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SUMMARY We propose a neutron diffractometer system based on MgB$_2$ thin film detectors and an SFQ signal processor. Small dimensions of MgB$_2$ thin film detectors and high processing capability of the single flux quantum (SFQ) circuits enable us to handle several thousand or more detectors in a cryocooler, leading to a very compact system. In addition, the system can provide many diffraction patterns for different kinetic energies simultaneously. Kinetic energy is determined for individual neutrons by means of the time-of-flight method by using SFQ time-to-digital converters (TDCs). Digital outputs of the TDCs are multiplexed in time domain and sent to room-temperature electronics with reduced number of cables. A dual-input SFQ signal processor including TDCs and a multiplexer has been successfully demonstrated with a time resolution of 20 ns and power consumption of 400 $\mu$W. These values show high feasibility of the neutron diffraction system proposed here.

key words: neutron, diffraction, single flux quantum, time-to-digital converter, time-of-flight

1. Introduction

A neutron diffraction system is a strong tool for determining the atomic and magnetic structure of a material. In particular, the system has high sensitivity to light atoms such as hydrogen. The system is expected to be applied to drug-discovery research, because affinity for biological bodies is affected by the positions of hydrogen atoms inside a drug. The mechanism of superconductivity in oxide superconductors has not been revealed, while it is strongly related to the magnetic structures of the materials. Analyses based on neutron diffraction would help us to reveal the mechanism.

In recent years, several neutron sources with high flux density have been developed and have been easily accessible to researchers [1], [2]. At present, $^3$He gas tube detectors are used for detecting neutrons in any application because of high efficiency and high neutron-to-gamma flux ratio. However, gas tube detectors have typical dimensions of a few centimeters, so that detector array systems like a diffractometer become bulky. Response times and relaxation times of the gas tube detectors are of the order of 10 ms. These two kinds of times lead to very low counting rate, and users are obliged to spend relatively long time for obtaining experimental data.

In 2007, superconducting neutron detectors made of $^{10}$B-enriched MgB$_2$ thin films were demonstrated [3]. The detectors would use a non-equilibrium phenomenon caused by the nuclear reactions with energy of 2.3 MeV between $^{10}$B in MgB$_2$ and neutrons. A part of the energy is released to the superconducting MgB$_2$ film. The detectors have a meander line of MgB$_2$ and a hot spot is created inside the line when neutrons come to the detector. The temperature of the detector stage on which MgB$_2$ detectors are mounted needs to be set close to the transition temperature of an MgB$_2$ film for detecting neutrons effectively [3]. Typically, meander lines are confined to an area of 200 $\mu$m $\times$ 200 $\mu$m. The response time was measured to be smaller than 2 ns. These features make it possible to construct compact and fast detector array systems.

A neutron diffraction system is one of the most promising applications based on detector array systems. The systems will be made up of more than 1000 detectors. However, this leads to increased number of cables with which the detectors are connected to room-temperature electronics. Large heat inflow through these cables is unavoidable, so that the temperature of the detector stage becomes unstable in a conventional way. Thus, a low temperature multiplexing technique for the detector outputs is essential for reducing the number of the cables and heat inflow.

Single-flux-quantum (SFQ) circuits operate at a high frequency with very low power consumption [4], [5]. This feature is most appropriate for making a multiplexer working at low temperature. In fact, an SFQ multiplexer for a detector application has been studied so far [6].

In this paper, we propose a compact neutron diffraction system composed of MgB$_2$ thin film detectors and an SFQ signal processor. We describe configuration of the system and the operating principle of the processor. We also report preliminary results for an SFQ signal processor.

2. Configuration of the Neutron Diffraction System

Figure 1 shows a block diagram of our neutron diffraction system including a neutron source. A start signal is provided repeatedly to the neutron source and all the time-to-digital converters (TDCs) from a room-temperature generator. Triggered by each start signal, the source generates a flux of cold neutrons with various energies. These cold neutrons move to a detector array through a sample to be measured. Diffraction occurs in this process and a diffrac-
A detector probe is installed below the detector stage as shown in Fig. 2, and houses a sapphire substrate on which MgB$_2$ thin film detectors are formed. Several heaters and temperature sensors are installed around the detector probe to control the operating temperature of the MgB$_2$ thin film detectors. A scanner system based on a pulsed laser [7] is able to be installed in front of the detectors. The scanner is used for examining each detector before irradiation of neutrons because the response of the detectors to the pulsed laser is proven to be similar to the response to a neutron.

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The SFQ probe is set on the SFQ stage. The direction of the installation is the opposite side to the detector probe in order to avoid exposure of radiation. The SFQ probe is covered by double magnetic shield cans made of a kind of Permalloy. This enables us to reduce residual magnetic field at the probe. In addition, ferromagnetic materials are eliminated by a start signal. Japan Proton Accelerator Research Complex (J-PARC) has a representative neutron source. In the source, the spread is around 1 $\mu$s, while $T_{\text{neutron}}$ is 40 ms. Thus, dynamic range of 16 bits ($m = 16$) is enough for an actual system.

The number of detectors accommodated by the system $n$ is roughly expressed as

$$n = \frac{B T_{\text{neutron}}}{m},$$

where $B$ is smallest band width in the system. Usually, $B$ is determined by the throughputs of the room-temperature electronics in which real-time signal processing is executed. Our system prototype described later has $B$ of 2.5 MHz, which corresponds to the throughputs of a field programmable gate array (FPGA) used for the demultiplexer. If we assume $m = 16$ and $T_{\text{neutron}} = 40$ ms, $n$ becomes approximately 6000 in our system prototype. This means that heat inflow is suppressed remarkably through the cables because we use only 16 cables for 6000 detectors.

3. System Prototype

We have started to develop the system prototype. The aim of the development is to show potential of a system having a configuration indicated in Fig. 1. The development includes the installation of an SFQ signal processor to the SFQ stage and the installation of MgB$_2$ thin film detectors to the detector stage. We use a Gifford-Mac Mahon (GM) cryocooler for refrigerating these two stages. The temperature of the SFQ stage is kept as low as possible, while that of the detector stage is controlled precisely to be a temperature which is just below the transition temperature of the MgB$_2$ thin film detectors. The typical temperature of the SFQ stage and the detector stage are 4 K and 27 K, respectively.

Figure 2 shows a photograph of surrounding structures of the cold head in the GM cryocooler, though the cold head located at the center of the photograph is difficult to see. The cold head is thermally connected to the SFQ stage. The detector stage is fixed to the SFQ stage with stainless-steel pillars that have low thermal conduction.
nated from the inside of the shield cans and their neighborhoods.

As described above, impulse-like outputs of the detectors operating around 27 K have to be sent to the comparators of the SFQ circuits operating at 4 K with little distortion. In other words, we need both bandwidths and low thermal conduction for cables with which the two probes are connected. Considering lengths or attenuations of the cables, we employ CuNi coaxial semi-rigid cables. A similar situation occurs between the probes and room-temperature electronics. We need longer cables in this situation. Thus we use brass coaxial semi-rigid cables having higher electric conductivity than CuNi.

These coaxial cables are connected properly through the RF connectors mounted on the RF connector plate cooled down to the same temperature as that of the SFQ stage. DC bias lines are also provided to the two probes through connectors mounted on the DC connector plate. This enables us to do maintenance easily and to change connections if necessary.

Several other techniques are introduced to our system prototype for reducing noise including crosstalk, for suppressing the effect of vibration of the GM cryocooler, for widening bandwidth in signal lines, and for increasing testability. For example, several kinds of low-pass filters are used for signal lines or bias lines in order to suppress mixture of noises. In addition, all the setting values such as bias currents are remotely-operable, which is required in an actual experiment of neutron irradiation.

System noise is estimated by comparing this cryocooler-based system and a conventional system. The conventional system is composed of a liquid helium bath, low noise amplifiers, and an oscilloscope. We measured power spectrum of the same SFQ analog-to-digital converter (ADC). The ADC used here has very high current sensitivity [8], so that the ADC works as a good monitor of system noise. Noise power in the system prototype with a frequency band of 1 kHz–5 MHz is increased by 3 dB compared to that in the conventional system placed inside of an electromagnetic shielded room. We think from this estimation that our system prototype is applicable to an actual experiment of neutron irradiation.

4. Demonstration of SFQ Signal Processor

We also started to develop SFQ signal processors. Figure 3 shows the block diagram of a dual-input SFQ signal processor developed in this study. The dual-input SFQ signal processor is composed of three identical quasi-one-junction SQUIDs (QoS), two TDCs, and a multiplexer. The QoSs are used as comparators with a single threshold [6], though they have periodic response to magnitude of an input signal. The QoSs are designed so as to readout detector outputs through relatively long CuNi cables. Current sensitivity of the QoSs is measured to be a few μA, which is sufficient for picking up the detector outputs.

In this study, all the inputs for generating start signals and stop signals are provided from external signal sources. For simplicity, we supply a continuous sinusoidal wave to QOS 0 and also supply the same wave having a phase shift of π to QOS A and QOS B as the inputs. An embedded SFQ ring oscillator generates clocks with a frequency of 12.8 GHz. The clocks are provided to the QoSs. QOS 0 generates an SFQ pulse when the magnitude of the input exceeds the threshold of the QOS 0. This pulse serves as a start signal common to TDC A and TDC B. QOS A and QOS B generate a stop signal for TDC A and TDC B, respectively.

The main component of the TDCs is a 4-bit counter. The clock generator CLK A and CLK B generate 50-MHz clocks which are made by dividing master clocks with a frequency $f_m$ of 12.8-GHz. TDC A counts 50-MHz clocks of CLK A between a start signal from QOS 0 and a stop signal.
Fig. 4 Microphotograph of a dual-input SFQ signal processor. The processor was fabricated with the SRL standard process based on 2.5-kA/cm² Nb/AlOₓ/Nb Josephson integrated circuit technology.

Dynamic range of 4-bits for the TDCs is insufficient for an actual diffraction system. However, it is very easy to expand the dynamic range because the counters are made up of conventional SFQ toggle-flip-flops (TFFs). Time resolution is set to be 20 ns in the TDCs. This time resolution is the best value under the restriction of our signal source used here as described later. Note that the time resolution is easy to be adjusted to the specification of an actual neutron source, because the clock generators CLK A and CLK B are binary frequency dividers composed of the same TFFs.

Figure 4 shows a microphotograph of a dual-input SFQ signal processor. The processors were fabricated with the SRL standard process [9] based on 2.5-kA/cm² Nb/AlOₓ/Nb Josephson integrated circuit technology. The SFQ components except the QOSs were designed using the CONNECT top-down design tools [10]. The total number of Josephson junctions was 1252, and the whole processor occupied 1.8 mm × 1.8 mm.

Figure 5 displays an example of a set of waveforms in a test experiment. SFQ processors are examined in the conventional system described above. Output waveforms of corresponding SFQ/DC converters are observed for CLK A, CLK B, and Bit 0. Thus, an SFQ pulse is generated both at each rising edge and at each falling edge in the waveforms. These signals are amplified by 46 dB with very low noise semiconductor amplifiers with bandwidth of 120 MHz, and recorded in a digital oscilloscope. The repetition rates in CLK A and CLK B are set to be about 50 MHz by adjusting bias current supplied to the embedded ring oscillator. We found from these waveforms that an SFQ pulse was generated 10 ns later at CLK B than at CLK A.

We show a sinusoidal waveform of Input S and the threshold of QOS 0 at the bottom of Fig. 5. Here, Input S is a current supplied to QOS 0 as shown in Fig. 3. When the magnitude of Input S exceeds the threshold at the rising edge, a start signal is sent to TDC A and TDC B. The same wave with a phase shift of π is provided to both Input A and Input B. Thus, a stop signal for QOS A and that of QOS B are generated at the timing when the magnitude crosses the threshold at the falling edge. The threshold of QOS A and QOS B are the same and indicated in Fig. 5. In the case shown in Fig. 5, 15 clocks are provided to both TDC A and TDC B during a period between the start signal and the stop signal. Thus, 4-bit parallel digital outputs of “1111” would be obtained. The waveform ‘Bit 0’ indicated in Fig. 5 shows that TDC A outputs “11” as the least significant bit after the stop signal is generated. TDC B also outputs “11” 10 ns later, both TDCs output “11” for each bit. We successfully demonstrated the measurement of the time difference and the time-division multiplexing. In this experiment, dual-input SFQ signal processor consumed 400 μW.

Figure 6 shows measured time difference as a function of input time difference determined by period of the sinusoidal wave. The linear dependence was obtained. This means that our TDCs worked correctly. We also observe the spread of the data of ±20 ns. This is caused by a time
jitter of 20 ns in our signal source used here.

As mentioned in Sect. 2, our diffraction system has capability to accommodate 6000 detectors with dynamic range of 16 bits. If $T_{\text{neutron}}$ is 40 ms, clocks with a frequency of 2.1 MHz ($= f_{m}/6000$) to be distributed to each TDC can be generated for 6000 TDCs by using the master clocks with a frequency of 12.8 GHz. A 16-bit serial read/write memory should be added to each TDC for handling many data. Multiplexing is executed by reading serial data stored in memories in an ascending order with the master clocks [11], and then serial/parallel conversion is done. Power consumption can be estimated to be $250 \mu W$ for a single input. We can easily reduce the power consumption to $25 \mu W$/input by decreasing a value of a bias resistance, because power is consumed mostly at bias resistors [12]. From the point of view of the power consumption, SFQ signal processor consumes only 150 mW for 6000 detectors. This value is still acceptable for refrigeration by our GM cryocooler, though the acceptable input power for refrigeration by our GM cryocooler is limited to around 20 mW because of insufficient uniformity in characteristics of detectors and small integration level of SFQ circuits.

5. Conclusion

We described a concept of our neutron diffractometer system based on MgB$_2$ thin film detectors and an SFQ signal processor. The system has high potential to accommodate several thousand or more detectors in a commercially-available cryocooler. The total system would be very compact compared to a system based on conventional gas tube neutron detectors. In our system, kinetic energy is determined for individual neutrons detected at the detectors by measuring TOF with SFQ-TDCs. Mapping of the number of the detected neutrons for each kinetic energy corresponds to a diffraction pattern. An SFQ signal processor including SFQ-TDCs and a time-domain multiplexer can handle outputs of a large number of detectors in a cryocooler because the SFQ circuits have the nature of low power consumption as well as the high-speed nature. A dual-input SFQ signal processor has been successfully demonstrated with a time resolution of 20 ns and powerconsumption of $400 \mu W$. These values show high feasibility of our neutron diffraction system.

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References

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