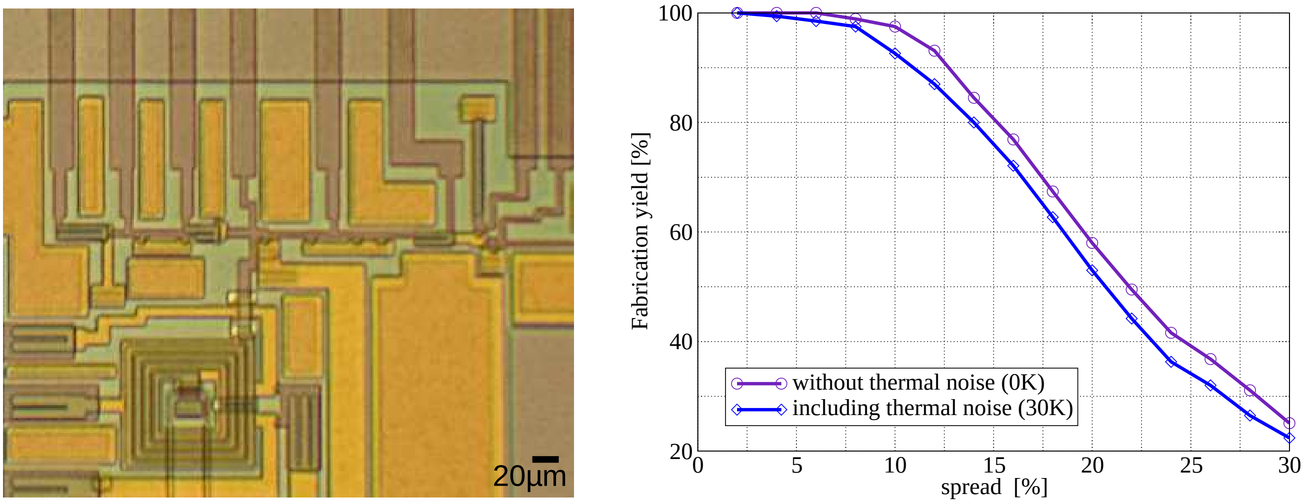


Fig. 6. Cross section of a Josephson junction in HTS ramp-type technology with 3 superconducting layers [12].

The design process gives aditional challenges. An operation temperature around 30K is high in comparison to 4.2K for the Niobium LTS technology and must be considered for the optimization prozess by including thermal noise [13]. Further restricions in the orientation of ramp-type Josephson junctions degreades the degree of freedom for an optimum design. Nevertheless we realized the single-stage digital SQUID, fabricated at University of Twente (NL), shown in Fig.7(a). The simulated fabrication yield over parameter spread was performed for only the digital components of the circuit including thermal noise at a temperatur of 30K. It gives a good prospect for correct digital function for reasonable spread quantities for technological parameters around 10% [14] (Fig.7(b)).



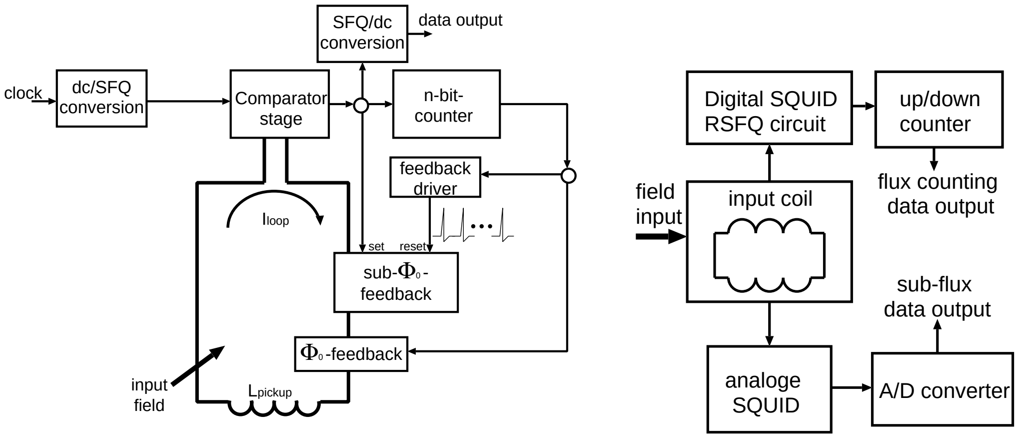
(a)

(b)

Fig. 7. Single-stage digital SQUID in HTS ramp-type technology: (a) chip photograph, (b) estimated fabrication yield for digital components of the single-stage digital SQUID (spread parameters: global inductances and local critical currents).

DIGITAL SQUID FOR HIGH SENSITIVE MAGNETIC FIELD MEASUREMENTS

For the measurement of magnetic fields the digital SQUID devices can be seen as a well promising candidate due to high slew rates and the very large dynamic range. But its intrinsic resolution of one flux quantum brings an indisputable disadvantage for high sensitive magnetic field measurement. It will be hard to achieve the field resolution of analog SQUIDs [15], e.g. required to detect the magnetic field of fetal heart beat or human brain activities. But the digital SQUID characteristics are well promising for operation in unshielded environment, suitable for nondestructive evaluation (NDE) [16] and several other applications. Realizing a digital SQUID device with the capability of a sub-Φ_0-resolution there are several possibilities. To get a full digital solution (Fig.8(a)) we performed extensive concept and simulation studies to extract information about the feasibility of the SFQ technique based digital SQUID for high sensitive magnetic field measurements, extensive reported in [17]. In conclusion (see also [18]): the improved flux respectively field resolution has to be bought by a decreased slew rate and an significant increased complexity in superconducting circuitry. For example to achieve a flux resolution of 1/64 Φ_0 the number of Josephson junctions increases to around 160, which is out of question for any HTS technology. Improving the flux resolution by some orders seems to be not practicable with such an approach. A more promising possibility is the combination of the single-stage digital SQUID with a direct or indirect coupled dc-SQUID (Fig.8(b)). This device comes up with a improved flux resolution by several orders, but the dynamic performance will be degraded. Table I gives a comparison of the performance estimations for three digital SQUID approaches applied in magnetometer devices.



(a) (b)

Fig. 8. High resolution approaches: (a) Function principle of a multi-level (here 2-level) digital SQUID, described in [17]: in difference to the single-stage digital SQUID the intrinsic flux feedback is replaced by an on-chip feedback circuitry, (b) digital SQUID with coupled dc-SQUID

TABLE I

COMPARISON OF DIFFERENT MAGNETOMETER APPROACHES APPLYING THE DIGITAL SQUID

	single-stage digital SQUID	multi-level [18] digital SQUID	Digital+ dc-SQUID
slew rate $SR_{flux}[\Phi_0]$ (a)	very high (f_s)	low ($1.56\ 10^{-2} f_s$)	very high (f_s)
resolution capabilities	low	high	very high
-flux [Φ_0]	1	$1.56\ 10^{-2}$	$<10^{-4}$ (b)
-field [T] (c)	$64.6\cdot10^{-12}$	$\approx1\cdot10^{-12}$ (d)	$<6{,}46\cdot10^{-15}$
i/o complexity	very low	very low	high
superc. complexity	very low (11 JJ)	high ($\approx$160 JJ)	very low
HTS realization suitable?	yes	not yet	yes

(a) f_s is sampling frequency, some ten Gigahertz are possible for SFQ electronics,

(b) theoretical estimation, (c) for a reasonable pickup loop area of 32mm^2, (d) for m=3 and n=4, feasible for f_s=1GHz,

CONCLUSIONS

We presented a novel digital SQUID device based on very fast and low power consuming superconducting SFQ electronic. The device is characterized by its very low complexity of 11 Josephson junctions, which gives a good prospect for realization in the more critical high temperature superconductor (HTS) ramp-type technology. Further simulation studies show an impressive performance for flux slew rates and dynamic range. Proper function is proven by experiments in low frequency range. This is an important step towards a magnetometer realization utilizing this digital SQUID device. For high sensitive magnetic field measurement we investigated modifications of the digital SQUID topology to overcome the field sensitivity restriction due to the intrinsic resolution of one flux quanta. We conclude, that the hybrid magnetometer device, composed by the single-stage digital SQUID with its low complexity and the coupled dc-SQUID with high flux sensitivity, is the most promising way to apply our digital SQUID for high sensitive magnetic field measurements.

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