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Design of Digital DROS for Wide Dynamic Operation Range with sub-single flux quantum resolution

Hiroaki Myoren\textsuperscript{a}, Kohsuke Terui\textsuperscript{a}, Naoya Shimada\textsuperscript{a}, Tohru Taino\textsuperscript{a}

\textsuperscript{a}Graduate School of Science and Engineering, Saitama University, 255 Shimo0Okubo, Sakura-ku, Saitama 338-8570, JAPAN

Abstract

We designed a digital double relaxation oscillation SQUID (DROS) with an single flux quantum (SFQ) feedback circuit for digital SQUID magnetometers. The DROS is magnetically coupled to a feedback SQUID loop and a signal magnetic flux is input to the feedback SQUID loop. The DROS generates two kinds of voltage pulses corresponding to the total magnetic flux in the feedback SQUID loop. Those voltage pulses are converted to SFQ and anti-SFQ pulses and input to the feedback SQUID loop to keep the magnetic flux in the feedback SQUID loop constant. A read-out dc SQUID (R/O SQUID) is also magnetically coupled to the feedback SQUID loop for monitoring the actual magnetic flux in the feedback SQUID loop. The number of the generated SFQ pulses is estimated by SFQ feedback steps on output voltage curves generated from the R/O SQUID. Wide dynamic operation range is realized by the SFQ feedback and sub-$\Phi_0$ magnetic flux resolution is realized by the R/O SQUID, where $\Phi_0 = h/2e$ is the single magnetic flux quantum. Also one digital DROS magnetometer can be operated with less than 10 mA. We fabricated a designed digital DROS using ISTEC SRL 2.5 kA/cm\textsuperscript{2} Nb standard process II and are trying to confirm the correct operation of the digital DROS.

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1. Introduction

Some applications such as a biomagnetism and nondistuctive evaluation (NED) in unshielded environment require small magnetic field measurements with both wide dynamic range and high slew rate. Digital SQUID based on a flux-locked loop operation using an on-chip digital circuit is very suitable for the above listed applications.

The double relaxation oscillation SQUID (DROS) has been studied as a highly sensitive SQUID with a flux noise spectral density of sub-$\mu\Phi_0/\sqrt{\text{Hz}}(@1\text{ kHz})$ [1], where $\Phi_0 = h/2e$ is the single magnetic flux quantum. An integrated digital SQUID, called the Smart DROS, that is combined with an on-chip flux locked-loop (FLL) circuit has been proposed [2]. We proposed a few types of digital DROSs with on-chip digital FLL circuits combined with up/down counters and D/A converters [3, 4, 5]. Using single flux quantum (SFQ) logic circuits [6] for the on-chip digital FLL circuits, we could expect higher slew rate using only dc biasing scheme without resorting to ac current bias[7, 8]. However the D/A converter limited the dynamic range less than $\pm 0.3\Phi_0$. To obtain wide dynamic range, we introduced a feedback loop connected to an input signal coil and a DROS as a comparator and feedback operation realized using SFQ pulses from...
the DROS[9]. For the proposed digital DROS, we expected a wide dynamic range and high slew rate [10]. Numerical simulation results suggested the designed digital DROS has a dynamic range exceeding ±100 Φ₀ and a magnetic slew rate of 3×10⁹ Φ₀/s[9].

In this study, we propose a digital DROS with an SFQ feedback circuit that would be operated under DC bias current of about 10 mA, for SQUID array magnetometers. A read-out dc SQUID (R/O SQUID) is connected feedback SQUID loop for monitoring the actual magnetic flux in the feedback SQUID loop. The number of the generated SFQ pulses is estimated using SFQ feedback steps on output voltage curve from the R/O SQUID. Wide dynamic operation range is realized by the SFQ feedback and sub-Φ₀ magnetic flux resolution is realized by the R/O SQUID.

2. Digital DROS with SFQ FLL Circuit

The block diagram of the digital DROS is shown in Fig. 1. The feedback SQUID, drawn with thick solid lines, is mutually coupled to an input coil for an input flux signal Φₘ, a DROS as a comparator and a dc SQUID for readout. The DROS generates two kinds of voltage pulses, Vₘ and Vᵣ, corresponding to the total magnetic flux in the SQUID loop. The voltage pulses are converted to SFQ pulses S and S, and input to the feedback SQUID loop to keep the magnetic flux in the SQUID loop constant. The number of the generated SFQ pulses can be estimated by SFQ feedback steps on an output voltage curve generated from the R/O SQUID. The SFQ pulses generated are also counted using an SFQ up/down counter optionally. Thus, the count corresponds to the input magnetic flux with Φ₀ resolution.

The typical circuit structure of a DROS has two hysteretic DC-SQUIDs, a signal SQUID and a reference SQUID, in series, shunted by an external inductance and a resistance. The signal SQUID is mutually coupled to the feedback SQUID loop whereas a constant magnetic flux apply to the reference SQUID to keep critical current of the reference SQUID around half modulated value. In our DROS circuit, the reference SQUID is replaced with a reference Josephson junction (JJ) in order to eliminate the need for an input coil for the reference SQUID, as shown in Fig. 1[11]. The critical current of the signal SQUID was set to be 200 μA and modulated down to 150 μA by an input current Iᵢ, whereas the critical current of the reference JJ was set to be 180 μA in this study. Relaxation oscillation is generated when the bias current Iᵦ (≥200 μA)

![Fig. 1. Block diagram of the digital DROS.](image-url)
Fig. 2. Result of dynamic simulation for a digital DROS. (a) Input current $I_{in}$, re-constructed magnetic flux $\Phi_{\text{Digital}}$ from digital outputs and output of the R/O SQUID and (b) the same as (a) with enlarged time scale. Thick solid line is guide to the eyes.

Fig. 3. Comparison between re-constructed magnetic flux $\Phi_{\text{Digital}}$ from digital outputs and re-construcuted magnetic flux $V_{\text{analog}} - \Delta V\Phi_{\text{Digital}}$.

Fig. 4. Mask layout of digital DROS with R/O SQUID.

$\mu$A) is correctly chosen. The frequency of relaxation oscillation, $f_{\text{DROS}}$ is mainly determined by the shunt inductance and the shunt resistance and was set to be 200 MHz in this study. This is limited by a bandwidth of our room-temperature measurement setup.

The R/O SQUID had the same circuit parameters of the signal SQUID, besides JJs parameters: the R/O SQUID has two overdamped JJs whereas the signal SQUID had two underdumped JJs. During digital SQUID operation, the R/O SQUID is applied a magnetic flux of around $\Phi_0/4$ from the feedback SQUID loop.

We carried out dynamic simulations for the digital DROS using the superconducting circuit simulation program Jsim[12]. All circuit parameters corresponded to those of the fabrication process of the ISTEC SRL Nb standard process II[13]. Most of SFQ digital circuits were referred from the CONNECT cell library[14]. Fig. 2 shows simulation results of a digital DROS with the R/O SQUID. Re-constructed magnetic flux $\Phi_{\text{Digital}}$
are corresponding to input current $I_{in}$ as shown in Fig. 2(a). Output voltage of the R/O SQUID contains structure related to the SFQ digital feedback and also the analog magnetic signal below $\Phi_0$, as shown using thick solid line in Fig. 2(b). We may extract the digital signals of the SFQ feedback operation and the analog signals $\Phi_{sig} - n\Phi_0$ from the output voltage of the R/O SQUID. Fig. 3 shows comparison between re-constructed magnetic flux $\Phi_{digital}$ from digital outputs and re-constructed magnetic flux $V_{analog} - \Delta V\Phi_{digital}$ from output signal of R/O SQUID. Here $\Delta V$ corresponds to a voltage change of the R/O SQUID with magnetic flux change of $\Phi_0$. As shown in Fig. 3, sub-$\Phi_0$ resolution is realized using the R/O SQUID.

From the simulation result, the slew rate and dynamic range of the digital DROS with R/O SQUID were $2\times10^8\Phi_0/s (= f_{DROS} \times \Phi_0)$ and more than $\pm 100\Phi_0 (= \pm f_{DROS}/2\pi f_{signal} \times \Phi_0)$ for $f_{signal}$=300 kHz, respectively. Here $f_{signal}$ is a frequency of the input magnetic flux signal with sine-wave function. The slew rate depends on the SFQ feedback frequency and was determined by the relaxation oscillation frequency $f_{DROS}$ of 200 MHz in the simulation. The dynamic range for a narrow-band-width signal should be unlimited for a DROS with an SFQ feedback loop in principle, but for the digital DROS with $n$-bit up/down counter circuit, the dynamic range is $\pm 2^{n-1}\Phi_0$, limited by the bit length of the up/down counter. Also one digital DROS magnetometer can be operated with less than 10 mA without an optional SFQ up/down counter.

### 3. Fabrication and Measurement results of components of digital DROS

We fabricated a DROS and a digital DROS, as shown in Fig. 4, using SRL ISTEC Nb standard process II, in which critical current density is 2.5 kA/cm$^2$. Fig. 5 shows the DROS response with changing $I_{input}$. In accordance with the input current $I_{input}$, the reference JJ generated voltage pulses at $I_{input} < 1\mu A$ and the signal SQUID generated voltage pulses at $I_{input} > 1\mu A$, and we also confirmed the correct DROS operation as a magnetic flux comparator.

Fig. 5(a) shows the DROS response with changing $I_{in}$. In accordance with the input current $I_{in}$, the reference JJ generated voltage pulses at $I_{in} < 1\mu A$ and the signal SQUID generated voltage pulses at $I_{in} > 1\mu A$, and we also confirmed the correct DROS operation as a magnetic flux comparator. Fig. 5(b) shows the measurement result for a fabricated digital DROS with SFQ pulse feedback using voltage readouts from the signal SQUID and the reference JJ. Since output voltages from the signal SQUID and the reference JJ are proportional to the pulse density, observed voltage curves correspond to positive and negative derivatives of the input current $I_{in}$. We confirmed correct FLL operation of the fabricated digital DROS.

Fig. 6 shows output voltage from the R/O SQUID, accompany with two outputs of the DROS. The output voltage from the R/O SQUID was similar to the output of the DROS and seemed to be affected by those
signals. So we changed the layout design of digital DROS to avoid mutual coupling between the DROS output and the R/O SQUID.

4. Conclusion

We designed a digital DROS with a relaxation oscillation frequency of 200 MHz and a R/O SQUID mutually coupled to the feedback SQUID loop to achieve sub-$\Phi_0$ magnetic flux resolution. Numerical simulation results suggested the designed digital DROS has a dynamic range exceeding $\pm 100 \Phi_0$ for $f_{\text{signal}}$ less than 300 kHz and a magnetic slew rate of $2 \times 10^8 \Phi_0/s$ for $f_{\text{DROS}}=200$ MHz. Digital DROS magnetometer can be operated with less than 10 mA without an optional SFQ up/down counter and suitable for digital SQUID arrays. We fabricated the designed digital DROS using ISTEC SRL 2.5 kA/cm$^2$ Nb standard process II and confirmed the correct operation of the main components, the DROS and the digital DROS with SFQ pulse feedback. To realize sub-$\Phi_0$ resolution of the digital DROS, further study will be needed.

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