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Reduction of the supply current of single-flux-quantum time-to-digital converters by current recycling techniques for the operation in cryo-cooler

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***Abstract*—We have been developing superconducting time-of-flight mass spectrometry systems that utilize superconducting strip particle detectors and single-flux-quantum (SFQ) time-to-digital converters (TDCs). We previously demonstrated a 24-bit SFQ TDC with a 3 by 24-bit first-in first-out (FIFO) buffer using the AIST Nb standard process (STP2) with a time resolution of 100 ps. In this study, we improved the SFQ TDC by using a current recycling technique. The technique enables us to increase the FIFO buffer capacity without increasing the total supply current, and the result is an improvement of ion count rates. We designed and demonstrated the SFQ TDC with a 12 by 24-bit FIFO buffer, whose total supply current was reduced by 71% with the current recycling technique.**

***Index Terms*—SFQ circuits, TDC, FIFO, current recycling, TOF MS, superconducting detectors**

I. Introduction

WE have been developing novel superconducting mass spectrometry (MS) systems that use highly sensitive superconducting strip particle detectors (SSPDs) [1]-[3] and high-speed single-flux-quantum (SFQ) digital circuits [4]. For time-of-flight (TOF) MS, which is often used to identify proteins because of its simplicity, high resolution and sensitivity [5], we are developing SFQ time-to-digital converters (TDCs) [6], [7]. SFQ TDC can measure the time intervals of multiple input signals with the time resolution of several picoseconds [8] and directly convert them into digital data. Our SFQ TDC is composed of a 24-bit counter to measure the TOF of biomolecules, an *n* by 24-bit first-in first-out (FIFO) buffer to store *n* TOF data and a shift register (SR) to read out the TOF data. In a previous study, we demonstrated the SFQ TDC with a 3 by 24-bit FIFO buffer [7] fabricated by using the AIST 2.5 kA/cm^2 Nb standard process (STP2) [9] and a CONNECT cell library [10] with a time resolution and a dynamic range of 100 ps and 1.68 ms, respectively. In the TOF MS using the matrix-assisted laser desorption/ionization method [11], [12], tens of ions are successively detected for a single laser shot. Therefore, we need tens of buffers to measure the TOF of ions without missing a reading. However, it is difficult to simply increase the number of buffers, because the increase in circuit scale causes large heat dissipation in the normal metal wires between the cryogenic temperature and the room temperature due to the increase in supply current.

To solve this problem, we applied a current recycling technique [13]-[15] to the FIFO buffer in SFQ TDCs. The technique enables us to increase the circuit scale without increasing the supply current. In this study, we improved the structure of magnetically coupled pulse transfer circuits for the current recycling technique, and designed and demonstrated SFQ TDCs with a 12 by 24-bit FIFO buffer.

II. Current Recycling

A. Serial biasing for current recycling

In conventional SFQ circuits, bias currents are supplied to each circuit block in parallel and all circuit blocks are placed on a common ground plane (GP). In current recycling, bias currents are supplied to each circuit block serially and recycled as shown in Fig. 1, so that the total supply current is reduced to 1/N. This technique is attractive especially for very large-scale SFQ circuits.

In the current recycling technique, each circuit cannot be connected directly because each circuit is placed on different GPs, which have electric potential differences between the SFQ circuits on different GPs. Therefore, signal transfer circuits

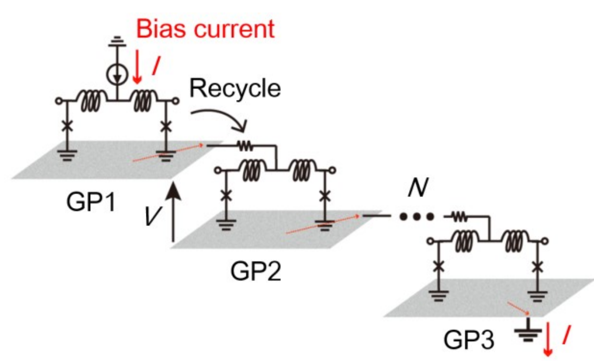

Fig. 1. Schematic of serial biasing (current recycling)

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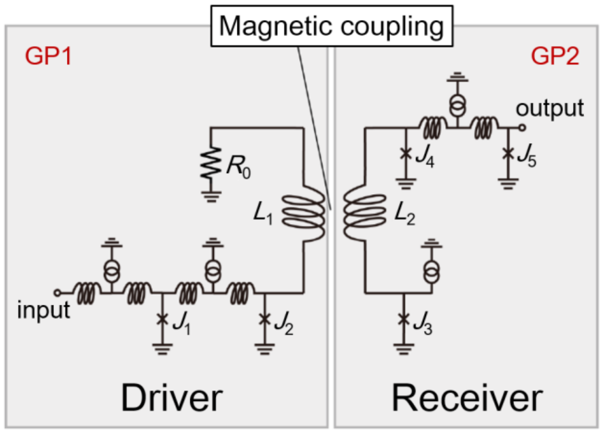

Fig. 2. Schematic of driver/receiver circuit. I_c (J_1) = 280 μA, I_c (J_2) = 400 μA (β_c = 15), I_c (J_3) = 95 μA (unshunted), I_c (J_4) = 100 μA (β_c = 0.03), I_c (J_5) = 216 μA, R_0 = 0.5 Ω, L_1 = 6.26 pH, L_2 = 9.04 pH, k = 0.409.

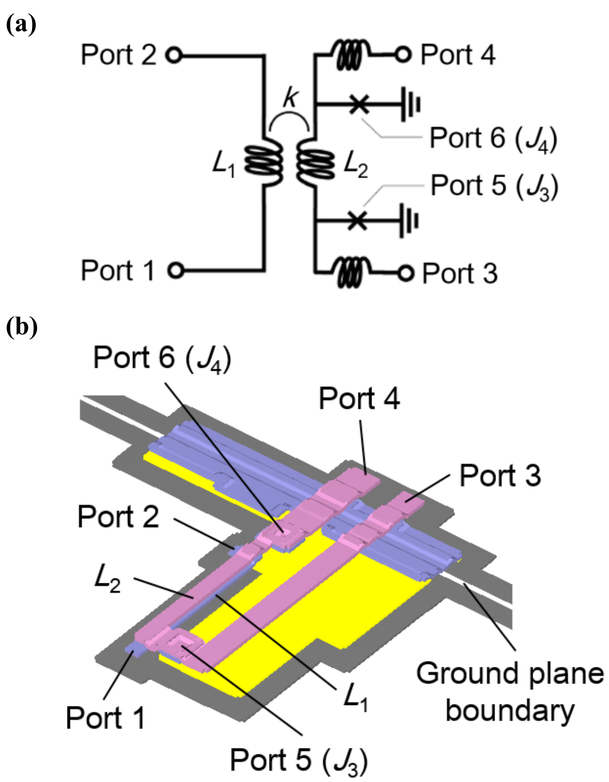

Fig. 3. (a) Schematic of magnetically coupled part for extracting parameters. (b) 3D image of magnetically coupled part of vertical type of D/R circuit.

without direct contact are required to transfer SFQ pulses between SFQ circuits on different GPs.

B. Signal transfer circuits

A schematic of signal transfer circuits, where the driver circuit and the receiver circuit are magnetically coupled, is shown in Fig. 2. An input SFQ pulse propagates to the driver output through the coupling structure composed of L_1 and L_2. The superconducting quantum interference device (SQUID) in the receiver detects the magnetic flux and generates an SFQ pulse. The SQUIDs in the transfer circuits are very sensitive to a magnetic field. Therefore, the operation margins of the transfer circuits are considered small due to the effects of ground currents concentrating along the edge of the GP. In this study, we adopted a structure of a magnetic coupling part perpendicular (vertical) to the GP boundary, as shown in Fig. 3. In the structure, the receiver has high tolerance to the magnetic field due to the current along the edge of the GP.

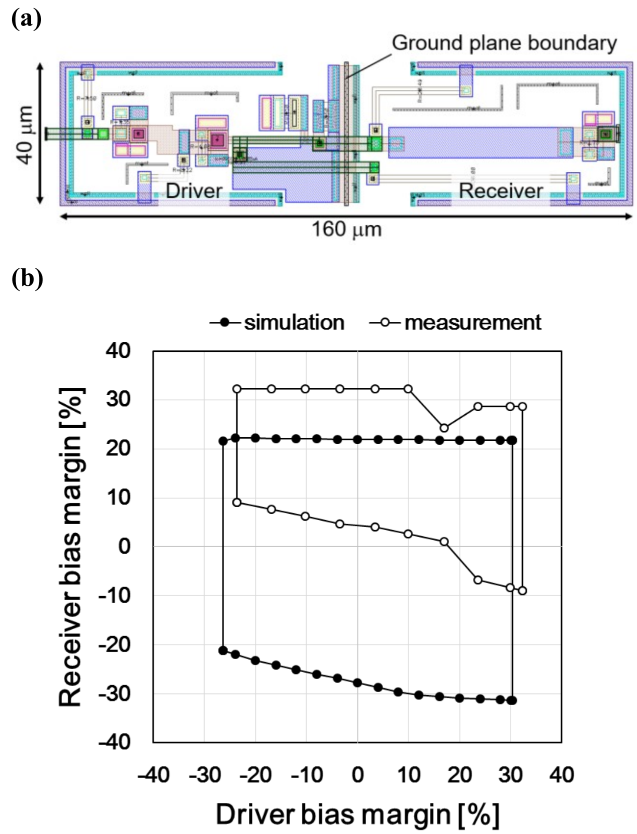

Fig. 4. (a) Layout of driver/receiver (D/R) circuit for current recycling. (b) Bias margins of D/R circuits, where the margins are obtained by simulation (JSIM) and measurement.

Using the parameters of the circuits shown in Fig. 2, we designed the driver/receiver circuits shown in Fig. 4(a). The values of L_1, L_2 and the coupling factor k are very important for the driver/receiver circuits. Although we often use Lmeter [16] to extract the values of inductance from a layout, it is not suitable for such a complicated three-dimensional inductance extraction. We extracted these values by using InductEx [17], where the values of L_1, L_2, and k were 6.26 pH, 9.04 pH, and 0.409, respectively. We used Lmeter for evaluating other inductances. We measured the operation of the driver/receiver circuits at low frequency and plotted the bias margin in Fig. 4(b). In Fig. 4(b), the areas surrounded by black and white circles are operating margins obtained by a simulation using the Josephson Integrated Circuit Simulator (JSIM) [18] and by measurement, respectively. We confirmed correct operation of the driver/receiver circuits and wide bias margins. The measured bias margin of the receiver circuit was smaller than that of the simulation and the operating area shifted toward a higher bias level in comparison with the simulated bias margin. Although the driver/receiver seemed to be applicable to our TDC, we plan to improve the receiver circuits in the near future.

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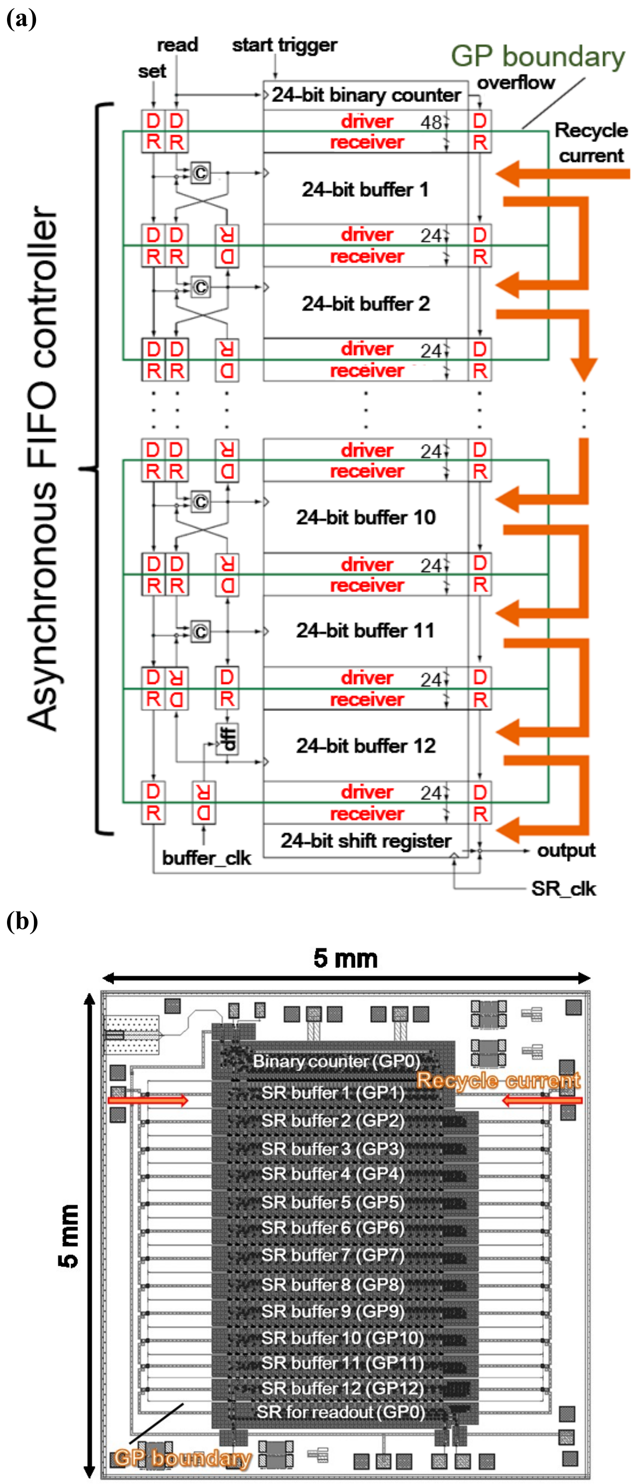

Fig. 5. (a) Block diagram of current recycling SFQ TDC with a 12 by 24-bit FIFO buffer. (b) Layout of the SFQ TDC, which is composed of 9,570 Josephson junctions and has a total supply current of 224.7 mA.

III. SFQ Time-to-Digital Converters (TDCs) with Current Recycling

A. Application of current recycling technique to SFQ TDC

Our SFQ TDC is composed of a 24-bit binary counter to measure TOF, an asynchronous FIFO controller using Muller-C circuits, an *n* by 24-bit FIFO buffer, and a 24-bit SR for readout. The details of the TDC design are described elsewhere [6], [7]. In this study, we designed current recycling SFQ TDCs with a 12 by 24-bit FIFO buffer by using the driver/receiver circuits shown in Fig. 5(a). In this design, we applied the current recycling technique to each buffer and the SR for readout because the circuit scale of these SFQ circuit blocks is almost the same as the supply current of 88.5 mA. Each circuit block is placed on different GPs and the bias current applied to buffer 1 is recycled to other circuit blocks (i.e., buffer 2, buffer 3, and so on, serially). The driver/receiver circuits are inserted between the binary counter and buffer 1 through buffer 12 and the SR for readout, where the total number of driver/receiver circuits is 386. In this TDC, the bias current of about 90 mA is recycled twelve times.

In the operation, when a "start trigger" signal is input to the binary counter, the counter starts to measure time. By inputting a "set" signal asynchronously with the "start trigger", the FIFO buffer controller turns ON. When "read" signals are input, the measured data in the counter are sent to the FIFO buffer and stored there asynchronously. The stored data can be read out to the room temperature electronics by inputting a "buffer_clk" signal and 24 "SR_clk" signals. The SFQ TDC can measure time intervals up to about 1.68 ms ($\cong$ 100 ps $\times$ (2^{24} -1)) because the time resolution of the TDC is set to 100 ps. When the counter overflows, it sends an "overflow" signal and finishes the measurement.

The layout of the current recycling TDC is shown in Fig. 5(b). The recycling TDC is composed of 9,570 Josephson junctions. The supply current to the binary counter is 136.2 mA and the total supply current of the SFQ TDC is 224.7 mA. By using the current recycling technique, we were able to reduce the supply current by 71%. It should be noted that we do not need to increase the supply current even if we further increase the capacity of the FIFO buffers.

B. Measurement results

We measured the time intervals of the "start trigger" and the "read" signals from a room-temperature pulse pattern generator (DG2020A, SONY Tektronix) by using the TDC, where the

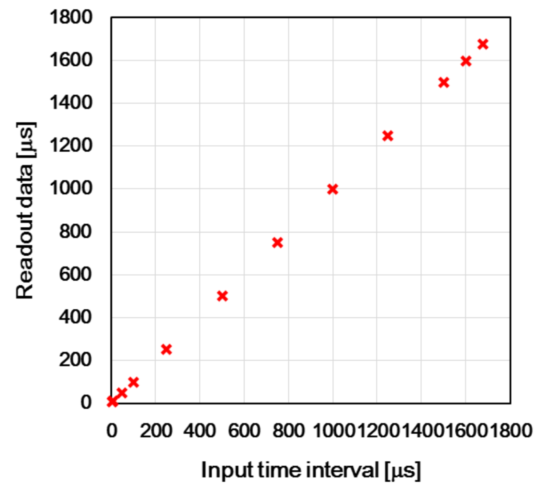

Fig. 6 Readout results using SFQ TDC. Measured time intervals are 5, 10, 50, 100, 250, 500, 750, 1000, 1250, 1250, 1500, 1600, and 1677.7 µs.

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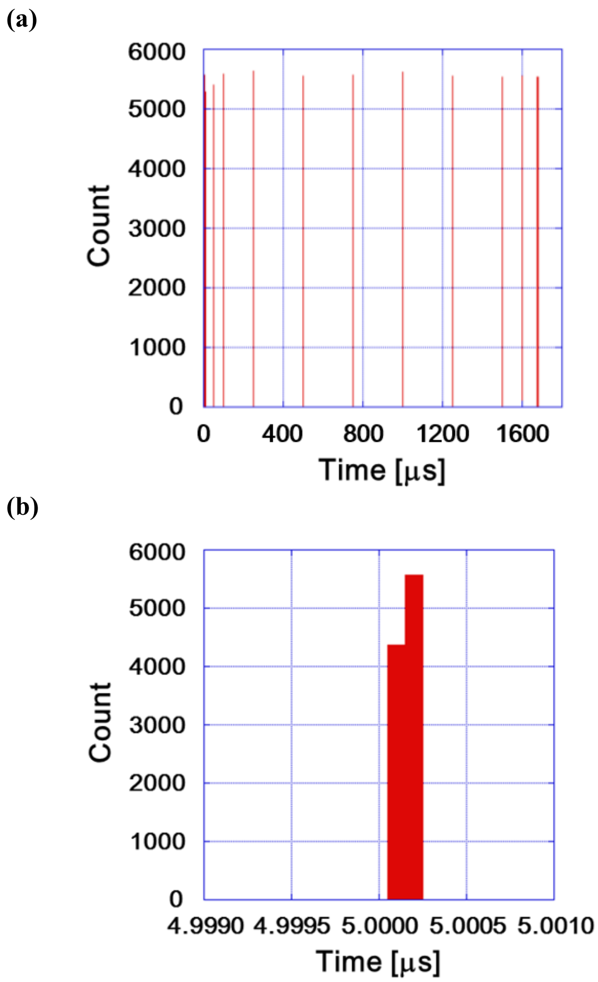

Fig. 7 (a) Histograms obtained by SFQ TDC. Measured time intervals are 5, 10, 50, 100, 250, 500, 750, 1000, 1250, 1250, 1500, 1600, and 1677.7 μs, where the time resolution of the SFQ TDC is 100 ps. (b) Example of enlarged view of the histograms, where the time interval is 5 μs.

input intervals were 5, 10, 50, 100, 250, 500, 750, 1000, 1250, 1500, 1600, and 1677.7 μs. Because the TDC has 12 buffers to store TOF data, we can measure 12 intervals at the same time. The relation between the input time intervals and the readout data is shown in Fig. 6. We were able to obtain a reasonable linear relation, confirming correct operations of the SFQ TDC. We repeated this measurement 10,000 times, recorded the results by using a LabVIEW system, and made histograms, as shown in Fig. 7. We can clearly see the large peaks corresponding to the input intervals in Fig. 7(a). Fig. 7(b) shows that the measured time distribution is within 100 ps. These results indicate that the TDC could measure time intervals with high precision at low error rates. However, the bias margin was very narrow and the correct operation could be observed only when the recycle current was 99 mA. We considered that the operation margin of the buffers is limited by the variation of the bias margins of the receiver circuits.

IV. Conclusion

We designed and confirmed the correct operation of signal transfer circuits for current recycling. In these transfer circuits, the magnetic coupling part is vertical against the GP boundary. By using these transfer circuits, we designed an SFQ TDC with a 12 by 24-bit FIFO buffer. We were able to reduce the total supply current of the TDC by 71% and demonstrated the operation. The results indicate that we can increase the capacity of the buffer in the SFQ TDC without increasing the supply current. This is the first demonstration of large current recycling of about 100 mA. This method could also be applied to any other large-scale SFQ circuit.

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